



MSP-REFRAM

Coordination and Support Action (CSA)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 688993.

Start date : 2015-12-01 Duration : 19 Months



Management of waste from secondary resource processing: identification, environmental evaluations

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MSP-REFRAM - Contract Number: 688993
Multi-Stakeholder Platform for a Secure Supply of Refractory Metals in Europe

Document title	Management of waste from secondary resource processing: identification, environmental evaluations
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Number of pages	69
Document type	Deliverable
Work Package	WP3
Document number	D3.4
Issued by	CARTIF
Date of completion	2017-02-03 08:22:02
Dissemination level	Public

Summary

Management of waste from secondary resource processing: identification, environmental evaluations

Approval

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0. INTRODUCTION

The objectives of this task were very ambitious at the proposal phase. It was stated that several recovery processes from industrial wastes and tailings were going to be studied using the **Life Cycle Assessment (LCA)** methodology in order to determine the environmental impacts of those processes, assessing several scenarios and covering several impact categories, for the five metals studied. A brief description of how LCA is structured can be read below.

Life Cycle Assessment methodology

Life Cycle Assessment is an environmental tool that allows the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040:2006)¹. The LCA methodology is clearly described by the following international standards:

- ISO 14040:2006. Environmental management. Life Cycle Assessment. Principles and framework.
- ISO 14044:2006². Environmental management. Life Cycle Assessment. Requirements and guidelines.

The LCA methodology is structured in four steps, as it can be seen in figure 1.

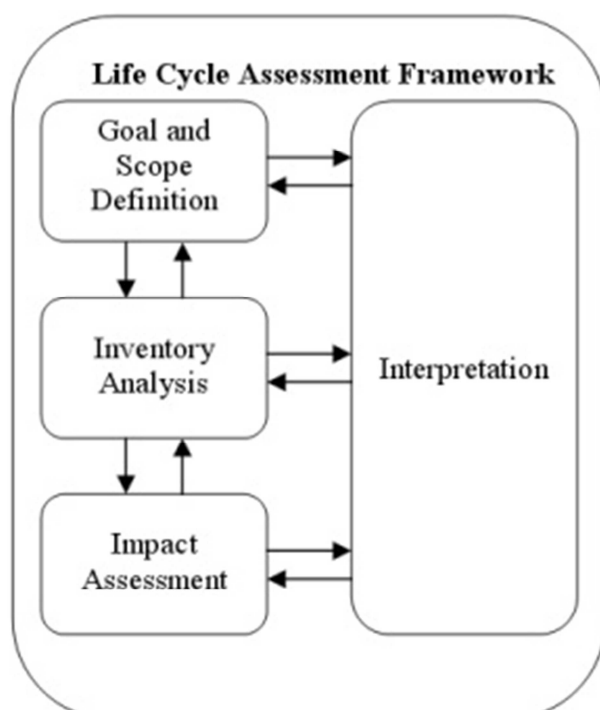


Figure 1. Life Cycle assessment framework. Source: ISO 14040

1. - *Goal and scope:*

The first stage of the LCA methodology defines why the assessment is developed, which the target audience is, and some important decisions, among others, as:

- Functional unit selection
- System boundaries
- Impact indicators selection

2. - *Inventory analysis:*

In this stage, the complete information about the system studied is collected, including energy and material inputs and outputs, as well as emissions to air, soil and water. Special attention must be paid to the data quality and the acquisition methods.

3. - *Impact assessment:*

After inventory compilation, classification and characterization are developed in this stage, in order to sort the inventory according to the effect on the environment and the multiplication by a factor in order to evaluate its contribution to that effect. Depending on the indicators selected, other stages (normalization or weighting are optional).

4. - *Interpretation:*

The final conclusions of the study are obtained in order to select strategies to improve the environmental performance of the system evaluated.

The deployment of this methodology in this context would provide useful information to incorporate to the global knowledge generated in this project in order to establish strategies for the selection of the best recycling and recovery options.

It would have provided also information about the environmental impact of recovery and recycling from secondary sources and industrial waste vs. the traditional extraction.

But at this stage of the Project, it is evident that the preliminary approach of the task was too ambitious and in many cases, unrealizable.

First of all, the on-going research and the info collected in the previous delis of this task (D3.2 and D3.3) has proved that it is only worth to study one metal, and that metal is **Tantalum**, as time and human resources are limited, and considering also that this metal offers the most promising options for innovation

In the other hand, LCA is a methodology that needs a very complete data input (materials, energy, waste generation, etc.) and as it has been proven, that info is not available. There is a lot info missing in the recovery and recycling processes, which does not allow developing a LCA robust enough to be considered as representative.

So, the consortium has agreed to select one representative process for the secondary resources (industrial wastes and tailings) for Ta, and the main objective of the task will be trying to identify and describe one Ta recovery process, and assess how that process meets the EU criteria in terms of environmental releases, waste fluxes, energy savings, etc.

As a first general approach, along this deliverable, information about the European Commission position in terms of Wastes and Energy will be detailed. But also information about the extractive industry, mining and non-ferrous metal industry will be collected, in order to described the EU targets and determine what are the main gaps between the Ta recovery process studied and the EC objectives and recommendations.

01. EUROPEAN STRATEGY REGARDING PREVENTION AND RECYCLING OF WASTE

Starting from a generic point of view, the EU policy has always contributed to improve the resource-efficiency and reduce negative environmental impacts.

In December 2005, the Commission published a Communication on the Thematic **Strategy on the Prevention and recycling of waste** ³, entitled “*Report from the commission to the European parliament, the council, the European economic and social committee and the committee of the Regions on the thematic strategy on the prevention and recycling of waste Sec (2011) 70 final*”

The Strategy is based in seven key actions to achieve its objectives:

- Implementation and enforcement of existing EU waste legislation
- Simplification and Modernisation
- Introducing life-cycle thinking in waste policy
- Waste Prevention
- Improving the knowledge base
- Development of recycling standards
- Further elaboration of the EU's recycling policy

The main objective of the Strategy is focused on avoiding waste as much as possible and use waste as a new resource. Avoiding landfill as final destination, developing more and better recycling processes and obtaining energy recovery from wastes is expected to have environmental, social and economic benefits.

Based in this strategy, several improvements and simplification of legislation has been achieved, including the life cycle thinking approach, focusing on the waste prevention and establishing recycling ambitious targets.

Although current policies have developed higher recycling rates and a decrease in the landfill destination, the increase in waste generation is an issue to be considered.

Aligned with the waste and recycling strategy, in 2005 the European Commission proposed a **Strategy on the Sustainable Use of Natural Resources** ⁴, in order to reduce the environmental impacts associated with resources.

The European Commission reported that in the past 50 years, humans have changed ecosystems more rapidly and extensively than any comparable period of time in human history. Sustainability must be strongly related to sustainability production and consumption (also end of life management), but considering the trend in population and consumption

growth, the overall objective is therefore to reduce the negative environmental impacts generated by the use of natural resources in a growing economy.

The activities described in the strategy are included in the following actions:

- improve our understanding and knowledge of European resource use, its negative environmental impact and significance in the EU and globally,
- develop tools to monitor and report progress in the EU, Member States and economic sectors,
- foster the application of strategic approaches and processes both in economic sectors and in the Member States and encourage them to develop related plans and programmes, and
- raise awareness among stakeholders and citizens of the significant negative environmental impact of resource use

The environment policy has been adopted an integrated approach during the last years, considering all life cycle stages of the activities. This life-cycle thinking is reflected in particular in the Thematic Strategy on the Prevention and Recycling of Waste previously mentioned.

Also the **Integrated Product Policy** ⁵ (IPP), that seeks to minimise the environmental impact of products by looking at all phases of a products' life-cycle and taking action where it is most effective. The life cycle approach includes:

- Raw materials
- Transportation
- Manufacturing
- Distribution, use
- Maintenance
- End of life

But it also includes the intervention of a lot of actors in the product supply chain. With this amount of products, stages and actors involved, it is not possible to have one only policy measure for everything, so a whole variety of tools can be used to improve this approach, such as:

- economic instruments
- substance bans
- voluntary agreements

-
- environmental labelling
 - product design guidelines

All these strategies are devoted to obtain a global ***Sustainable Development***. The European Commission presented the ***Sustainable Consumption and Production and Sustainable industrial Policy (SCP/SIP) Action Plan*** ⁶. This plan is focused on the improvement of the environmental impact of products (along their life cycle).

Related policies to this strategy are:

- Eco-design of Energy-related Products Directive (EuP)
- Eco-Innovation Action Plan (EcoAP)
- Ecolabel Scheme
- Eco-Management and Audit Scheme (EMAS)
- Energy Labelling
- European Compliance Assistance Programme
- Environmental Technology Verification (ETV)
- European SCP Food Round Table
- Green Public Procurement (GPP)
- Guidance on unfair Commercial Practices - extract on misleading green claims
- Integrated Product Policy (IPP)
- Retail Forum
- Roadmap to a Resource Efficient Europe
- Thematic Strategy on the Sustainable Use of Natural Resources
- Thematic Strategy on Waste Prevention and Recycling

After the last ***revision of the EU waste policy*** and legislation, the ***Circular Economy Approach*** ⁷ and the legislative proposal on waste established ambitious objectives for waste reduction, management and recycling. Key elements of the revised waste proposal include, among others:

- **Target for recycling 65% of municipal waste** by 2030;
- **Target for recycling 75% of packaging waste** by 2030;
- A binding landfill target to reduce landfill to maximum of 10% of municipal waste by 2030;

- A ban on landfilling of separately collected waste;
- Promotion of economic instruments to discourage landfilling ;
- Simplified and improved definitions and harmonised calculation methods for recycling rates throughout the EU;
- Concrete measures to promote re-use and stimulate industrial symbiosis –turning one industry's by-product into another industry's raw material;
- Economic incentives for producers to put greener products on the market and support recovery and recycling schemes (e.g. for packaging, batteries, electric and electronic equipment, vehicles).

A **waste prevention guideline**⁸ was developed by the Commission and published in 2012, establishing a clear difference between waste prevention and waste management.

Although waste management is a key point, waste prevention is considered priority in order to develop a more sustainable model.

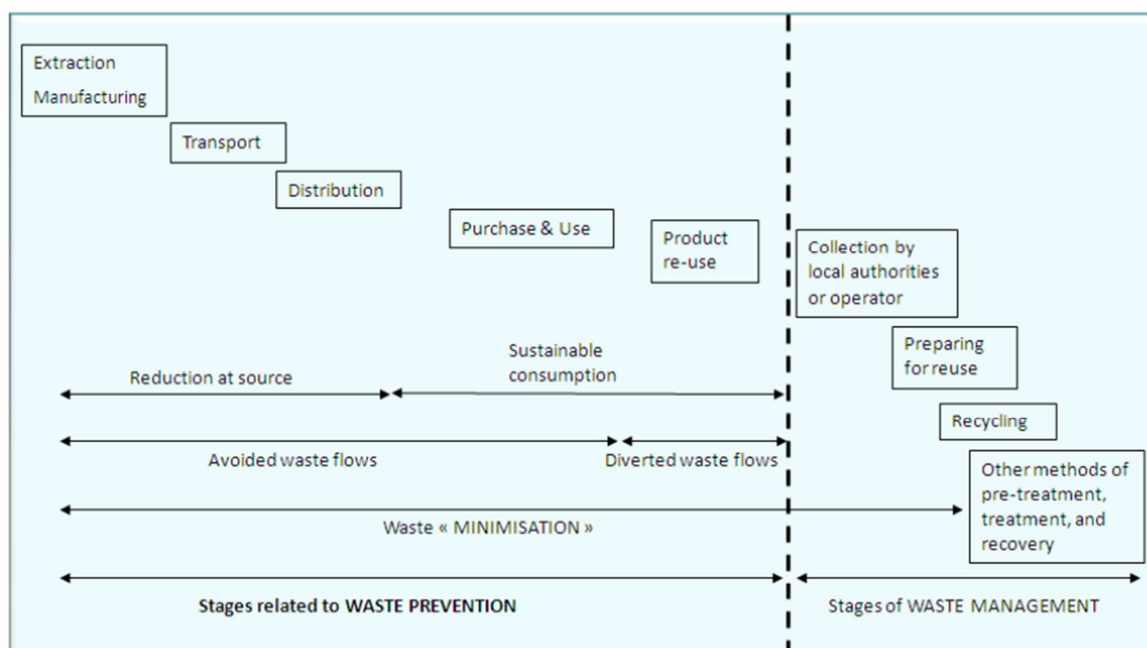


Figure 2. Waste prevention vs. waste management. Source: Waste prevention guideline by the EC.

In the same way, the scope of Waste prevention adopted from by the European Environment Agency can be seen in figure 3.

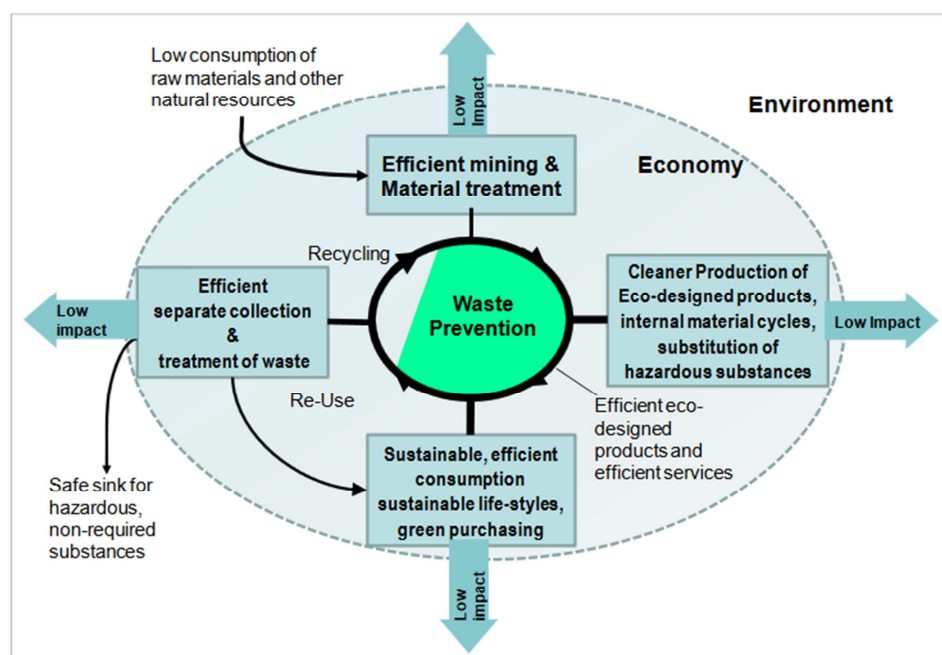


Figure 3. Waste prevention scheme. Source: Waste prevention guideline by the EC.

The waste hierarchy adopted by European Union was clearly established, in order of preference:

- Waste prevention
- Preparing for reuse
- Recycling
- Other recovery
- Disposal

The strategies proposed by the waste prevention guideline document are structured in three different alternatives

- a) Informational strategies**, aimed to change behaviour and make informed decisions, include:
 - Awareness campaigns
 - Information on waste prevention techniques
 - Training programmes for competent authorities
 - Ecolabelling
- b) Promotional strategies**, incentivising behavioural change and providing financial and logistical support for beneficial initiatives, include:

-
- Support for voluntary agreements
 - Promotion of reuse and repair
 - Promotion of environmental management systems
 - Clean consumption incentives
 - Promotion of research and development

c) Regulatory strategies, enforcing limits on waste generation, expanding environmental obligations and imposing environmental criteria on public contracts, include:

- Planning measures
- Taxes and incentives, such as pay as you throw schemes
- Extended Producer Responsibility policies
- Green Public Procurement policies
- Ecodesign requirements

There is an existing interest from the European Commission for the integration of the waste prevention into other policy areas, as

- Integrated Product Policy (IPP),
- Integrated Pollution Prevention and Control Directive (IPPC),
- Eco-Management and Audit Scheme (EMAS)
- EU Ecolabel,
- The Ecodesign Directive,
- The REACH Directive,
- The Environmental Technologies Action Plan (EATP),
- The Sustainable Consumption and Production and Sustainable Industrial Policy (SCP/SIP) Action Plan
- The European Commission's Communication on Green Public Procurement (GPP).

The waste prevention strategy, as it should be developed according to the European Commission, should include the following stages:

1. Current situation assessment
2. Setting priorities
3. Strategy elaboration

-
4. Planning and implementation
 5. Monitoring progress

The ***Roadmap to a Resource Efficient Europe*** ⁹ specify several actions that must be developed in terms of sustainable production and consumption, as

Improving products and changing consumption patterns

Objective 2020: Citizens and public authorities have the right incentives to choose the most resource efficient products and services, through appropriate price signals and clear environmental information

Boosting efficient production

Objective 2020: Market and policy incentives that reward business investments in efficiency are in place.

The EC will strength the requirements on Green Public Procurement, will assess products, services and companies based on a comprehensive assessment of environmental impacts (environmental footprint), Ecodesign directive and support networking activities.

Changing waste into resources

Objective 2020, waste is managed as a resource. Waste generated per capita is in absolute decline. Recycling and re-use of waste are economically attractive options for public and private actors due to widespread separate collection and the development of functional markets for secondary raw materials.

The EC will stimulate secondary markets, assess the introduction of minimum recycling rates in products, will fight illegal waste shipment and facilitate BATs documents.

Support of research an innovation

Objective 2020 scientific breakthroughs and sustained innovation efforts have dramatically improved how we understand, manage, reduce the use, reuse, recycle, substitute and safeguard and value resources.

The EC will develop innovation partnerships for meeting resource efficiency goals, develop Joint Technology Initiatives (private-public partnerships), support for eco-innovation, and focus H2020 funding on key resources objectives.

Mining and metals is considered in this document as a key sector, and textually it is addressed:

“Improved efficiency of natural resources such as metals and minerals are essential aspects of resource efficiency. Their specific risks, including security of supply, are addressed in the Raw Materials Initiative, as well as the climate and energy policies under the Resource Efficiency Flagship, so they will not be treated extensively in this section, although the interaction between their use and other resources is recognised.

As we move towards a genuinely consumption based, sustainable materials management or a "circular economy", where waste becomes a resource, a more efficient use of minerals and metals will result. The steps outlined in section 3 of this roadmap will have a direct impact on the efficiency of minerals and metal resources, through measures to take life-cycle impacts more into account, to avoid waste, reuse and recycle more, improved research and innovation and other measures to improve market structures”.

03. EUROPEAN STRATEGY REGARDING ENERGY RELATED TO ENVIRONMENT

Energy is probably one of the most complex concepts to be evaluated. Europe energy demand is increasing, but European policies want to reduce the environmental impact of the energy consumption.

The European Strategy is focused in assuring three main goals:

- Security of supply
- Competitiveness
- Sustainability

The EU has quantified the targets in terms of energy for several deadlines:

Table 1. Energy targets. Source: European Energy Roadmap.

Year	2020	2030	2050
Target	<ul style="list-style-type: none"> - Reduction of GHG (20%) compared to 1990 level, - 20% energy form renewable sources - 20% energy efficiency improvement 	<ul style="list-style-type: none"> - 40% reduction in greenhouse gas emissions - At least 27% EU energy from renewables - Increase energy efficiency by 27-30% - 15% electricity interconnection (i.e. 15% of electricity generated in the EU can be transported to other EU countries) 	<ul style="list-style-type: none"> - 80-95% cut in greenhouse gases compared with 1990 levels

The **European Energy Roadmap** ¹⁰, developed in 2011, states that the pattern of energy production and use in 2050 is already being set. Considering that environmental targets are focusing on an 80-95% reduction in GHG from 1990 levels, an important challenge must be addressed. The 80% GHG reduction puts great pressure on energy systems. The main goal is the decarbonisation of the energy system, and a big expectation is focused on the Carbon Capture and Storage solutions, so uncertainty is the major barrier to the investment.

In order to achieve the energy system transformation, the Roadmap establishes ten structural changes that need to be accomplished:

- Decarbonisation of the energy system
- Higher capital expenditure and lower fuel costs
- Increasing role of electricity
- Electricity prices increase (until 2030) and posterior decrease
- Increase of expenditure in household
- Energy savings throughout the system
- Important increase of the renewables
- Carbon capture and storage
- Contribution of the nuclear energy
- Decentralisation and centralised system increasingly interaction

The scheme of primary energy consumption expected in the EU can be seen in figure 4.

As it can be seen, the primary energy consumption is expected to decrease from 2005 to 2050 in the EU28.

This is a great challenge not only for the state members, but also for the society, as it is a conceptual change in the energy system.

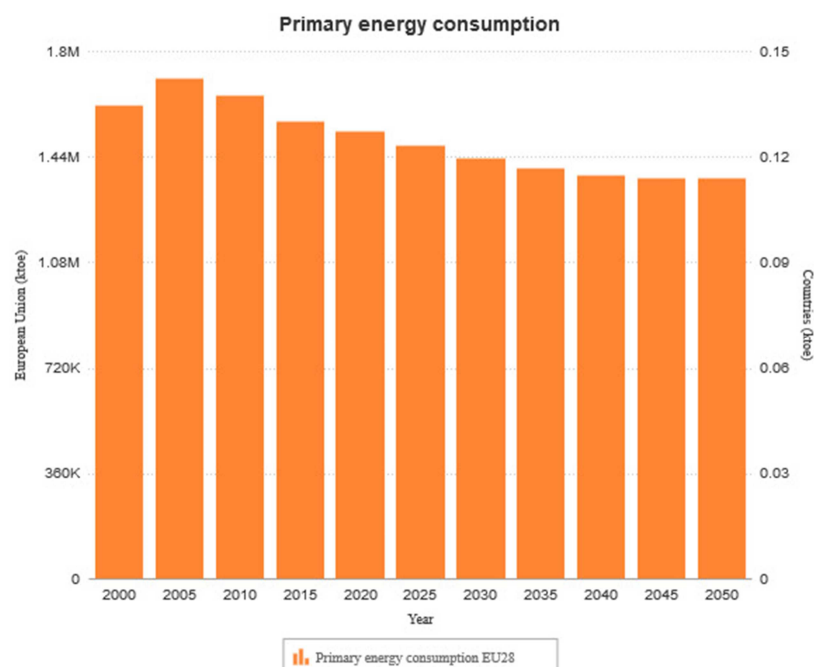


Figure 4. Primary energy consumption estimation. *Source:* Energy modelling-interactive graphs (<https://ec.europa.eu/energy>)

But this primary energy consumption reduction is not enough. That reduction must be linked to a stronger CO₂ emissions decrease (figure 5), in order to be aligned with the energy targets (related to the environment) in 2050.

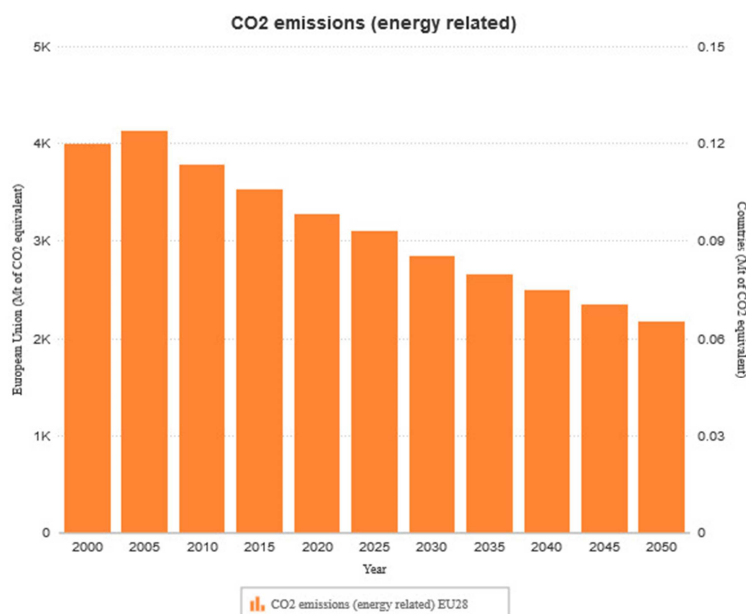


Figure 5. CO₂ emissions (energy related). Source: Energy modelling-interactive graphs (<https://ec.europa.eu/energy>)

Only ensuring both scenarios (primary energy decrease and lower CO₂ emissions per kWh production) will lead to the sustainability objectives established by the EC, in order to ensure a responsible management of the energy, resources and climate objectives.

As it has been described before, energy plays a key role in the EU climate objectives, and needs to be considered as a priority towards a new model.

04. ESPECIFIC MINING AND EXTRACTIVE INDUSTRY LITERATURE AND EUROPEAN COMMISSION REFERENCES RELATED TO THE ENVIRONMENT

In order to know how far the current and future actions related to the waste management in refractory metals extractive industries are from the European programmes and strategies, a summary of several documents have been collected and commented in this section, only related to the extractive mining industry.

The following documents (briefly commented) will help to know the current objectives and the Best Available Techniques (BATs) proposed by different organizations and Public Authorities in terms of waste from extractive industries management.

Concerning to **Directive 2006/21/EC**¹¹ several references for measures, procedures and guidance are provided, with the objectives to reduce, as far as possible, any adverse effects on the environment, in particular water, air, soil, fauna and flora and landscape as a result of the management of waste from the extractive industries.

In this directive, prospecting, extraction, treatment and storage of mineral resources and the working of quarries (extractive waste) are included.

One of the objectives of this Directive is that Member States take the necessary measures to ensure that extractive waste is managed without endangering human health and without using processes or methods which could harm the environment. Also the uncontrolled depositing of extractive waste must be avoided.

The environmental and/or human health effects must be reduced as far as possible in terms of effects related to the extractive waste, during the process development but also after its closure, and the companies are encouraged to use the best available techniques, taken into account the technical characteristics of the waste facility, its geographical location and the local environmental conditions.

This directive also makes the member states ensure that the operator draws up a *Waste Management Plan* for the management of the extractive waste, taking into account a sustainable development approach.

The management plan is established on the basis of three main pillars:

- *Reduction of waste production.* Depending on the mineral to be extracted, a waste management strategy must be designed during the design phase, recommending placing extractive waste back into the excavation void after extraction of the mineral as far as is technically, environmental and economically feasible, including putting topsoil back in place after the closure of the waste facility,
- Encourage the *recovery of extractive waste* by means of recycling, reusing or reclaiming wastes,
- Ensure *short and long-term safe disposal of the extractive waste*, stimulating low or zero monitoring management of closed facility, ensuring avoiding long term negative effects and the geotechnical stability.

In order to achieve the previously mentioned objectives, the Waste Management Plan should also include the following elements:

- Classification of the waste facility (Annex III of the directive)
- Waste characterization (Annex II)
- Waste generation process and post-treatment
- Waste effects on the environment and human health
- Control and monitoring procedures
- Closure plan
- Water deterioration prevention measures

All this information should be enough for the competent authority to evaluate the operator's ability to meet the objectives of the waste management plan. The competent authority shall approve the waste management plan on the basis of procedures to be decided by the Member States and shall monitor its implementation.

The directive also refers to the *construction and management of waste facilities*, but in a very simple and obvious way, paying special attention to the evaluation of the technical skills of the staff involved, the location of the plant regarding protected areas and considering soil, air, groundwater or surface water pollution prevention. Also the closure plan must be considered during the plant design phase. Some details about the incidents communication plan are explained in the Directive, as well as the emergency and contingency plan to be deployed.

A *prevention of water status deterioration, air and soil pollution* is also included, considering and evaluating, in terms of leachate issues:

- the leachate generation potential during both the operational and after-closure phase of the waste facility
- preventing or minimising leachate generation and surface water or groundwater and soil from being contaminated by the waste
- collecting and treating contaminated water and leachate from the waste facility to the appropriate standard required for their discharge

Also measures for dust and emissions must be adopted, as well as risk measurements.

The ***Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities*** ¹² was generated by the European Integration Pollution Prevention Control Bureau (EIPPCB), an output oriented team which produces reference documents on Best Available Techniques, called BREFs, the main reference documents used by competent authorities in Member States when issuing operating permits for the installations that represent a significant pollution potential in Europe.

This BREF on tailings and waste rock in mining activities is based on ores that have the potential for a significant environmental impact, and the starting point of it is related to the Communication from the European Commission COM(2000) 644 on the “Safe Operation of Mining Activities”.

This document is the result of the exchange of information between the European Union's member States and the mining industry, as an agreement to develop a BAT reference document after Aznalcollar and Baia Mare tailings dam bursts.

The BREF includes references to the following metals (aluminium, cadmium, chromium, copper, gold, iron, lead, manganese, mercury, nickel, silver, tin, tungsten, zinc).

As a first approach, the BREF enumerates several options for managing tailings and waste-rock. The most common methods are:

- discarding slurred tailings into ponds
- backfilling tailings or waste-rock into underground mines or open pits or using them for the construction of tailings dams
- dumping more or less dry tailings or waste-rock onto heaps or hill sides
- using the tailings and waste-rock as a product for land use, e.g. as aggregates, or for restoration
- dry-stacking of thickened tailings
- discarding tailings into surface water (e.g. sea, lake, and river) or groundwater.

The selection of any of the previous management actions depends mainly of cost, environmental performance and risk of failure

According to the BREF “The main environmental impacts from tailings and waste-rock management facilities are impacts associated with the site location and relative land take as well as the potential emissions of dust and effluents during operation or in the after-care phase. Furthermore, bursts or collapses of tailings and/or waste-rock management facilities can cause severe environmental damage and even loss of human life. The bases for the successful management of tailings and waste-rock are a proper material characterisation, including an accurate prediction of their long-term behaviour, and a good choice of site location.”

Considering that several of the Best Available Techniques are specifically referred to the metals previously enumerated, just a few of the generic BATs are listed below, as a simplified summary:

- Selection of the mining method during the design stage in order to minimize tailings and rock wastes
- Maximize the opportunities for the alternative use of tailings and waste-rock, such as aggregate, restoration of other mine sites or backfilling
- Preference of underground mining vs. open pit (if possible)
- Life cycle management plan
- Reagent consumption reduction
- Prevent water erosion
- Prevent dusting
- Prevent acid rock drainage (ARD) or control its impact
- Re-use process water
- Process water mix
- Sedimentation ponds
- Suspended solids removal

- Alkaline effluents neutralizing
- Arsenic and ferric salts addition
- For treating acidic effluents, deployment of active (limestone or caustic soda) and/or passive treatments (wetlands, drains and wells)
- Use of continuous working systems, belt drives encapsulation
- Special care for the dam design and operation

There is also a section for the emerging techniques for the management of tailings and waste-rock in mining activities, including information about:

- Co-disposal of iron ore tailings and waste-rock
- Inhibiting progress of ARD
- Recycling of cyanide using membrane technology
- Lined cells
- Utilisation of treated red mud to remediate problems of ARD and metals pollution
- Combination of SO₂/air and hydrogen peroxide technique to destroy cyanide

This BREF is a very detailed document that can be consulted in order to include interesting strategies for a good recovery process from tailings and waste rocks.

05. SPECIFIC NON FERREOUS METALS INDUSTRIES PREVENTION AND CONTROL. RECOMMENDATIONS BY THE EC

The document ***Best Available Techniques (BAT) Reference Document for the Non-Ferrous Metals Industries***¹³ is a specific document focused on the secondary metal sources. 42 non-ferrous metals were identified, and eight groups of metal with similar processing and production methods have been described. Those metals groups conformed are:

- Copper and its alloys;
- Aluminium and its alloys and the recycling of salt and aluminium from salt slags;
- Lead and tin;
- Zinc and cadmium;
- Precious metals;
- Ferro-alloys (e.g. FeCr, FeSi, FeMn, SiMn, FeTi, FeMo, FeV, FeB);
- Nickel and Cobalt;
- Carbon and graphite electrodes

The conclusions of this document are related to the environmental impacts in the non-ferrous metals, examining the conditions under which this environmental performance has been achieved and selecting the best available techniques.

No specific reference is made in this document to the metal selected (Tantalum), except in the description of the Lead and Tin manufacturing, where it is described that the refining stage of lead generates other metal-rich solids that can be recycled to the appropriate production process, being the slag from the production of tin the main source of Tantalum and Niobium.

Also some references regarding the high temperatures of the refractory metals are described: *“The very high melting temperatures of refractory metals like tungsten and molybdenum, tantalum or niobium do not allow melting in a normal melting furnace. For high melting point metals, the electron beam furnace has been developed using accelerated electrons as an energy source to impart their energy into the furnace charge. The electron beam melting furnace is used to produce high-purity inclusion-free metals. The ability to melt high-purity metals is due to the perfectly clean high temperature heat source (electrons) and the water-cooled copper hearth. The melted metal freezes against the copper so that the melt is only in contact with its own solid. Electron beam melting and refining is a well-established process for the production of ultra-clean refractory metals”*

This document also describes several techniques for reducing the environmental impact of the installation that can be structured in three main categories:

- Management techniques
- Process integrated techniques
- Energy reduction and abatement techniques

Table 2 shows some examples in recycling and reuse

Table 2. Recycling and reuse examples. Source: BAT for the non-ferrous metal industries.

Source of the residues	Associated metals	Intermediate product or residue	Options for recycling or reuse
Raw material handling, etc.	All metals	Dust, sweepings	Feed for the main process
Smelting furnace	All metals	Slag	Return to smelting; construction material; abrasive industry; part of slag may be used as refractory material, e.g. slag from the production of chromium metal
Melting furnace	All metals	Skimmings/ dross	Return to process after treatment
Furnace linings	All metals	Refractory	Use as slagging agent, disposal; reuse as a refractory
Dry abatement systems	Most metals (using fabric filters or ESPs)	Filter dust	Return to process; recovery of other metals

06. TANTALUM

As it has been reported before, Tantalum is the only metal that will be study in this task, considering that it is the option with higher potential for recycling-reuse.

Secondary resources of Tantalum have been identified in Deliverable 3.2 “State of the art on the recovery of refractory metals from secondary resources”:

- Municipal landfills, MSW containing WEEE
- Disposal areas of incineration slags. MSW incineration slags
- Industrial landfills containing waste from WEEE processing
- Tin mining residues
- Tailings and waste from tin mining
- Tin slag
- Tailings of china clay extraction
- Mine waste and tailings
- Slag
- Mine waste
- Waste from uranium mining
- Mine tailings, pegmatite-granite
- Scrap from Ta powder and castings manufacturing
- Waste from manufacturing of Ta capacitors, super alloys and alloy products,
- Hard metal products
- End-of-life waste (capacitors, industrial applications of Ta alloys and superalloys, hard metal products, etc.)

The **Properties of secondary resources of tantalum**, identified also in Deliverable 3.2, can be found in the following table:

Table 3. Properties of secondary resources of Tantalum. *Source:* Deliverable 3.2 REFRAM.

Material type	Particle size	Main components	Impurities and other valuable elements
Municipal landfills; MSW containing WEEE	Soiled small electronic devices or their components	Capacitors and other electronic components mixed in large amounts of MSW and materials used for daily cover	Mainly organic waste, plastics, fine particles. 3-4 % metals, mainly Al and Fe, smaller amounts of several other metals
MSW incineration slags at disposal areas and earth constructions	Mostly in >2mm particles	Estimated 3-5 mg Ta/kg	Minerals, molten slag, grit, unburnt organics; Fe, Al, Zn, Cu, Ni, minor metals
Industrial landfills containing waste from WEEE processing	Mostly crushed materials, particle sizes from very fine to over 10 cm, may contain also specimens that are not crushed	n.a.	Plastics, mineral material, base (mainly Fe, Cu, Al, Zn), precious and critical metals
Tin mining residues tantalite	n.a.	Ta concentrations not available	n.a.
Tailings and waste from tin mining	n.a.	Tailings 48 g/t; Waste dump 27 g/t	Tailings 390g Sn/t; Waste dump 29 g Nb/t, 460 g Sn/t
Golbejas, Salamanca Spain: Tin slag	n.a.	n.a.	n.a.
St Austell, Cornwall	Fine particles	Several locations	Nb, Ti, Sn
Bessa, Portugal: Mine waste and tailings	n.a.	n.a.	n.a.
Söve, Norway: Slag	n.a.	Containing Ta (1.34 % Ta ₂ O ₅), Th, Zircon;	Radioactive containing Th and Zircon
Echassieres France: Mine waste	n.a.	n.a.	n.a.
Hagendorf, Germany: Mine waste	n.a.	n.a.	n.a.
Straz, Czech republic: Waste from Uranium mining	n.a.	n.a.	Radioactive
Rosendal, Finland; Minetailings, pegmatitegranite	n.a.	Li-Nb-Ta	REE, Sn, Zn
Scrap from Ta powder and Castings manufacturing	n.a.	n.a.	n.a.
Waste from manufacturing of Ta capacitors, super alloys and alloy products. Hard metal products	n.a.	n.a.	n.a.

End-of-life waste (capacitors, industrial applications of Ta alloys and superalloys, hard metal products, etc.)	n.a.	n.a.	n.a.
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06.1 ENVIRONMENTAL DATA FOR TANTALUM. PRIMARY EXTRACTION.

The collection of data for the refractory metals is quite complex. Some efforts have been made in order to study the environmental impact of metal extractive industry, and in particular some are focused on the refractory ones.

According to the paper *Life Cycle Assessment of Metals: A Scientific Synthesis* ¹⁴, the following results for the Ta has been reported, considering a cradle to gate approach and considering a primary extraction of the metal (table 4):

Table 4. Tantalum environmental data. Source: Life cycle assessment of Metals.

Impact category	Value	Units	Consideration
Global warming potential	260	Kg CO ₂ eq / kg	Medium impact
Cumulative energy demand	4,360	MJ eq / kg	Medium impact
Terrestrial acidification	1.7	Kg SO ₂ eq / kg	Medium impact
Freshwater eutrophication	1.5 E-01	Kg P eq / kg	Medium impact
Human toxicity	1.2 E-04	CTUh/kg	Medium impact

The following figures shows the relative impact of Tantalum vs. other metals in the previously mentioned five impact categories, justifying a “medium impact” of the metal compared with the other ones.

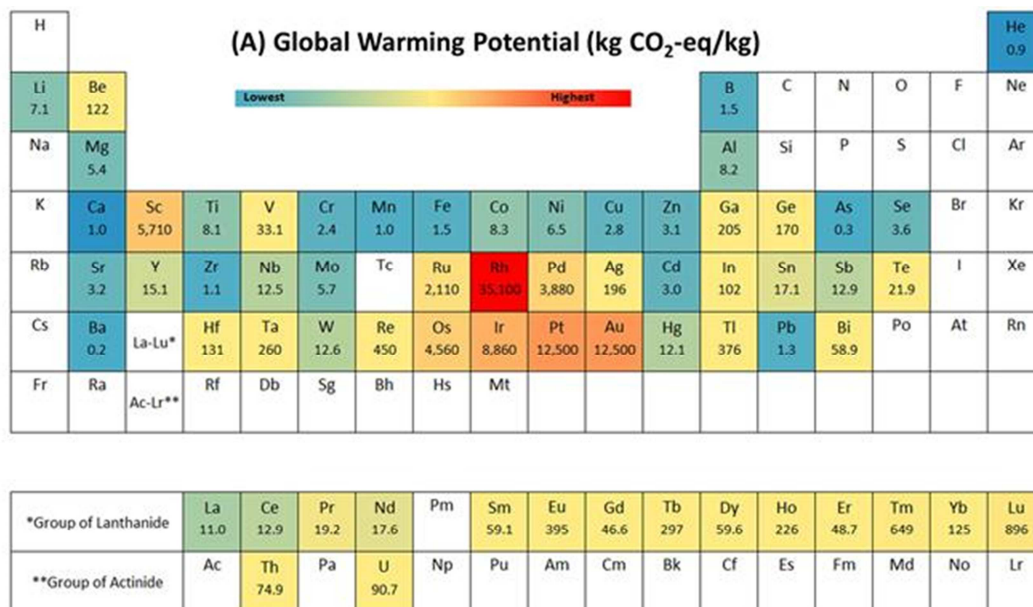


Figure 6. Global warming potential of metals. *Source:* Life Cycle Assessment of Metals: A Scientific Synthesis

(A) Cumulative Energy Demand (MJ-eq / kg)

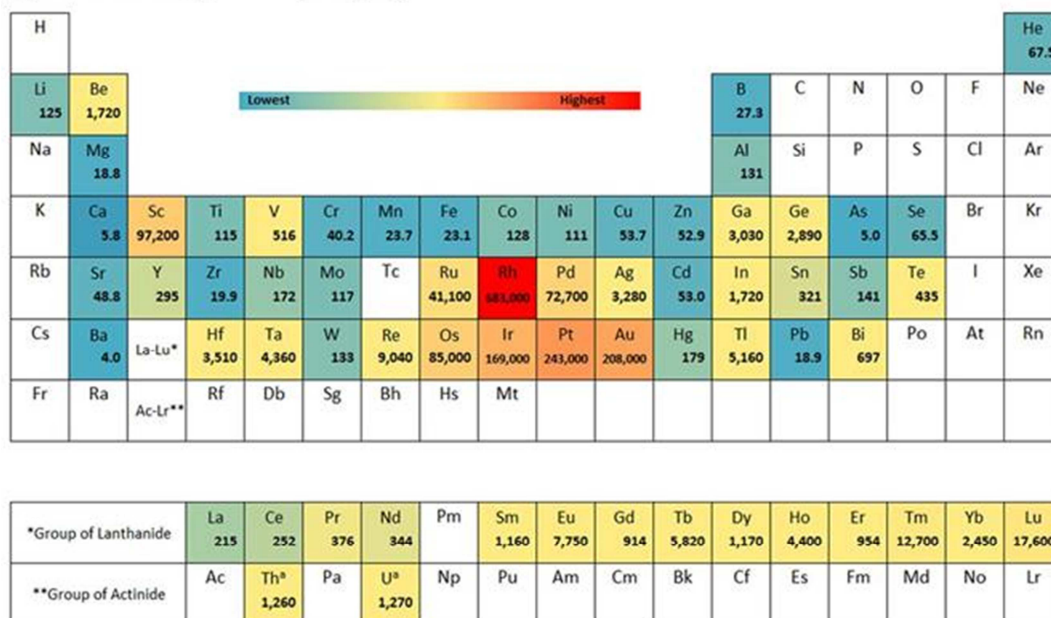


Figure 7. Cumulative energy demand of metals. *Source:* Life Cycle Assessment of Metals: A Scientific Synthesis

(B) Terrestrial Acidification (kg SO₂-eq / kg)


H																	He 2.3E-03
Li 3.8E-02	Be 5.2E-01											B 6.6E-03	C	N	O	F	Ne
Na	Mg 2.3E-03											Al 3.4E-02	Si	P	S	Cl	Ar
K	Ca 8.3E-04	Sc 3.8E+01	Ti 3.6E-02	V 1.4E-01	Cr 1.7E-02	Mn 9.4E-03	Fe 5.2E-03	Co 8.9E-02	Ni 1.5E+00	Cu 3.9E-01	Zn 3.9E-02	Ga 4.5E-01	Ge 1.9E+00	As 8.2E-03	Se 2.3E-01	Br	Kr
Rb	Sr 1.9E-02	Y 6.4E-02	Zr 5.8E-03	Nb 5.3E-02	Mo 1.6E-01	Tc	Ru 3.0E+02	Rh 5.2E+03	Pd 1.7E+03	Ag 8.5E+00	Cd 2.2E-02	In 1.2E+00	Sn 4.3E-01	Sb 2.2E-01	Te 2.5E+00	I	Xe
Cs	Ba 8.2E-04	La-Lu*	Hf 7.7E-01	Ta 1.7E+00	W 2.9E-01	Re 1.1E+01	Os 2.4E+03	Ir 3.1E+03	Pt 2.2E+03	Au 1.2E+02	Hg 7.7E-02	Tl 4.4E+00	Pb 2.8E-02	Bi 3.8E-01	Po	At	Rn
Fr	Ra	Ac-Lr**	Rf	Db	Sg	Bh	Hs	Mt									
*Group of Lanthanide			La 4.7E-02	Ce 5.5E-02	Pr 8.1E-02	Nd 7.5E-02	Pm	Sm 2.5E-01	Eu 1.7E+00	Gd 2.0E-01	Tb 1.3E+00	Dy 2.5E-01	Ho 9.6E-01	Er 2.1E-01	Tm 2.8E+00	Yb 5.3E-01	Lu 3.8E+00
**Group of Actinide			Ac	Th 4.4E-01	Pa	U 1.2E+00	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Figure 8. Terrestrial acidification of metals. *Source:* Life Cycle Assessment of Metals: A Scientific Synthesis

Figure 10. Human toxicity of metals. *Source:* Life Cycle Assessment of Metals: A Scientific Synthesis

As it can be seen in the table 5, considering the five metals studied, Re presents the higher impact in the five categories, followed by **Tantalum**.

Table 5. Refractory metals environmental comparison.

Impact category	Ta	Re	W	Nb	Mo
Global warming potential (kg CO ₂ eq / kg)	260	450	12.6	12.5	5.7
Cumulative energy demand (MJ eq / kg)	4,360	9,040	133	172	117
Terrestrial acidification (kg SO ₂ eq / kg)	1.7	11	0.29	0.053	0.16
Freshwater eutrophication (kg P eq / kg)	1.5E-01	3.5E+01	9.3E-6	3.7E-03	0.54
Human toxicity (CTUh/kg)	1.2E-04	5.9E-02	3.4E-05	6.4E-06	9 E-04

These results can be considered as reference in terms of environmental impact.

For the specific case of Ta, the environmental impact of the recovery or recycling processes from secondary sources should not be higher than the values observed in table 5, because it is expected that a recovery/recycling process presents a lower environmental impact than the virgin primary extractive process.

In terms of **energy consumption**, the Ecoinvent database ¹⁵ provides these values for the obtention of Tantalum, powder, capacitor grade.

- Electricity 200.53 kWh
- Diesel burned in building machine 1,065.1 MJ
- Heat, industrial, natural gas 0.28 MJ

Considering **waste**, the database allocates non sulfidic tailing (near 9 tonnes per kg of Ta obtained).

06.2 RECYCLING/RECOVERY PROCESS FOR TANTALUM FROM SECONDARY RESOURCES

Estimation of mass and energy flow diagrams of the complete recovery technique for tantalum

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6.2.1 INTRODUCTION

In the absence of the data about the exact form and physical-chemical composition of the raw materials, laboratory testing data and pilot testing, it is quite difficult to estimate the mass and energy balances and diagrams for the complete recovery technique for the tantalum production. Of course, already existing recovery techniques can be found in available literature and then analysed, but even in this case, many uncertainties exist. For example, the solvent extraction or oxidation processes can be carried out on various industrial units differing from each other in productivity, power consumption and the use of additional materials.

Despite of the obvious difficulties, it is still possible to estimate roughly the mass and energy flow diagrams of the complete recovery technique for the tantalum production based on literature survey. The strategy for such estimation consists of the following stages:

1. Define the possible physical properties and chemical composition of the raw material input;
2. Select one of the existing flow diagrams for the complete recovery of the tantalum;
3. Detalize the selected flow diagram as much as it possible;

4. Compile a list of all utilized technological equipment;
5. Compile a list of all chemical reactions from all stages of production;
6. Based on chemical reactions, estimate the mass balances;
7. Based on selected equipment and chemical reactions, estimate the energy balances;

6.2.2 EXISTING FLOW DIAGRAM FOR THE TANTALUM RECOVERY

A list of secondary resources for tantalum is available in Table 2-1 in one of the MSP-REFRAM project reports [16]. It is obvious that every particular type of recourse will have its own unique recovery flow sheet (some of them are economically viable and some of them are not) with unique mass and energy balances.

6.2.2.1 SELECTION OF THE RAW MATERIAL INPUT

For further consideration, a secondary recourse in form of *tin slag* was chosen as a raw material input. The reason for this decision was that, in one hand, according to [17] it has been estimated that 10-20% of the global tantalum supply is produced from tin slags, and, in the other hand, EU has its own recourse of tin slag in Spain. Tin slag resource characteristics are presented in Table 6.

Table 6. *Tin slag resource characteristics [16].*

Material type	Size of source	Location	Owner	Comments	Ref.
Tin slag	n.a	Golbejas, Salamanca Spain	n.a	Tin and Ta mine closed in early 1980s, potential to start mining again has been studied (Goldtech). Waste areas have been at least partly reprocessed in 1980's	[18]

Unfortunately, the tin slag amount and physical and chemical properties are not available in open-access literature. Nevertheless, the mentioned characteristics can be estimated from market available data and from open access sources. Table 7 contains the found tin slag parameters from different suppliers.

Table 7. *Tin slag properties from different suppliers.*

Concentrate name	Place of origin and supply ability	Particle size	Chemical composition	Ref.
Tin slag #1	Chhattisgarh, India. Supply ability: 800 t/year	10-100 mm (Lumps)	Al_2O_3 : 9,07% SiO_2 : 28% TiO_2 : 4,14% CaO : 14,09% Fe_2O_3 : 24,29% SrO : 0,05% Nb_2O_5 : 1,62%	[19]

			SnO_2 : 4,86% Ta_2O_5 : 2,12% WO_3 : 3,44% Other : 8,32%	
Tin slag #2	Tianjin, China (Mainland). Supply ability: 6000 t/year	n.a	Ta_2O_5 : 4 – 6% Other: 94-96%	[20]
Tin slag #3	Malaysian tin slag	n.a	Ta_2O_5 : 4,0% Nb_2O_5 : 4,0% Fe_2O_3 : 11% SiO_2 : 21% CaO : 25% TiO_2 : 11% Al_2O_3 : 9% WO_3 : 8% ZrO_2 : 3% MgO : 0,5% MnO_2 : 0,5% SnO : 0,5% V_2O_5 : 0,5%	[21]

Table 2 shows that the total mass fraction of viable oxides ($\text{Ta}_2\text{O}_5 + \text{Nb}_2\text{O}_5$) in all tin slags found is less than 10% and this means that the present concentrates are characterized as low-grade. For further consideration, the tin slag concentrate #3 was chosen as raw material input because of more complete information about the chemical composition and fully described pyrometallurgy processing in US patents [21, 22].

6.2.2.2 SELECTION OF THE EXISTING FLOW DIAGRAM

The chosen tin slag-processing flow diagram consists of the following main stages:

- 1) Comminution process of input material;
- 2) Pyrometallurgy and hydrometallurgy upgrading of grinded concentrate to synthetic concentrate;
- 3) Solvent extraction and separation of Ta_2O_5 ;
- 4) Reduction melting for producing metallic Ta and its purification;

Overview of the flow diagram

The first processing stage, comminution process, is used for reducing the size of input tin slag material in form of lumps from 10-100 mm to 0,15 mm. The standard SAG milling – ball milling (wet) – filtration scheme is used. Then grinded and dewatered (10% w/w of water) concentrate is heated in the presence of sufficient carbon to convert the tantalum and niobium oxides to a hearth product containing the tantalum and niobium as carbides in admixture with a carbon-containing iron alloy. At this stage the hearth product can be separated from oxidic gangue constituents for further processing in arc furnace, where the said hearth product reacts with sodium nitrate and carbon. The described reaction is

exothermic and after ignition, it transforms the mixture to a fluid melt at temperature of about 1000 °C. It is then allowed to cool to solidification, whereupon the cooled solid is crushed to prepare it for subsequent water and mineral acid leaching. Water leaching is necessary to remove excess soda and other water-soluble sodium salts such as sodium silicate and sodium tungstate. The insoluble residue from the water leaching is then subjected to a mineral acid leaching to dissolve the calcium, iron, magnesium, manganese and sodium components of the leached solids. After filtration and cake drying, so-called synthetic concentrate (22,2% Ta₂O₅ and 25,5% Nb₂O₅) is produced. This product is then subjected to dissolution in hydrofluoric acid, solvent extraction by MIBK and selective precipitation. Wet purified tantalum oxide is dried and metallic tantalum (99,8%) is produced by carbo-thermic reduction. Finally, the 5N grade tantalum (99.999%) is produced by electron-beam melting.

The complete treatment flow sheet for tantalum recovery is presented in Figures 1 and 2.

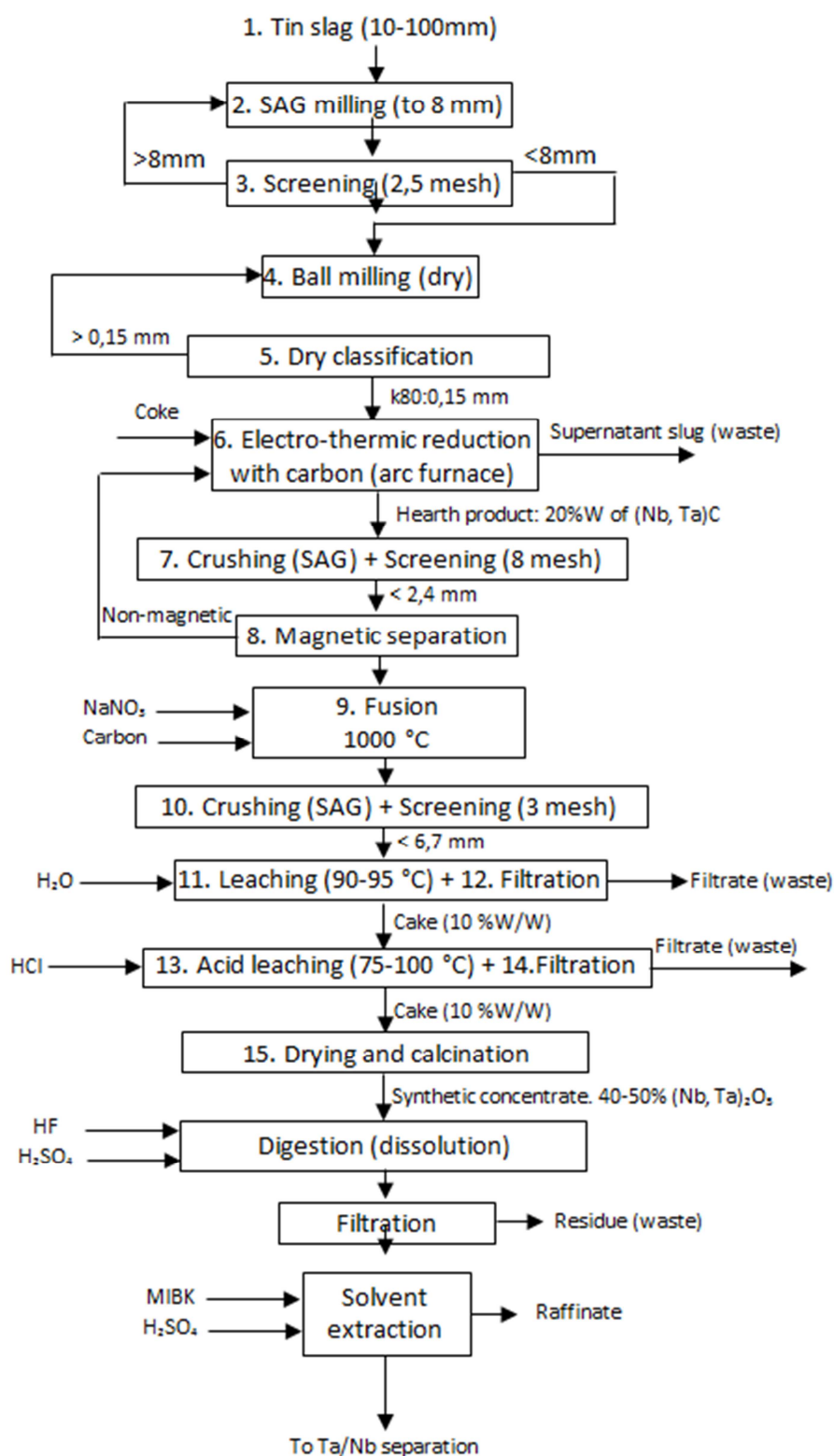


Figure 11. Part of Ta producing flowsheet [23, 24, 25].

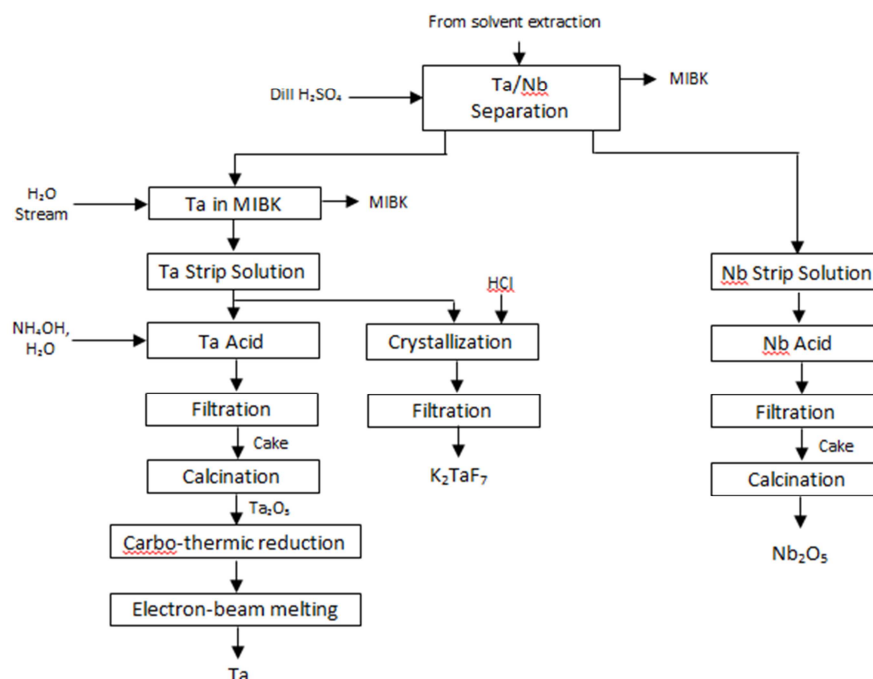


Figure 12. Part of Ta producing flowsheet [23, 24, 25].

Overall, each step in the recovery flowsheet causes the physical (comminution, filtration, melting) or chemical (pyro- and hydro-metallurgy processes) transformation of materials. Chemical equations can give us some theoretical understanding of transformations that take place at different stages of production. Using such equations and measured products parameters (taken from open-access materials), it is possible to estimate the mass flows of used materials.

Theoretically, the chemical equations can also answer to the question about energy balances. In case of complete system of reactions, it is possible to calculate the Gibbs energy for all of them. For energy balance, estimation of the power consumption of particular equipment can be used. Estimated energy balance *does not take into account* the energy needed for materials pumping, mixing, conveying, and storing. The calculations also *do not consider the energy efficiencies* of different process steps but assumptions are based on theoretical energy requirements.

6.2.3 DETALIZATION OF TANTALUM RECOVERY FLOWSHEET

1.-Input tin slag material

Tin slag #3 exists in form of 10-100 mm lumps, as it was assumed. All further calculations are based on assumption that the initial mass of input tin slag is **one ton**.

Based on the chemical composition tin slag #3 (Table 2) and initial mass of slag, the maximum theoretical extraction of viable components (Ta, Nb) can be calculated as it shown in Table 8.

Table 8. Maximum theoretical extraction of Ta and Nb from 1 ton of tin slag.

Viable metal	Mass fraction in tin slag (oxide form), [%]	Mass of oxide, [kg]	Mass fraction of metal in oxide, [%]	Mass of metal, [kg]
Ta	4,0	40,0	81,9	32,76
Nb	4,0	40,0	69,9	27,96

2.- SAG milling of tin slag

The purpose of the first SAG milling is reduction of lumps size from 10-100 mm (average 55 mm) to -8 mm fraction. Grinding type is dry with metallic linings. According to [26], grinding media in SAG mill is grinding feed plus 4-18% (average 11%) ball charge (ball dia. 100-125 mm). Amount of balls needed for grinding:

$$m_{balls} = 1000 \text{ kg} \cdot 0,11 = 110 \text{ kg}$$

Energy consumption estimation:

The most common formula for power consumption estimation of grinding is Bond formula [27]:

$$W = 10 \cdot W_i \cdot \left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}} \right), \quad (1)$$

where: W – specific power consumption, [kWh/t dry solids]; P – 80% passing size of product [μm]; F – 80% passing size of the feed, [μm]; W_i – Bonds work index, [kWh/short ton].

Estimate the power consumption of the SAG mill assuming that for slag $W_i = 10,24$ kWh/sh.t. [26]; $P = 8000$ μm ; $F = 55000$ μm :

$$W = 10 \cdot 10,24 \cdot \left(\frac{1}{\sqrt{8000}} - \frac{1}{\sqrt{55000}} \right) = 0,708 \quad [\text{kWh/t dry product}]$$

$$W_2 = 0,708 \quad [\text{kWh/t tin slag}]$$

The equipment selection (its dimensions and motor power) define the productivity of the SAG grinding. We can estimate the productivity (if all motor energy will go to grinding) for chosen SAG mill with the following characteristics [26]:

Table 9. Productivity estimation of SAG mill.

Standard mill size, [m]	EGL, [m]	Motor (typical), [kW]	Calculated max productivity, [t/h]
3,7 x 3,7	1,2	110 – 185 (average 147,5)	$147,5/0,708 = 208,33$

3.- Screening of grinded tin slag

The purpose of screening procedure is to pass the fraction < 8 mm to further processing and return the > 8 mm fraction back to the SAG mill.

Energy consumption estimation:

According to [26], in average 8 mm screen with screening area of 7,6 m² can process 105 tons in 1 hour. At the same time, if we choose a single inclination screen (Model VFS 42/18 2d with screen area 7,6 m²) for 1 working hour it will consume 15 kWh of energy. Therefore, it is possible to estimate energy consumption per 1 ton of feed material as follows:

$$W = \frac{15 \text{ kWh}}{105 \text{ t}} = 0,143 \quad [\text{kWh/t product}]$$

$$W_3 = 0,143 \quad [\text{kWh/t tin slag}]$$

4.- Ball milling

The purpose of ball milling is to continue grinding the material from average 8 mm size to 0,15 mm. Ball mill with grate discharge can mill dry solids with ball charge 35-40% of milling feed. Amount of balls needed for grinding:

$$m_{balls} = 1000 \text{ kg} \cdot 0,375 = 375 \text{ kg}$$

Energy consumption estimation:

Using equation (1) lets calculate the energy needed for milling process:

$$W = 10 \cdot 10,24 \cdot \left(\frac{1}{\sqrt{150}} - \frac{1}{\sqrt{8000}} \right) = 7,216 \quad [\text{kWh/t product}]$$

$$W_4 = 7,216 \quad [\text{kWh/t tin slag}]$$

Again, we can estimate the productivity of chosen mill from catalogue based on its characteristics:

Table 10. Productivity estimation of ball mill

Standard mill size [m]	Motor (typical) [kW]	Calculated max productivity [t/h]
2.7 x 3.7	325	$325 / 7.216 = 46.425$

5.- Dry classification

The purpose of classification is to separate the particles fraction < 0,15 mm for further processing. The fraction > 0,15 mm is returned to the ball mill. The *gravitational inertial classifier* (achieve separation from 360 µm/ 63µm) with the following *dust collector* are used.

Energy consumption estimation:

Analysing the technical data for air classifiers [28] the power consumption of typical gravitational inertial classifier can be estimated. The Metso air classifier AC22.5GI during one hour produces 50 t of the product and consumes 60 kWh of energy. Therefore, the energy consumption per one ton is:

$$W = \frac{60 \text{ kWh}}{50 \text{ t}} = 1,2 \quad [\text{kWh/t product}]$$

$$W_5 = 1,2 \quad [\text{kWh/t tin slag}]$$

6.- Electro-thermic reduction with carbon (arc furnace)

The purpose of the process is to reduce the iron, tantalum and niobium components of the slag with presence of sufficient amount of carbon.

The *supernatant slag* product, comprising mostly of the silica, titania, alumina, lime and magnesia of the tin slag charge is poured out of the furnace at a temperature of about 1550 °C. The *hearth product*, comprising of the tantalum, niobium, iron and tungsten predominantly in the form of a high-carbon Ferro alloy containing the tantalum and niobium

in the form of their carbides, is raked out of the furnace at a temperature about 1400 °–1800 °C.

Mass balance of smelting:

Table 11. Estimated mass balance of smelting.

In/Out	Material	Mass, [kg]. From literature [6]	Mass fraction, [%]	Mass per 1 ton of tin slag, [kg]
In1	Tin slag (milled)	3628,74		1000
In2	Coke (- 6,35 mm)	508,02	In1·14,0	141,14
Out1	Hearth product	1315,42	31,8	362,88
Out2	Supernatant slag	2041,17	49,3	562,58
Out3	Other (for balance)	780,18	18,6	212,25

Calculations:

$$m(\text{Tin slag}) = 1000 \quad [\text{kg}]$$

$$m(\text{Coke}) = \frac{1000 \cdot 508,023}{3628,738} = 141,140 \quad [\text{kg}]$$

$$m(\text{Hearth prod.}) = (1000 + 141,140) \cdot 0,318 = 362,883 \quad [\text{kg}]$$

$$m(\text{Supern. slag}) = (1000 + 141,140) \cdot 0,493 = 562,582 \quad [\text{kg}]$$

$$m(\text{Other}) = (1000 + 141,140) \cdot 0,186 = 212,252 \quad [\text{kg}]$$

Table 12. Supernatant slag composition [21].

Component	Mass fraction, [%]	Mass per 1 ton of tin slag, [kg]
-----------	--------------------	----------------------------------

TiO_2	1,6	9,001
Al_2O_3	19,0	106,890
CaO	46,0	258,788
SiO_2	32,0	180,026
MgO	1,6	9,001

Table 13. Hearth product composition [21]. Recalculated to carbides.

Component	Mass per 1 ton of tin slag, [kg]	Mass fraction, [%]
TaC	32,646	9,33
NbC	34,658	9,91
TiO_2	46,811	13,38
Al_2O_3	8,709	2,48
CaO	36,65	10,47
SiO_2	49,71	14,21
Fe	86,729	24,79
MgO	11,612	3,31
WC	14,69	4,19
Other	27,57	7,88

Energy consumption estimation:

According to [29, 30] the average energy consumption of arc furnace is about $W = 450 \text{ kWh/t}$ of product, therefore:

$$W_6 = 450 \cdot 0,362 = 162,9 \quad [\text{kWh/t tin slag}]$$

7.- Hearth product crushing

The hearth product is broken and crushed to -8 Tyler mesh (-2,4 mm). After screening, fraction -2,4 mm goes to further processing and fraction +2,4 mm is returned to SAG mill. Amount of balls needed for grinding:

$$m_{balls} = 362,883 \text{ kg} \cdot 0,11 = 39,91 \text{ kg}$$

Energy consumption estimation:

Assuming that the input heart product does not contain pieces larger than 400 mm (limit for SAG mill), we can estimate the energy consumption using equation (1):

$$W = 10 \cdot 10,24 \cdot \left(\frac{1}{\sqrt{2400}} - \frac{1}{\sqrt{400000}} \right) = 2,039 \quad [\text{kWh/t product}]$$

$$W_7 = 2,039 \cdot 0,362 = 0,74 \quad [\text{kWh/t tin slag}]$$

8.- Screening

Energy consumption of the screen:

$$W = \frac{15 \text{ kWh}}{30 \text{ t}} = 0,5 \quad [\text{kWh/t product}]$$

$$W_8 = 0,5 \cdot 0,362 = 0,181 \quad [\text{kWh/t tin slag}]$$

9.- Magnetic separation

Magnetic separation is used for separation of high-carbon Ferro alloy from non-viable components. According to [23], only such hearth product components as TaC , NbC , Fe and WC (excluding contaminants) react with $NaNO_3$. Let us assume that only the listed components are in form of magnetic Ferro alloy. Therefore, magnetic and non-magnetic fractions will have the compositions as follows:

Table 14. Non-magnetic fraction.

Component	Mass per 1 ton of tin slag, [kg]
<i>TiO₂</i>	46,811
<i>Al₂O₃</i>	8,709
<i>CaO</i>	36,65
<i>SiO₂</i>	49,71
<i>MgO</i>	11,612
Other	27,57
In total:	181,062

Table 15. *Magnetic fraction.*

Component	Mass per 1 ton of tin slag, [kg]
<i>TaC</i>	32,646
<i>NbC</i>	34,658
<i>Fe</i>	86,729
<i>WC</i>	14,69
In total:	168,723

Energy consumption estimation:

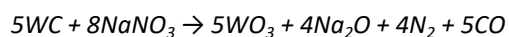
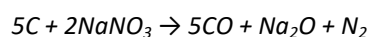
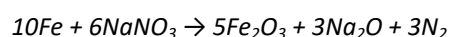
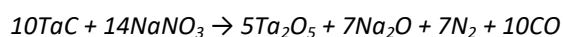
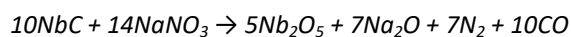
According to [26], estimated power consumption for dry low intensity magnetic separator – drum separator DS906 (D=0,916 m; L=0,6 m) with productivity 50 t/(h and m drum width):

$$W = \frac{4 \text{ kWh}}{30 \text{ t}} = 0,133 \quad [\text{kWh/t product}]$$

$$W_9 = 0,133 \cdot 0,168723 = 0,022 \quad [\text{kWh/t tin slag}]$$

10.- Fusion with NaNO₃

At this stage, the exothermic fusion with sodium nitrate and carbon is performed to form a fusion mass for further leaching with water and organic acid. Addition of carbon is needed to supplement the heat. The overall different reactions that take place on fusion are [23]:



The calculation results for mass balances of mentioned reactions are presented in Table 16. Grey colours are fusion mass components and their corresponding mass fractions.

Table 16. Calculated mass balances for the fusion reactions.

Component	Mass per 1 ton of tin slag, [kg]	Mass fraction in fusion product, [%]
TaC	32,646	
NbC	34,658	
Fe	86,729	
WC	14,69	
C	25,31 (15% of magn. hearth product) [x]	
NaNO ₃	146,821	

Ta_2O_5	37,381	14,35
Nb_2O_5	43,903	16,85
Fe_2O_3	124,000	47,59
CO	20,102	
WO_3	1,738	0,67
Na_2O	53,53	20,54
N_2	24,193	

The total mass of the fusion product is: 260,55 kg.

Energy consumption estimation:

Fusion reaction is exothermic reaction and do not need any significant energy income for supporting the reaction.

$$W_{10} = 0 \quad [\text{kWh/t}]$$

11.- Crushing of the cooled fusion mass

The cooled fusion mass is broken and crushed to – 6,7 mm. After screening, fraction -6,7 mm goes to water leaching and fraction +6,7 mm is returned to SAG mill.

Amount of balls needed for grinding:

$$m_{balls} = 260,55 \text{ kg} \cdot 0,11 = 28,66 \text{ kg}$$

Energy consumption estimation:

Assuming that the input heart product does not contain pieces larger than 400 mm (limit for SAG mill) we can estimate the energy consumption using equation (1):

$$W = 10 \cdot 10,24 \cdot \left(\frac{1}{\sqrt{6700}} - \frac{1}{\sqrt{400000}} \right) = 1,09 \quad [\text{kWh/t product}]$$

$$W_{11} = 1,09 \cdot 0,26055 = 0,284 \quad [\text{kWh/t tin slag}]$$

12.- Screening

Energy consumption of the screen:

$$W_{12} = \frac{15 \text{ kWh}}{70 \text{ t}} = 0,21 \quad [\text{kWh/t product}]$$

$$W_{12} = 0,21 \cdot 0,26055 = 0,0054 \quad [\text{kWh/t tin slag}]$$

13.- Water leaching

The purpose of water leaching stage is to convert sodium oxide to sodium hydroxide according the following equation:

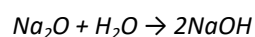


Table 17. Calculated mass balances for the reaction.

Component	Mass per 1 ton of tin slag, [kg]
Na_2O	53,53
H_2O	15,56
NaOH	69,09

According to [21] during the water leaching stage, the most of tungsten goes into leach liquor while tantalum and niobium oxides remain in residual. The following reaction takes place:

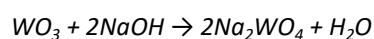


Table 18. Calculated mass balances for the reaction.

Component	Mass per 1 ton of tin slag, [kg]
WO_3	1,738
$NaOH$	0,599
$NaWO_4$	2,202
H_2O	0,135

The composition of the residue after leaching is presented in the following table.

Table 19. Residue composition after water leaching.

Component	Mass per 1 ton of tin slag, [kg]	Mass fraction in residue, [%]
Ta_2O_5	37,381	13,65
Nb_2O_5	43,903	16,03
Fe_2O_3	124,000	45,29
$NaOH$	68,49	25,01

Energy consumption estimation:

Leaching process takes place in heated and stirred water at temperature of 95 °C. The energy consumption for heating one ton of water from 20 °C up to 95 °C is 87,229 kWh. For one ton of dry residual we need only 56,83 kg of water, therefore the energy consumption of water leaching stage relating to one ton of dry residual is:

$$W_{13} = 1,76 \quad [\text{kWh/t tin slag}]$$

14.- Filtration after water leaching

The purpose of the filtration stage is to reduce the amount of liquid in the leaching residual. Assume that the cake moisture content after filtration is 10 w-%.

Energy consumption estimation:

Energy consumption of filtration stage depends on filter type used that depends on the capacity of the plant. There is an example of calculation of the filtration parameters for zinc concentrate [26]. Let us assume that the energy consumption for our filtration process will be about the same:

$$W = 15,41 \quad [\text{kWh/t product dry}]$$

$$W_{14} = 15,41 \cdot 0,273774 = 4,22 \quad [\text{kWh/t tin slag}]$$

15.- Mineral acid leaching

The purpose of mineral acid leaching is to remove sodium hydroxide form the residue and other contaminants. The main reaction is:

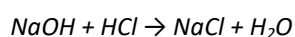


Table 20. Calculated mass balances for the reaction.

Component	Mass per 1 ton of tin slag, [kg]
<i>NaOH</i>	68,49
<i>HCl</i>	6,243
<i>NaCl</i>	10,007
<i>H₂O</i>	3,084

The composition of the residue after mineral acid leaching is presented in the following table. The results for tantalum and niobium oxide compositions are close to the data presented in the patent [21]

Table 21. Residue composition after mineral acid leaching.

Component	Mass per 1 ton of tin slag, [kg]	Mass fraction in fusion product, [%]
Ta_2O_5	37,381	18,20
Nb_2O_5	43,903	21,38
Fe_2O_3	124,000	60,40

Energy consumption estimation:

Leaching process takes place in heated and stirred 22° hydrochloric acid solution at temperature of 95 °C. Taking into account the thermal capacity of the acid (2,99 KJ/kg·K) and amount of acid water solution (28,37 kg) the energy consumption for heating is:

$$W_{15} = 4,957 \quad [\text{kWh/t tin slag}]$$

16.- Filtration after mineral acid leaching

The purpose of the filtration stage is to reduce the amount of liquid in the leaching residual. Assume that the cake moisture content after filtration is 10 w-%.

Energy consumption estimation:

Energy consumption of filtration stage depends on filter type used that depends on the capacity of the plant. There is an example of calculation of the filtration parameters for zinc concentrate [26]. Let us assume that the energy consumption for our filtration process will be about the same:

$$W = 15,41 \quad [\text{kWh/t product}]$$

$$W_{16} = 15,41 \cdot 0,205284 = 3,16 \quad [\text{kWh/t tin slag}]$$

17.- Drying and calcination

The purpose of drying is to reduce the amount of moisture in the concentrate from about 10 w-% down to 1 w-%. It can be performed by direct heat rotary dryer. Drying is the last stage of preparing so called synthetic concentrate containing mainly tantalum, niobium and iron oxides and other contaminants which are not taken into account in the present rough mass balance estimation.

Energy consumption estimation:

Initial mass of water (after water washing stage in filtration) is 22,81 kg (10% moisture content). The mass of water after drying is 2,07 kg (1% moisture). Therefore, the amount of water to be heated up and evaporated is 20,74 kg. Let us assume the initial and final temperature of 20 °C and 100 °C respectively. Using the equations for energy consumption for water heating and evaporating, we can calculate the total energy consumption as follows (for 1 ton of tin slag) [31,32]:

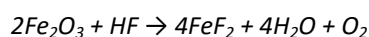
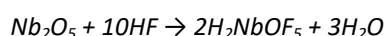
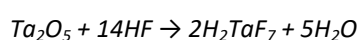
$$W_{17} = 4200 \frac{J}{kg \cdot K} \cdot 20,74 kg \cdot (373,15K - 293,12K) + 2246 \frac{kJ}{kg} \cdot 20,74 kg = 53,55 \cdot 10^6 J = 14,87 kWh$$

Let us assume that the dryer is heated by gas flaring. The calorific value for methane (CH₄) is 11,06 kWh/m³ [33]. The amount of gas needed to evaporate the mentioned mass of water is:

$$V_{CH_4} = \frac{14,87 kWh}{11,06 kWh/m^3} = 1,34 \quad [m^3]$$

18.- HF dissolution (digestion)

The purpose of the hydrofluoric acid dissolution is to form fluoride compounds of tantalum and niobium and separate them from other impurities and iron. The dissolution of oxides can be presented as follows (at low acidity):



The calculation results for mass balances of mentioned reactions are presented in table 22.

Table 22. Calculated mass balances for the reactions.

Component	Mass per 1 ton of tin slag, [kg]
Ta_2O_5	37,381
Nb_2O_5	43,903
Fe_2O_3	124,000
H_2TaF_7	53,454
H_2O	44,523
HF	118,873
H_2NbOF_5	68,020
FeF_2	145,737
O_2	12,423

Tantalum and niobium fluoride solution then goes to the solvent extraction phase.

Energy consumption estimation:

See section 21.

Solvent extraction

A lot of extractants exist for separation and purification of Ta and Nb. Despite of several disadvantages, *methyl iso-butyl ketone (MIBK)* is widely used in industry [34]. Tantalum extraction equation is:



Table 23. Calculated mass balances for the reaction.

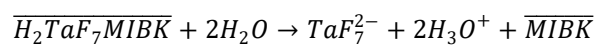
Component	Mass per 1 ton of tin slag, [kg]
TaF_7^{2-}	53,113
H^+	0,340
\overline{MIBK}	16,945
$\overline{H_2TaF_7MIBK}$	70,399

Energy consumption estimation:

See section 21.

20.- Tantalum stripping

The equation for tantalum stripping is as follows:



Energy consumption estimation:

See section 21.

Table 24. Calculated mass balances for the reaction.

Component	Mass per 1 ton of tin slag, [kg]
$\overline{H_2TaF_7MIBK}$	70,399
H_2O	6,095
TaF_7^{2-}	53,112
$2H_3O^+$	6,436

\overline{MIBK}	16,945
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21.- Tantalum precipitation

The equation for tantalum precipitation is as follows:

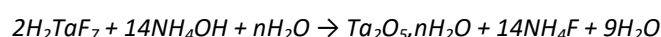


Table 25. Calculated mass balances for the reaction.

Component	Mass per 1 ton of tin slag, [kg]
H_2TaF_7	53,454
NH_4OH	41,504
Ta_2O_5	37,380
NH_4F	43,862
H_2O	13,715

Energy consumption estimation:

It is difficult to estimate the energy consumption for every stage in solvent extraction chain. But the work [35] can be used to estimate the average energy consumption for all solvent extraction plant (including such processes as dissolution, solvent extraction, stripping and precipitation). Based on this information and taking into account the continuous extraction processes we can assume that:

$$W_{solv.extr.plant} = 3 \quad [\text{kWh/kg of final product}]$$

$$W_{solv.extr.plant} = 3 \cdot 37,380 = 112,14 \quad [\text{kWh/t tin slag}]$$

22.- Tantalum oxide filtration

Assume the filtration of the tantalum oxide equal to the filtration in sections 14 and 16. Assume that the cake moisture content after filtration is 10 w-%.

Energy consumption estimation:

$$W = 15,41 \quad [\text{kWh/t product}]$$

$$W_{22} = 15,41 \cdot 0,037380 = 0,58 \quad [\text{kWh/t tin slag}]$$

23.- Tantalum oxide drying and calcination

Make the calculations for tantalum oxides drying and calcination the same way as drying after leaching (section 3.15). Initial mass of water is 5,94 kg (10 w-% moisture content) and final mass of water is 0,54 kg (1 w-% moisture content).

Energy consumption estimation:

Let us assume the initial and final temperature of 20 °C and 100 °C respectively. Using the equations for energy consumption for water heating and evaporating we can calculate the total energy consumption as follows (for 1 ton of tin slag):

$$W_{21} = 4200 \frac{J}{kg \cdot K} \cdot 5,4kg \cdot (373,15K - 293,12K) + 2246 \frac{kJ}{kg} \cdot 5,4kg = 13,94 \cdot 10^6 J == 3,87 kWh$$

Let us assume that the dryer is heated by gas flaring. The calorific value for methane (CH₄) is 11,06 kWh/m³ [33]. The amount of gas needed to evaporate the mentioned mass of water is:

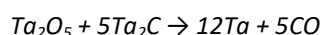
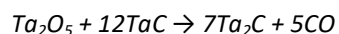
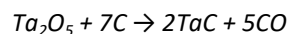
$$V_{CH_4} = \frac{3,87 kWh}{11,06 kWh/m^3} = 0,35 \quad [m^3]$$

24.- Carbo-thermic reduction

Carbo-thermic reduction of tantalum pentoxide allows producing the metallic tantalum. The industrial practice for the production of tantalum consists of two steps. In the first the tantalum carbide is made while in the second step it and the required amount of tantalum pentoxide are mixed, palletized, and fed to a reduction furnace where the reduction to the

metal occurs. The formation of tantalum carbide and as well as reduction to the metal occur at about 2000 °C. The Ta obtained is about 99,8% grade.

The process is described by the following equations [36]:



The summary equation is (very rough):

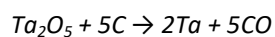


Table 26. Calculated mass balances for the reaction

Component	Mass per 1 ton of tin slag, [kg]
<i>Ta₂O₅</i>	37,380
<i>C</i>	5,079
<i>Ta</i>	30,613
<i>CO</i>	11,846

Energy consumption estimation:

The found open access literature (patent [37]) states that the energy consumption of vacuum arc furnace is about:

$$W = 2,22 \quad [\text{kWh/kg product}]$$

$$W_{24} = 2,22 \cdot 30,613 = 67,96 \quad [\text{kWh/t tin slag}]$$

25.- Electron-beam melting

Electron-beam melting is a final stage of tantalum purification. With this process tantalum purified up to 5N grade (Al < 0,002; C<0,0005; Cu<0,0025; Fe, Si, V < 0,0025; Mg, Mn, Ni, Sn < 0,001; O < 0,01; Ti < 0,005) [23]:

$$m(Ta) = 30,613 - (30,613) \cdot 0,2/100 = 30,55 \quad [\text{kg}]$$

Energy consumption estimation:

According to [39] the energy consumption of electron-beam melting of tantalum is:

$$W_{25} = 5,55 \quad [\text{kWh/kg}]$$

$$W_{25} = 55,55 \cdot 30,55 = 169,55 \quad [\text{kWh/kg}]$$

6.2.4 TANTALUM RECOVERY INVENTORY FOR THE ENVIRONMENTAL STUDY

The following table summarizes the estimated above mass and energy balance for the whole chain of the tantalum production.

Table 27. Calculated mass and energy balances for the process

Process name	Inputs [kg]	Outputs [kg]	Energy per 1 ton of tin slag (input) kWh/t
2. SAG milling of tin slag	Tin slag (10-100 mm): 1000kg ; Balls 110 kg	<u>Product:</u> Tin slag ~8mm	0,708

Table 27. Calculated mass and energy balances for the process

		<u>Wastes:</u> -	
3. Screening (2,5 mesh)	Tin slag ~8mm: 1000kg;	<u>Product:</u> Tin slag <8mm <u>Wastes:</u> Tin slag >8mm (to SAG mill)	0,143
4. Ball milling (dry)	Tin slag <8mm: 1000kg Balls 375 kg	<u>Product:</u> Tin slag ~0,15mm <u>Wastes:</u> -	7,216
5. Dry classification	Tin slag ~0,15mm: 1000kg	<u>Product:</u> Tin slag <0,15mm <u>Wastes:</u> dust (to electro-thermic reduction)	1,2
6. Electro-thermic reduction with carbon (arc furnace)	Tin slag <0,15mm: 1000kg; Coke: 141,140kg;	<u>Product:</u> Hearth product: 362,883kg; <u>Wastes:</u> Supernatant slag: 526,583kg; Other: 212,252kg	162,9
7. Crushing of the hearth product	Hearth product: 362,883kg; Balls: 39,91kg	<u>Product:</u> Hearth product ~2,4mm <u>Wastes:</u> -	0,74
8. Screening	Hearth product ~2,4mm: 362,883kg;	<u>Product:</u> Hearth product <2,4mm <u>Wastes:</u> Hearth prod. >2,4mm (to crushing)	0,181
9. Magnetic separation	Hearth product <2,44mm: 362,883kg	<u>Product:</u> Magn. fraction: 168,723kg <u>Wastes:</u> - Non-magn. fraction: 181,062kg	0,022
10. Fusion with NaNO ₃	Magn. Fraction: 168,723kg C: 25,31kg; NaNO ₃ : 146,821kg	<u>Product:</u> Fusion product: 260,55kg <u>Wastes:</u> - CO: 20,102kg; N ₂ : 24,193kg	0
11. Crushing of the cooled fusion mass	Fusion product: 260,55kg; Balls: 28,66kg	<u>Product:</u> Fusion product ~6,7mm <u>Wastes:</u> -	0,284
12. Screening	Fusion product ~6,7mm: 260,55kg	<u>Product:</u> Fusion product <6,7mm <u>Wastes:</u> Fusion product >6,7mm (to SAG mill)	0,0054
13. Water leaching	Fusion product: <6,7mm 260,55kg H ₂ O: 15,56kg	<u>Product:</u> Residue 273,774kg <u>Wastes:</u> NaWO ₄ : 2,202kg H ₂ O: 0,135kg	1,76
14. Filtration after water leaching	Residue 273,774kg moisture content >10%	Residue 273,774kg moisture content 10%	4,22

Table 27. Calculated mass and energy balances for the process

15. Mineral acid leaching	Residue 273,774kg; HCl: 6,243kg;	<u>Product:</u> Residue 205,284kg <u>Wastes:</u> NaCl: 10,007kg H ₂ O: 3,084kg	4,957
16. Filtration after mineral acid leaching	Residue: 205,284 kg moisture content >10%	Residue: 205,284kg moisture content 10%	3,16
17. Drying and calcination	Residue: 205,284kg moisture content 10% CH ₄ : 1,34 m ³	Residue: 205,284kg moisture content 1%	14,87
18. HF dissolution	Residue 205,284kg; HF: 118,873kg	<u>Product:</u> Ta-Nb solution: 165,997kg <u>Wastes:</u> H ₂ O: 44,523 kg; O ₂ : 12,423kg; FeF ₂ : 145,737kg;	112,14
19. Solvent extraction	Ta-Nb solution: 165,997kg MIBK: 16,945kg	<u>Product:</u> <u>H₂TaF₇MIBK</u> : 70,399kg <u>Wastes:</u> Nb-solution: 112,543kg (to Nb extraction)	
20. Tantalum stripping	<u>H₂TaF₇MIBK</u> : 70,399kg H ₂ O: 6,095kg	<u>Product:</u> H ₂ TaF ₄ : 53,454kg <u>Wastes:</u> MIBK: 16,945 (reuse); H ₃ O ⁺ : 6,436kg	
21. Tantalum precipitation	H ₂ TaF ₄ : 53,454kg H ₂ O: n kg; NH ₄ OH: 41,504kg	<u>Product:</u> Ta ₂ O ₅ : 37,380kg <u>Wastes:</u> NH ₄ F: 43,862kg; H ₂ O: n kg	
22. Tantalum oxide filtration	Ta ₂ O ₅ : 37,380kg moisture content >10%	Ta ₂ O ₅ : 37,380kg moisture content 10%	0,58
23. Drying and calcination	Ta ₂ O ₅ : 37,380kg moisture content 10% CH ₄ : 0,35 m ³	Ta ₂ O ₅ : 37,380kg moisture content 1%	3,87
24. Carbo-thermic reduction	Ta ₂ O ₅ : 37,380kg; C: 5,079kg	<u>Product:</u> Ta: 30,613kg <u>Wastes:</u> _CO: 11,846kg	67,96
25. Electron-beam melting	Ta: 30,613kg (99,8%)	Ta: 30,55 kg Slag: 0,063kg	169,55
Total energy consumption for 1 ton tin slag:			556,46

07. ENVIRONMENTAL IMPACTS ASSOCIATED TO THE RECYCLING/RECOVERY PROCESS

Before starting with the environmental results, the following assumptions have been considered in order to develop the environmental study.

a) Allocation

One of the first steps to be considered during the environmental evaluation is to determine what are the elements included in the process and how these processes must be allocated.

As it has been reported, tin slag contents (see table 8) is:

- 32.76 kg Ta /t of tin slag
- 27.96 kg Nb/t of tin slag

The first stages of the process are in the Ta/Nb fraction separation from the rest of the elements included in the slag (stages 1 to 18).

So the environmental results obtained during those stages must be allocated assuming the following ratios (mass allocation)

Table 28. Allocation rules for the Ta recovery process

Component	Mass per 1 ton of tin slag, [kg]	Percentage (%)	Allocation ratio
Ta	32,76	53,95	0,5395
Nb	27,96	46,05	0,4605
TOTAL	60,72	100,00	1,0000

Stages from 19 to 25 will be fully allocated to the Ta recovery process. Working this way, the environmental study will be fair in terms of environmental allocation of the metal studied (Ta).

b) Materials, energy and wastes

Although data for materials, energy and wastes have been reported, sometimes it is complex to assess the environmental impact of the waste flows, so the global assessment has been

made considering **mass** and **energy**, and wastes will be considered separately, assuming different options.

c) Environmental indicators

The environmental indicators used are Global warming potential, Cumulative energy demand, Terrestrial acidification, Freshwater eutrophication and Human toxicity.

Global warming potential

Table 29 shows the environmental results for 1 ton of tin slag and for 1 kg of Ta after the recovery process.

Table 29. Global warming potential results for the recovery treatment (For 1 ton of tin slag and 1 kg of Ta). Materials and energy.

Process stage		Per 1 ton of tin slag			Per kg of Ta recovered		
		Materials	Energy	Total	Materials	Energy	Total
		Kg CO2 eq	Kg CO2 eq	Kg CO2 eq	Kg CO2 eq	Kg CO2 eq	Kg CO2 eq
1	Input slag material	0,00	0,00	0,00	0,00	0,00	0,00
2	SAG milling of tin slag	0,00	0,34	0,34	0,00	0,01	0,01
3	Screening (2,5 mesh)	0,00	0,07	0,07	0,00	0,00	0,00
4	Ball milling (dry)	0,00	3,43	3,43	0,00	0,06	0,06
5	Dry classification	0,00	0,57	0,57	0,00	0,01	0,01
6	Electro-thermic reduction with carbon (arc furnace)	15,81	77,38	93,19	0,28	1,37	1,65
7	Crushing of the hearth product	0,00	0,35	0,35	0,00	0,01	0,01
8	Screening	0,00	0,09	0,09	0,00	0,00	0,00
9	Magnetic separation	0,00	0,01	0,01	0,00	0,00	0,00
10	Fusion with NaNO3	760,57	0,00	760,57	13,43	0,00	13,43
11	Crushing of the cooled fusion mass	0,00	0,13	0,13	0,00	0,00	0,00
12	Screening	0,00	0,00	0,00	0,00	0,00	0,00
13	Water leaching	0,01	0,84	0,84	0,00	0,01	0,01
14	Filtration after water leaching	0,00	2,00	2,00	0,00	0,04	0,04
15	Mineral acid leaching	3,80	2,35	6,15	0,07	0,04	0,11
16	Filtration after mineral acid leaching	0,00	1,50	1,50	0,00	0,03	0,03
17	Drying and calcination	0,00	3,70	3,70	0,00	0,07	0,07
18-21	Solution / Solvent extraction /Stripping / Precipitation	488,19	53,27	541,45	15,98	1,74	17,72
22	Tantalum oxide filtration	0,00	0,28	0,28	0,00	0,01	0,01
23	Drying and calcination	0,00	0,96	0,96	0,00	0,03	0,03
24	Carbo-thermic reduction	12,09	32,28	44,37	0,40	1,06	1,45

25	Electron-beam melting	0,00	80,54	80,54	0,00	2,64	2,64
TOTAL		1.280,46	260,09	1.540,55	30,15	7,12	37,27

According to these values, the comparison between primary extraction and the recovery process is:

- Primary extraction: 260 kg CO₂ eq /kg Ta
- Recovery process (considering materials and energy): 37,27kg CO₂ eq/kg Ta

The figure 13 shows the different stages impact in terms of global warming.

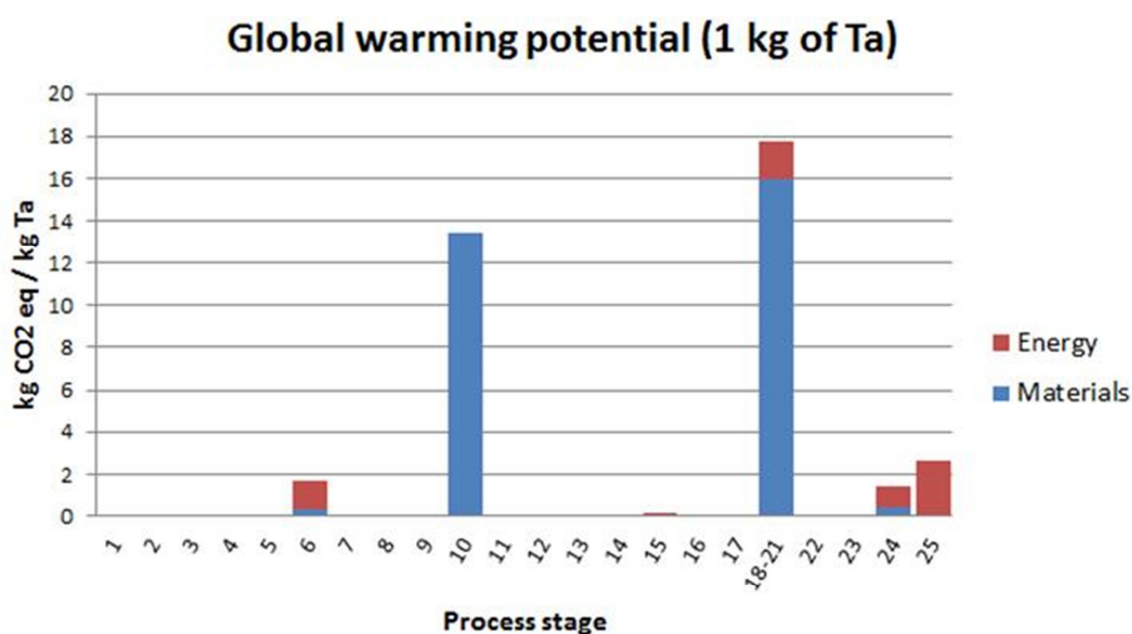


Figure 13. Global warming potential results for Ta recovery. Materials and energy

As it can be seen, the most impacting stage is the *Solution – Solvent extraction – Stripping – Precipitation* process, being a high material impact process, as well as the second process stage in order of relevance, the fusion with NaNO₃.

Global warming potential (1 kg of Ta)

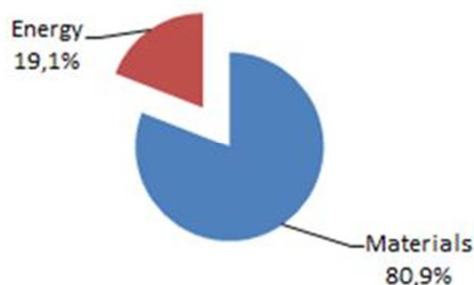


Figure 14. Global warming potential percentage results for Ta recovery. Materials and energy.

Also the electron-beam melting, the electro-thermic reduction with carbon (arc furnace) and the carbon thermic reduction have a slight impact, but in this case due to the energy consumption.

Figure 14 represents the percentage contribution of the two main inputs of the process (material and energy).

Materials contribution is the most impacting one (80,9 %), so the main efforts should be focused on that part.

NaNO₃ in the stage #10 followed by the Fluorhydric acid used in the stage #18 (HF dissolution).

The higher contribution of the whole process is

Cumulative energy demand

Table 30 shows the environmental results in terms of Cumulative energy demand, expressed en MJ.

Table 30. Cumulative energy demand results for the recovery treatment (For 1 ton of tin slag and 1 kg of Ta).Materials and energy

Process stage		Per 1 ton of tin slag			Per kg of Ta recovered		
		Materials	Energy	Total	Materials	Energy	Total
		MJ	MJ	MJ	MJ	MJ	MJ
1	Input slag material	0,00	0,00	0,00	0,00	0,00	0,00
2	SAG milling of tin slag	0,00	7,86	7,86	0,00	0,14	0,14
3	Screening (2,5 mesh)	0,00	1,59	1,59	0,00	0,03	0,03
4	Ball milling (dry)	0,00	80,10	80,10	0,00	1,41	1,41
5	Dry classification	0,00	13,32	13,32	0,00	0,24	0,24
6	Electro-thermic reduction with carbon (arc furnace)	1.256,15	1.808,19	3.064,34	22,18	31,93	54,11
7	Crushing of the hearth product	0,00	8,21	8,21	0,00	0,15	0,15
8	Screening	0,00	2,01	2,01	0,00	0,04	0,04
9	Magnetic separation	0,00	0,24	0,24	0,00	0,00	0,00
10	Fusion with NaNO ₃	8.228,20	0,00	8.228,20	145,31	0,00	145,31
11	Crushing of the cooled fusion mass	0,00	3,15	3,15	0,00	0,06	0,06
12	Screening	0,00	0,06	0,06	0,00	0,00	0,00
13	Water leaching	147,04	19,54	166,58	2,60	0,34	2,94

14	Filtration after water leaching	0,00	46,84	46,84	0,00	0,83	0,83
15	Mineral acid leaching	80,42	55,02	135,44	1,42	0,97	2,39
16	Filtration after mineral acid leaching	0,00	35,08	35,08	0,00	0,62	0,62
17	Drying and calcination	0,00	63,94	63,94	0,00	1,13	1,13
18-21	Solution / Solvent extraction /Stripping / Precipitation	8.258,46	1.244,75	9.503,21	270,33	40,74	311,07
22	Tantalum oxide filtration	0,00	6,44	6,44	0,00	0,21	0,21
23	Drying and calcination	0,00	16,64	16,64	0,00	0,54	0,54
24	Carbo-thermic reduction	452,03	754,36	1.206,39	14,80	24,69	39,49
25	Electron-beam melting	0,00	1.882,01	1.882,01	0,00	61,60	61,60
TOTAL		18.422,30	6.049,35	24.471,65	456,63	165,68	622,31

According to these values, the comparison between primary extraction and the recovery process is:

- Primary extraction: 4,360 E+03 MJ /kg Ta
- Recovery process (considering materials and energy): 6,22 E+02 MJ/kg Ta

The figure 15 shows the different stages impact in terms of Cumulative energy demand.

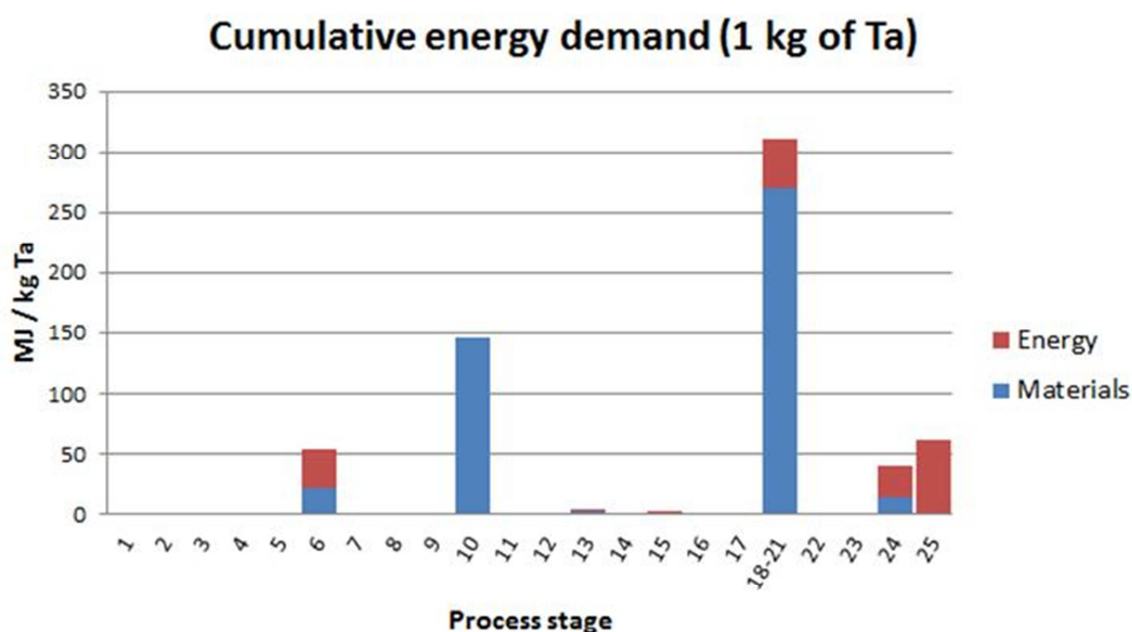


Figure 15. Cumulative energy demand results for Ta recovery. Materials and energy

The results obtained in this category are quite similar as the previously reported in the CO₂ emissions category.

The *Solution – Solvent extraction – Stripping – Precipitation* process is again the most impacting stage, followed by the Fusion stage.

In this case, the Materials impact represents nearly 75 % of the global impact of the recovery process.

HF in the stage #18 and NaNO₃ in stage #10 are the main impacts in the process.

In terms of energy, the most impacting stages are the electro-beam melting, followed by the *Solution – Solvent extraction – Stripping – Precipitation* and the Electro-thermic reduction with carbon (arc furnace).

Cumulative energy demand (1 kg of Ta)

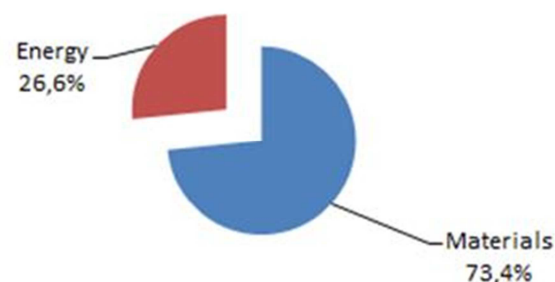


Figure 16. Cumulative energy demand percentage results for Ta recovery. Materials and energy.

Terrestrial acidification

Table 31 shows the environmental results in terms of Terrestrial acidification expressed in kg SO₂ eq.

Table 31. Terrestrial acidification results for the recovery treatment (For 1 ton of tin slag and 1 kg of Ta). Materials and energy

Process stage		Per 1 ton of tin slag			Per kg of Ta recovered		
		Materials	Energy	Total	Materials	Energy	Total
		Kg SO ₂ eq	Kg SO ₂ eq	Kg SO ₂ eq	Kg SO ₂ eq	Kg SO ₂ eq	Kg SO ₂ eq
1	Input slag material	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
2	SAG milling of tin slag	0,00E+00	1,42E-03	1,42E-03	0,00E+00	2,50E-05	2,50E-05
3	Screening (2,5 mesh)	0,00E+00	2,86E-04	2,86E-04	0,00E+00	5,05E-06	5,05E-06
4	Ball milling (dry)	0,00E+00	1,44E-02	1,44E-02	0,00E+00	2,55E-04	2,55E-04
5	Dry classification	0,00E+00	2,40E-03	2,40E-03	0,00E+00	4,24E-05	4,24E-05
6	Electro-thermic reduction with carbon (arc furnace)	1,30E-01	3,26E-01	4,56E-01	2,29E-03	5,75E-03	8,04E-03
7	Crushing of the hearth product	0,00E+00	1,48E-03	1,48E-03	0,00E+00	2,61E-05	2,61E-05
8	Screening	0,00E+00	3,62E-04	3,62E-04	0,00E+00	6,39E-06	6,39E-06
9	Magnetic separation	0,00E+00	4,40E-05	4,40E-05	0,00E+00	7,77E-07	7,77E-07
10	Fusion with NaNO ₃	3,06E+00	0,00E+00	3,06E+00	5,40E-02	0,00E+00	5,40E-02
11	Crushing of the cooled fusion mass	0,00E+00	5,68E-04	5,68E-04	0,00E+00	1,00E-05	1,00E-05
12	Screening	0,00E+00	1,08E-05	1,08E-05	0,00E+00	1,91E-07	1,91E-07

13	Water leaching	3,53E-05	3,52E-03	3,56E-03	6,24E-07	6,22E-05	6,28E-05
14	Filtration after water leaching	0,00E+00	8,44E-03	8,44E-03	0,00E+00	1,49E-04	1,49E-04
15	Mineral acid leaching	1,41E-02	9,91E-03	2,40E-02	2,49E-04	1,75E-04	4,24E-04
16	Filtration after mineral acid leaching	0,00E+00	6,32E-03	6,32E-03	0,00E+00	1,12E-04	1,12E-04
17	Drying and calcination	0,00E+00	2,62E-03	2,62E-03	0,00E+00	4,62E-05	4,62E-05
18-21	Solution / Solvent extraction /Stripping / Precipitation	6,18E+00	2,24E-01	6,40E+00	2,02E-01	7,34E-03	2,10E-01
22	Tantalum oxide filtration	0,00E+00	1,16E-03	1,16E-03	0,00E+00	3,80E-05	3,80E-05
23	Drying and calcination	0,00E+00	6,81E-04	6,81E-04	0,00E+00	2,23E-05	2,23E-05
24	Carbo-thermic reduction	3,06E-02	1,36E-01	1,66E-01	1,00E-03	4,45E-03	5,45E-03
25	Electron-beam melting	0,00E+00	3,39E-01	3,39E-01	0,00E+00	1,11E-02	1,11E-02
TOTAL		9,41E+00	1,08E+00	1,05E+01	2,60E-01	2,96E-02	2,89E-01

According to these values, the comparison between primary extraction and the recovery process is:

- Primary extraction: 1,7 kg SO₂ eq /kg Ta
- Recovery process (considering materials and energy): 2,89 E-01 kg SO₂ eq/kg Ta

The figure 17 shows the different stages impact in terms of Terrestrial acidification.

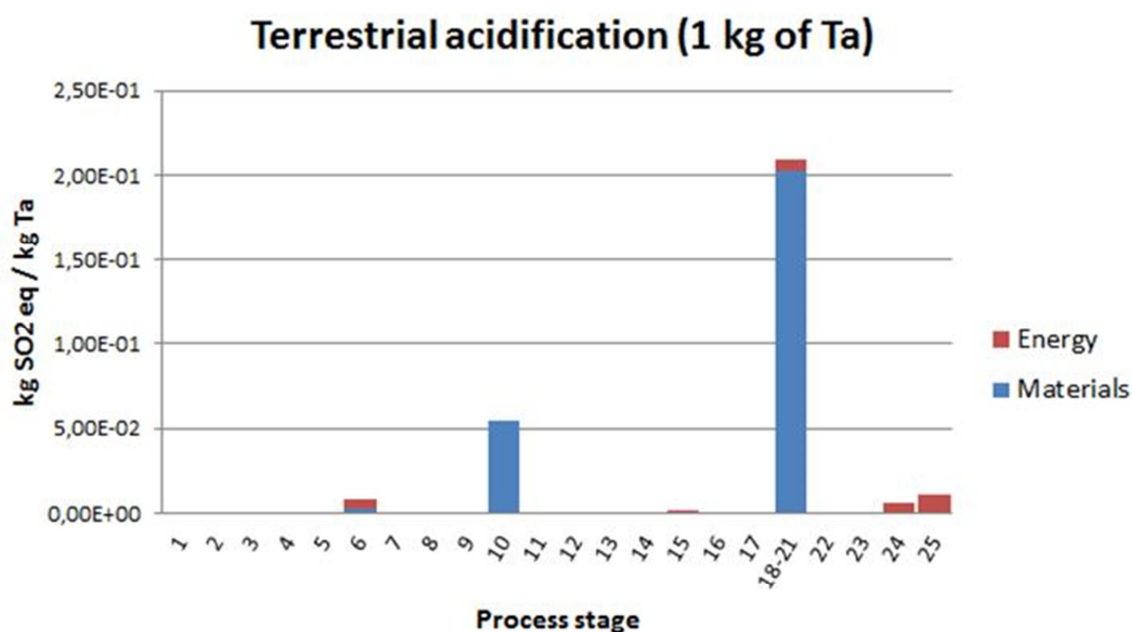


Figure 17. Terrestrial acidification results for Ta recovery. Materials and energy

The results obtained in this category prove that the five stages previously mentioned are the main ones to be considered. The *Solution – Solvent extraction – Stripping – Precipitation* process is again the most impacting stage, followed by the Fusion stage in the same way as in the two previous environmental indicators results.

The Materials impact represents nearly 90 % of the global impact of the recovery process.

HF in the stage #18 and NaNO₃ in stage #10 are the main impacts in the process (same result as in cumulative energy demand category).

In terms of energy, the most impacting stages are the electro-beam melting, followed by the *Solution – Solvent extraction – Stripping – Precipitation* and the Electro-thermic reduction with carbon (arc furnace).

Terrestrial acidification (1 kg of Ta)

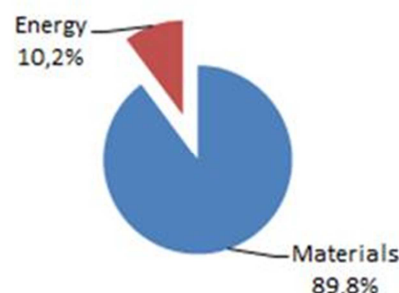


Figure 18. Terrestrial acidification percentage results for Ta recovery. Materials and energy

These results are also the same as in the two previous categories. This situation will help to clearly identify the most interesting stage to study in order to improve the environmental results.

Freshwater eutrophication

Table 32 shows the environmental results in terms of Freshwater eutrophication expressed in kg P eq.

Table 32. Freshwater eutrophication results for the recovery treatment (For 1 ton of tin slag and 1 kg of Ta). Materials and energy.

Process stage		Per 1 ton of tin slag			Per kg of Ta recovered		
		Materials	Energy	Total	Materials	Energy	Total
		Kg P eq	Kg P eq	Kg P eq	Kg P eq	Kg P eq	Kg P eq
1	Input slag material	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
2	SAG milling of tin slag	0,00E+00	2,90E-04	2,90E-04	0,00E+00	5,13E-06	5,13E-06
3	Screening (2,5 mesh)	0,00E+00	5,86E-05	5,86E-05	0,00E+00	1,04E-06	1,04E-06
4	Ball milling (dry)	0,00E+00	2,96E-03	2,96E-03	0,00E+00	5,22E-05	5,22E-05
5	Dry classification	0,00E+00	4,92E-04	4,92E-04	0,00E+00	8,69E-06	8,69E-06
6	Electro-thermic reduction with carbon (arc furnace)	1,88E-03	6,68E-02	6,87E-02	3,31E-05	1,18E-03	1,21E-03
7	Crushing of the hearth product	0,00E+00	3,03E-04	3,03E-04	0,00E+00	5,36E-06	5,36E-06
8	Screening	0,00E+00	7,42E-05	7,42E-05	0,00E+00	1,31E-06	1,31E-06
9	Magnetic separation	0,00E+00	9,02E-06	9,02E-06	0,00E+00	1,59E-07	1,59E-07

10	Fusion with NaNO ₃	1,36E-01	0,00E+00	1,36E-01	2,40E-03	0,00E+00	2,40E-03
11	Crushing of the cooled fusion mass	0,00E+00	1,16E-04	1,16E-04	0,00E+00	2,06E-06	2,06E-06
12	Screening	0,00E+00	2,21E-06	2,21E-06	0,00E+00	3,91E-08	3,91E-08
13	Water leaching	4,51E-06	7,22E-04	7,26E-04	7,97E-08	1,27E-05	1,28E-05
14	Filtration after water leaching	0,00E+00	1,73E-03	1,73E-03	0,00E+00	3,06E-05	3,06E-05
15	Mineral acid leaching	1,35E-03	2,03E-03	3,39E-03	2,39E-05	3,59E-05	5,98E-05
16	Filtration after mineral acid leaching	0,00E+00	1,30E-03	1,30E-03	0,00E+00	2,29E-05	2,29E-05
17	Drying and calcination	0,00E+00	5,46E-05	5,46E-05	0,00E+00	9,64E-07	9,64E-07
18-21	Solution / Solvent extraction /Stripping / Precipitation	3,12E-01	4,60E-02	3,58E-01	1,02E-02	1,50E-03	1,17E-02
22	Tantalum oxide filtration	0,00E+00	2,38E-04	2,38E-04	0,00E+00	7,78E-06	7,78E-06
23	Drying and calcination	0,00E+00	1,42E-05	1,42E-05	0,00E+00	4,65E-07	4,65E-07
24	Carbo-thermic reduction	5,23E-04	2,79E-02	2,84E-02	1,71E-05	9,12E-04	9,29E-04
25	Electron-beam melting	0,00E+00	6,95E-02	6,95E-02	0,00E+00	2,28E-03	2,28E-03
TOTAL		4,52E-01	2,21E-01	6,72E-01	1,27E-02	6,06E-03	1,87E-02

According to these values, the comparison between primary extraction and the recovery process is:

- Primary extraction: 1,5 E-01 kg P eq /kg Ta
- Recovery process (considering materials and energy): 1,87 E-02 kg P eq /kg Ta

The figure 19 shows the different stages impact in terms of Freshwater eutrophication.

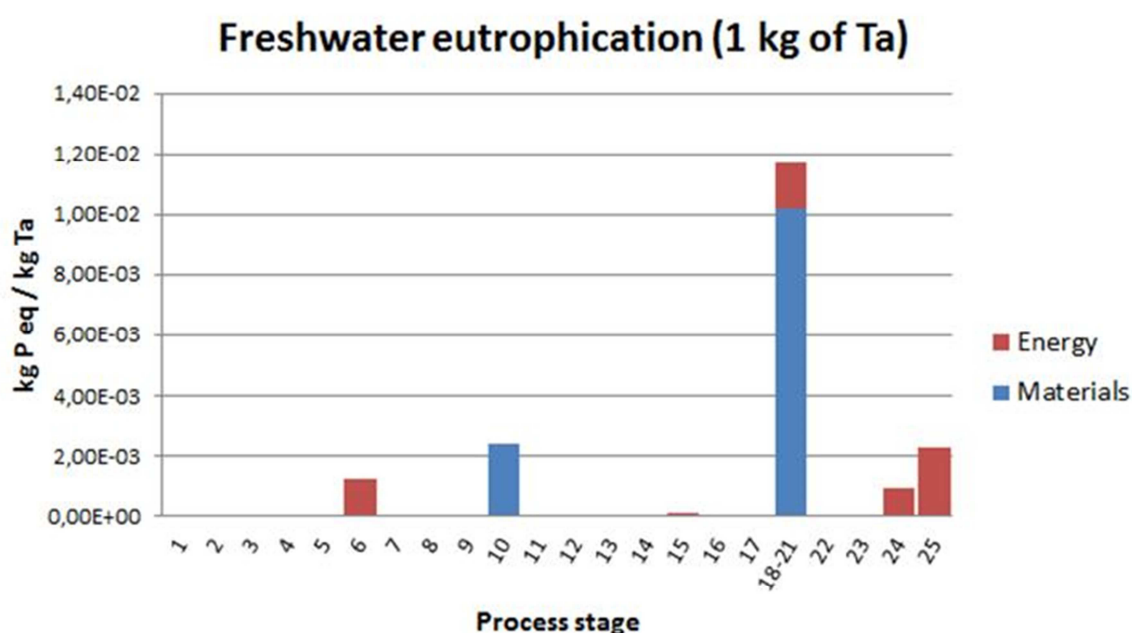


Figure 19. Freshwater eutrophication results for Ta recovery. Materials and energy.

Once again the *Solution – Solvent extraction – Stripping – Precipitation* process and the Fusion stage are the most impacting stages, mainly due to the impact of the materials involved in those stages.

Materials is again the most impacting input in the global process (67,7%).

In the materials part, HF in the stage #18 and NaNO₃ in stage #10 are the main impacts in the process.

In terms of energy, the most impacting stages are the electro-beam melting, followed by the *Solution – Solvent extraction – Stripping – Precipitation* and the Electro-thermic reduction with carbon (arc furnace). These results are in accordance with the three previous indicators.

Freshwater eutrophication (1 kg of Ta)

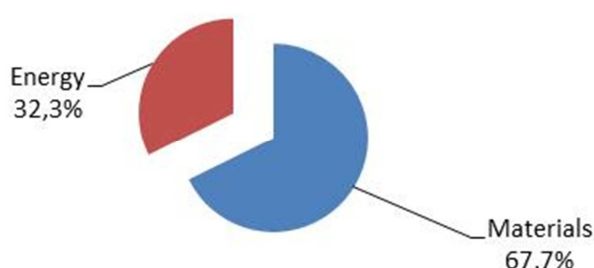


Figure 20. Freshwater eutrophication percentage results for Ta recovery. Materials and energy.

Human toxicity

Table 33 shows the environmental results in terms of Human toxicity expressed in CTUh.

Table 33. Human toxicity results for the recovery treatment (For 1 ton of tin slag and 1 kg of Ta). Materials and energy.

Process stage		Per 1 ton of tin slag			Per kg of Ta recovered		
		Materials	Energy	Total	Materials	Energy	Total
		CTUh	CTUh	CTUh	CTUh	CTUh	CTUh
1	Input slag material	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
2	SAG milling of tin slag	0,00E+00	1,24E-11	1,24E-11	0,00E+00	2,19E-13	2,19E-13
3	Screening (2,5 mesh)	0,00E+00	2,50E-12	2,50E-12	0,00E+00	4,42E-14	4,42E-14
4	Ball milling (dry)	0,00E+00	1,26E-10	1,26E-10	0,00E+00	2,23E-12	2,23E-12
5	Dry classification	0,00E+00	2,10E-11	2,10E-11	0,00E+00	3,71E-13	3,71E-13
6	Electro-thermic reduction with carbon (arc furnace)	9,10E-10	2,85E-09	3,76E-09	1,61E-11	5,03E-11	6,64E-11
7	Crushing of the hearth product	0,00E+00	1,30E-11	1,30E-11	0,00E+00	2,29E-13	2,29E-13
8	Screening	0,00E+00	3,17E-12	3,17E-12	0,00E+00	5,59E-14	5,59E-14
9	Magnetic separation	0,00E+00	3,85E-13	3,85E-13	0,00E+00	6,80E-15	6,80E-15

10	Fusion with NaNO ₃	3,74E-08	0,00E+00	3,74E-08	6,60E-10	0,00E+00	6,60E-10
11	Crushing of the cooled fusion mass	0,00E+00	4,97E-12	4,97E-12	0,00E+00	8,78E-14	8,78E-14
12	Screening	0,00E+00	9,45E-14	9,45E-14	0,00E+00	1,67E-15	1,67E-15
13	Water leaching	4,16E-13	3,08E-11	3,12E-11	7,34E-15	5,44E-13	5,51E-13
14	Filtration after water leaching	0,00E+00	7,39E-11	7,39E-11	0,00E+00	1,30E-12	1,30E-12
15	Mineral acid leaching	1,53E-09	8,67E-11	1,62E-09	2,71E-11	1,53E-12	2,86E-11
16	Filtration after mineral acid leaching	0,00E+00	5,53E-11	5,53E-11	0,00E+00	9,77E-13	9,77E-13
17	Drying and calcination	0,00E+00	1,51E-10	1,51E-10	0,00E+00	2,68E-12	2,68E-12
18-21	Solution / Solvent extraction /Stripping / Precipitation	2,15E-08	1,96E-09	2,35E-08	7,05E-10	6,42E-11	7,69E-10
22	Tantalum oxide filtration	0,00E+00	1,02E-11	1,02E-11	0,00E+00	3,32E-13	3,32E-13
23	Drying and calcination	0,00E+00	3,94E-11	3,94E-11	0,00E+00	1,29E-12	1,29E-12
24	Carbo-thermic reduction	9,86E-11	1,19E-09	1,29E-09	3,23E-12	3,89E-11	4,22E-11
25	Electron-beam melting	0,00E+00	2,97E-09	2,97E-09	0,00E+00	9,71E-11	9,71E-11
TOTAL		6,14E-08	9,60E-09	7,10E-08	1,41E-09	2,63E-10	1,67E-09

According to these values, the comparison between primary extraction and the recovery process is:

- Primary extraction: 1,2 E-04 CTUh /kg of Ta
- Recovery process (considering materials and energy): 1,67 E-09 CTUh /kg Ta

The figure 21 shows the different stages impact in terms of Human toxicity.

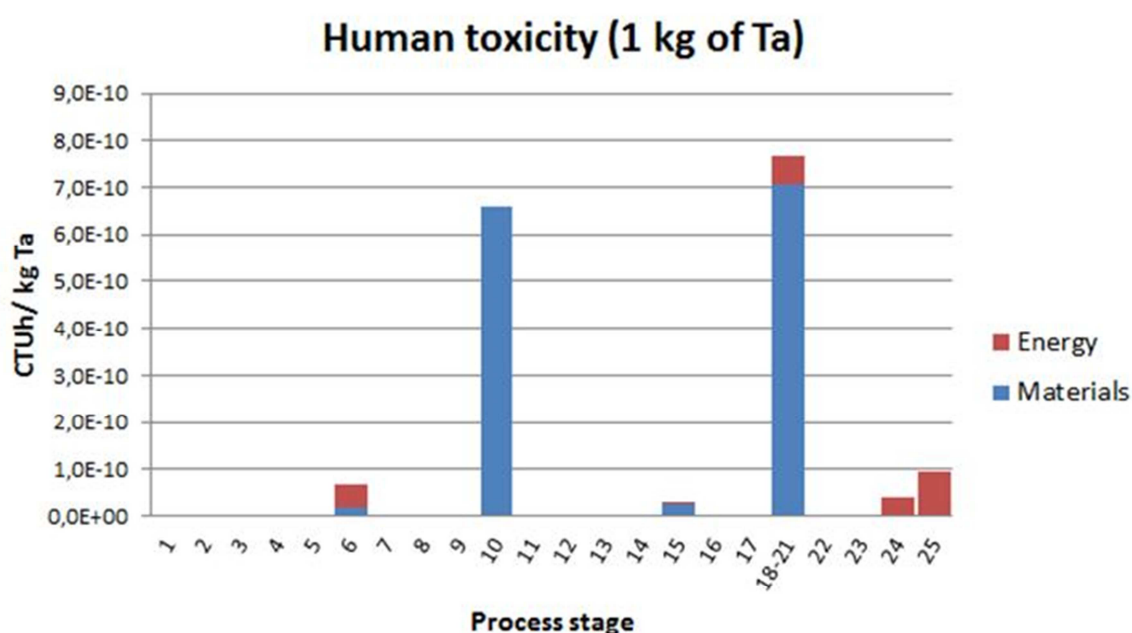


Figure 21. Human toxicity results for Ta recovery. Materials and energy

In this case, the *Solution – Solvent extraction – Stripping – Precipitation* process and the Fusion stage are very similar, with high contribution of the materials involved in those stages.

Materials is again the most impacting input (84,3%).

In the materials part, NaNO₃ in stage #10, HF in the stage #18, stage #21 with the NH₄OH are the main impacts in the process.

In terms of energy, the most impacting stages are the electro-beam melting, followed by the *Solution – Solvent extraction – Stripping – Precipitation* and the Electro-thermic reduction with carbon (arc furnace).

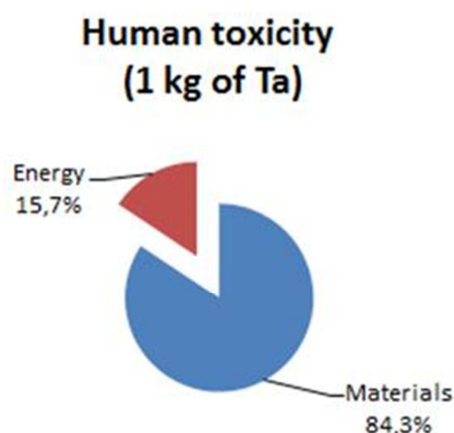


Figure 22. Human toxicity percentage results for Ta recovery. Materials and energy.

08. CONCLUSIONS

Regarding to the part of wastes, no specific flows have been found in the literature in order to assess the environmental impact of wastes, so a final comparison between the primary extraction and the secondary recovery will be shown in the following figures (23 to 27):

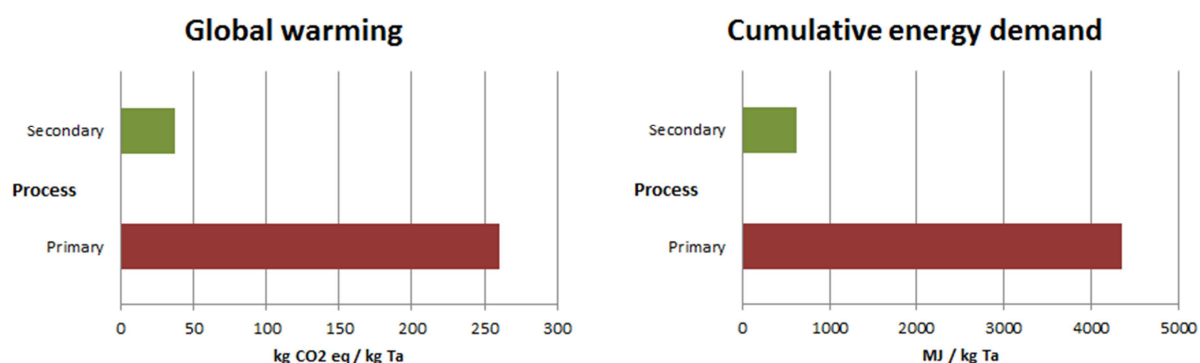


Figure 23. Primary extraction vs. Secondary recovery.
Global warming.

Figure 24. Primary extraction vs. Secondary recovery.
Cumulative energy demand

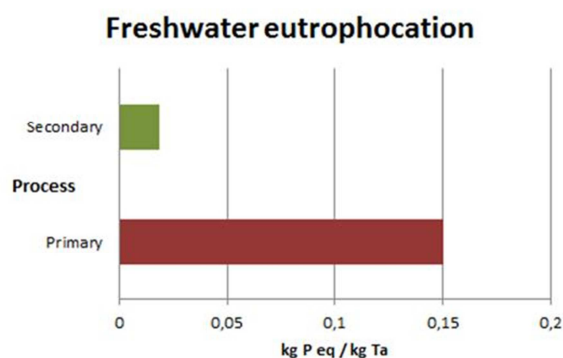
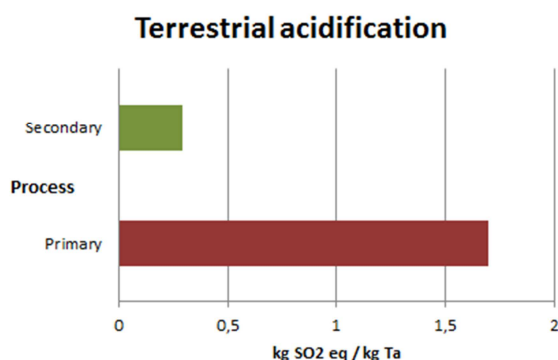


Figure 25. Primary extraction vs. Secondary recovery.
Terrestrial acidification

Figure 26. Primary extraction vs. Secondary recovery.
Freshwater eutrophication

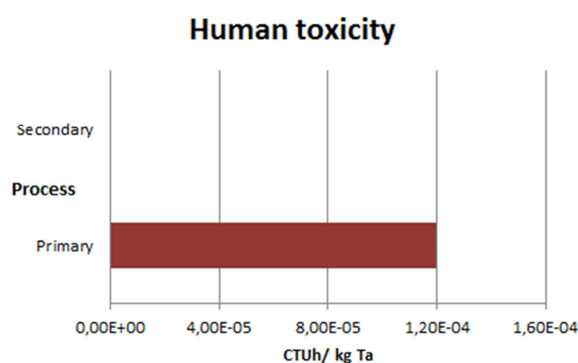


Figure 27. Primary extraction vs. Secondary recovery. Human toxicity

As it can be seen in the figures, for all the environmental impact categories, there is an important gap between the impact of the secondary recovery process and the primary extractive process.

In the first four indicators, the recovery process implies (more or less) 15 % of the environmental impacts of the primary process, while human toxicity is even lower.

Waste management during the recovery process has not been considered, so the main objective would be that the waste management do not exceed the gap between the primary and the secondary, in order to improve the overall process.

Further development and research should be done in the waste management for the recovery process, but also considering and taking into account the difficulties of the environmental impact assessment in that specific flows.

The recovery process proposed offers a good opportunity for recycling in terms of the environmental impact. Other issues as logistic or economic matters should be also considered.

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