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Application of International Standards to Evaluate the Potential of Sustainable Secondary Production of Tin and Tungsten in Portugal †

Md Ariful Islam [1,*], José E. Brito Iria [1], Georg Meissner [1], George Barakos [2] and Helmut Mischo [1]

[1] Institute of Mining and Special Civil Engineering, TU Bergakademie Freiberg, 09599 Freiberg, Germany
[2] Western Australian School of Mines: Minerals, Energy and Chemical Engineering, Curtin University, Bentley, WA 6102, Australia
* Correspondence: md-ariful.islam@mabb.tu-freiberg.de; Tel.: +49-(0)-3731-39-3809
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Abstract: The ambitious movement towards industry 5.0 technologies and the green transition drives the efforts towards securing critical metals' supply chains globally. In Europe, highly economically important Tin and Tungsten are raising concerns regarding supply security due to geographical reserves' uniformity and socio-political reluctance to mining. Nevertheless, mines that have seized operations in Portugal due to not being sustainable in the past are attracting renewed attention for further exploitation due to growing market demand and reclamation efforts for environmental concerns. Such abandoned resources need to be reassessed for their feasibility from economic, social, and environmental perspectives to ensure sustainable exploitation. Presenting the production criticality of Tin and Tungsten, this study implements the United Nations Framework Classification for Resources (UNFC) to assess the viability of abandoned mines and tailings dumps in Portugal, considering the indicators of Sustainable Development Goals (SDGs). The work indicates that Portugal's abandoned Vale das Gatas Tin and Tungsten mine has good potential for further development. Furthermore, social perception towards new and abandoned mining is evaluated by collecting opinions from different parts of the country. It has been identified that sustainable technology and job opportunities are the driving parameters for the social acceptance of mining projects in Portugal.

Keywords: Tin; Tungsten; secondary production; abandoned mines; UNFC; SDGs

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1. Introduction

Tin and Tungsten have strategic and economic importance to industrialized countries due to their extensive usage in various industrial applications and unique characteristics. However, primary production of Tin and Tungsten is heavily concentrated in a handful of countries. In 2022, 90% of Tungsten was produced in only two countries and 65% of Tin was produced in three Asian countries.

The Tin and Tungsten supply chain for the European Union (EU) heavily depends on imports and is subject to international responsible sourcing standards evaluation requirements [1]. Furthermore, the EU's green energy transition, e-mobility, and Industry 5.0 ambitions require batteries, magnets, and electronics, where Tin and Tungsten play crucial roles [2,3].

In the EU, Portugal has contributed significantly to the world's primary Tungsten production for over a century. It peaked during 1910–1920 and 1940–1950, accounting for more than 10% of the world's output [4]. Nevertheless, the nation's production levels have varied over the past few decades, from 1340 metric tons (Mt) in 1997 to 500 Mt in 2022. The lengthy production history has resulted in 40 abandoned Tin and Tungsten mines or tailing deposits in Portugal. Researchers emphasize the potential of extraction of minerals

from abandoned mines and tailings to enhance the EU's self-sufficiency and environmental remediation [5,6].

Moreover, such abandoned mines are a risky source of pollution of surface waterways [6] and the nearby soil, ranging from significantly to ultra-highly contaminated with As and Cd [7]. Additionally, flora growing in abandoned mines contains vast amounts of Antimony, Arsenic, and Tungsten [8]. Therefore, sustainable reproduction from such abandoned mines or their tailings might reduce the risk of pollution and contribute to key performance indicators (KPIs) of the SDGs.

The objectives of the research are to examine:

i. The KPIs of the United Nations' SDGs that are related to the potentiality and problems of secondary production from abandoned mines in Portugal;
ii. The parameters and sub-parameters required for classifying the abandoned mines using the definition of the UNFC axes;
iii. social perception for secondary production in Portugal;
iv. the viability of the secondary production of Tin and Tungsten from abandoned mines in Portugal using the UNFC framework.

2. Tin and Tungsten Abandoned Mines and Tailings in Portugal

With a long history of primary production, Portugal's center to northern regions are home to 40 abandoned Tin and Tungsten mines or tailing deposits (Figure 1). The majority of the abandoned deposits are part of northern Portugal's Variscan granitic complex, which is composed of peraluminous S-type, two-mica granite (muscovite > biotite) with fine- to medium-grained porphyritic structure [9].

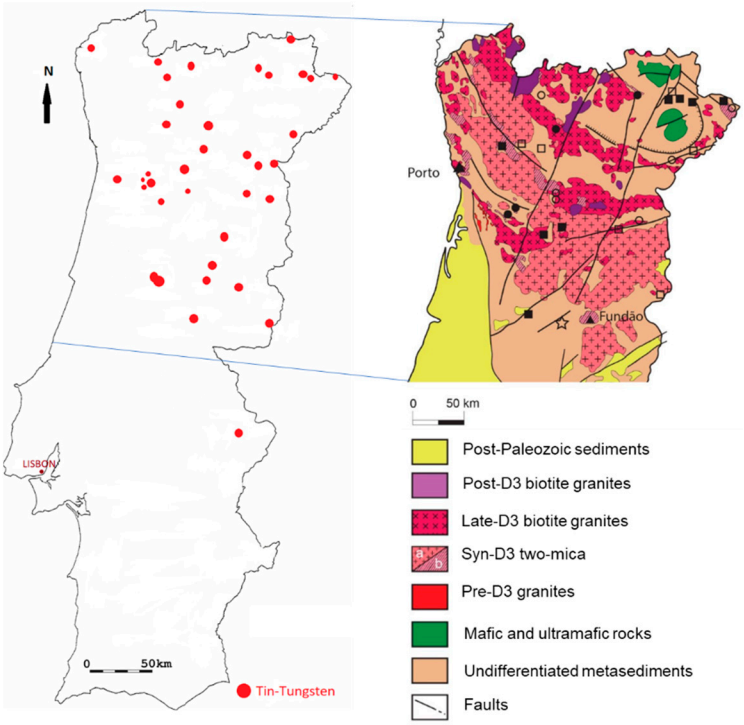

Figure 1. Location of the Tin and Tungsten abandoned mining/tailing sites in Portugal (**left**); Streamlined geological map of northern and central Portugal with the main varieties of granite and metasedimentary formations (**right**) (modified after [9]).

Moreover, abandoned mines have piles of waste rock, tailings, slags, and mine water from earlier mineral extraction, beneficiation, and processing [10]. Several economically valuable ore minerals are found in these abandoned mines or tailing piles, the most notable being wolframite [(Fe, Mn)WO_4], scheelite ($CaWO_4$), cassiterite (SnO_2), ferberite ($FeWO_4$), and chalcopyrite ($CuFeS_2$).

However, numerous abandoned mines in Portugal are a source of acid mine drainage, arsenic, and toxic elements mixed with soil and water, causing radiological risks to public health [11,12]. Thus, they violate several KPIs of the United Nations' Sustainable Development Goals (SDGs), and at the same time, production in these abandoned mines can support many indicators (Table 1). Table 1 shows five KPIs related to the restoration of abandoned mines or tailings sites, where the related factors would support the achievement of the goals of KPIs-7,8,9 and factors that would violate the goals are associated with KPIs-11,15.

Table 1. Sustainable Development Goals (SDGs)—KPIs and related factors from secondary production of abandoned mines and tailings.

UN—Sustainable Development Goals (SDGs)—KPIs	Related Factors	Sources
7: Affordable and Clean Energy	- Tungsten and Tin are crucial to the renewable energy sector	[13]
8: Decent Work and Economic Growth	- Sustainable extraction creates responsible job opportunities	[14]
9: Industry, Innovation, and Infrastructure	- Tungsten is required in aerospace, alloys, arc welding, automotive, permanent magnets, nanoelectronics, nuclear reactors, radiology, etc. - Tin-copper alloys may have a new use 148 in the framework for electric cars and renewable energy sources.	[2,3]
11: Sustainable Cities and Communities	- Radiological risks for public health from abandoned or tailing sites	[11]
15: Life on Land	- Creation of Acid mine drainage (AMD) - Sources of high arsenic and toxic elements in water - Generate chemical contamination in water and soil	[11,12]

3. International Standard for Sustainable Project Classification

3.1. United Nations Framework Classification (UNFC)

The UNFC system uses numerical coding in terms of three mandatory criteria in three-dimensional axes, which are: environmental-socio-economic viability (E), technical feasibility (F), and degree of confidence (G). Each of the axes has several categories (E1, E2, E3; F1, F2, F3 and F4; G1, G2, G3 and G4) and the definition of each category is summarized in Table 2.

Table 2. Definition of categories for E, F and G axes of the UNFC.

	1	2	3	4
E	Confirmed the viability	Expected to be viable	Not expected to be viable or too early stage	
F	Viability is confirmed	Subject to further evaluation	Limited data	No development
G	High level	Moderate level	Low level	Indirect evidence

The UNFC framework has no guidelines for selecting parameters when classifying the targeted projects in the three axes (E, F, G). The study has adopted four measures to minimize the gaps: (i) Identifying the assessment parameters and sub-parameters by analyzing existing similar efforts ([15,16]); (ii) Choosing appropriate techniques for evaluating the sub-parameters; (iii) Techniques into practice and connecting them to the three UNFC axis,

and, (iv) Classifying the candidate projects following the UNFC requirements. The adopted parameters, sub-parameters, pertinent methodologies, and UNFC axes are summarized in Table 3, which has been applied in the cases.

Table 3. Parameters, sub-parameters, and methods are considered when classifying abandoned mines and tailings.

Parameters	Sub-Parameters		Methods/Sources	UNFC Axis
Geography	Location, Topography, Climate			
Geogenic deposit	Mineralization and Status	-	Existing literature	G
Abandoned/Tailing deposit	Main Mineral, Quantity and Quality	-	Company documents	E, G
	Environmental Impacts and Reclamation	-	Valorization Efforts by the EDM company	E, G
	Tailing's Grade (WO_3%)	-	Different Websites	F, G
	Societal Impacts	-	Published literature and data collection	E, G
	Market demand	-	Analysis based on available information	E, G
Technology	Mining and Reprocessing Methods	-	Evaluation of Similar Successful Cases	F, G
	Recoverable Concentrate and Rate	-	Comparison, Identification, and Estimation	F, G
Infrastructure	Old and Existing Facilities	-	Collection of data	G
	Transportation Facilities	-	Analysis	G
Politics, Legislation, and Licensing	Political Interest and Framework	-	Literature, Articles, News	E, G
	Social License/Perception	-	Questionnaire, Survey & Data Analysis	E, G
Physio-Chemical	Harmfulness and Toxicity	-	Literature	E, G
Economic Conditions	Revenue, Capital and Operating Cost	-	Discounted Cash Flow (DCF) Method	E, G
	Net Present Value (NPV)			E, G

Furthermore, to evaluate the public perceptions of restarting activity in abandoned mines in Portugal, a survey link* with a questionnaire (17 questions) was generated in Portuguese and later shared to different social media (LinkedIn, Facebook, Website) to collect opinions. Linear, probit, and logit regression models were developed based on the various hypotheses to analyses the collected opinion data. Freely accessible RStudio software (2021.09.1, Build 372) was used for regression model development, and the findings provided input to the social parameter of the E-axis in the UNFC for each case.

3.2. Application of UNFC in Abandoned Mines and Tailings in Portugal

To implement all the parameters (Table 3) and determine the exact number of the three UNFC axes (based on Table 2), 40 abandoned Tungsten and Tin mines in Portugal were initially assessed. However, the data from six of the abandoned sites can be used to conclude (https://docs.google.com/forms/d/e/1FAIpQLSf3FhZ013d5FyTGA3BlYYg0KabgME31jFwGnOGT81f6TanruQ/viewform, accessed on 18 August 2022) the UNFC axis. The Panasqueira site is one of the six; however, it is left out of the study because it has already been analyzed in previous literature [15]. Five deposits are summarized in Table 4, based on the available data.

Table 4. Summary of classification of five Abandoned Mines using the definition of the UNFC axis.

Mine	Location	Years of Production	Ore Minerals	Elements	UNFC axis		
					E	F	G
Murçós	Terra de Cavaleiros	1948–1976	Scheelite, cassiterite	As, Mn, W	3	2	3
Vale das Gatas	Vila Real	1883–1986	Wolframite, cassiterite, scheelite	Pb, As, P, W, Zn	2	2	3
Regoufe	Arouca, Aveiro	1915–1944 1946–1970's	Wolframite, cassiterite	As, Pb, Zn, W	3	2	3
Borralha—heaps	Vila Real	1902–1986	Wolframite, scheelite, molybdenite	Cu, Fe, Mn, Sn, Ti, Zn, Zr	3	3	4
Borralha—sulfide deposit				Ba, Ni, Cu, Zn, Hg, As, Se, Pb, Mo, Sn	3	3	4
Covas	Vila Nova de Cerveira	1951–1960	Wolframite, scheelite, ferberite	W	3	3	4

4. Results of UNFC Classification

Five abandoned Tungsten and Tin mines—Murçós, Vale das Gatas, Regoufe, Borralha—heaps, Borralha—sulfide deposit, and Covas—are shown in Table 4 as classified findings. The UNFC defines Borralha and Covas as 334 (prospective projects) and Murçós and Regoufe as 323 (non-viable projects). Moreover, Vale das Gatas exhibits sufficient reasons to consider it as 223 (potentially viable project).

Covas from prospective projects, Murçós from non-viable projects and Vale das Gatas are described only in terms of characterization procedures according to the conditions of the UNFC axes. Additionally, 55 data on public opinion are collected and the conclusions from the evaluation are considered in the classification of each project's (E-axis).

Murçós has 50,000–100,000 m^3 of waste in volume, of which the obtainable metal is Tungsten (W) with an ore grade of 0.04% (W) and a 61–62% (W) recovery rate. The total estimated revenue might be summed up to 2.9–5.9 million USD or 9.81 USD/Metric-ton (Mt) (Tungsten price in May 2023—index box), but compared expenditures stand at 10.25 USD/Mt (Capital cost: 597,000 USD and Operating cost: 9.25 USD/Mt). Considering the higher expense than revenue per Mt and the heavy solid content in the dump, the project is not expected to become environmentally, socially or economically viable in the near future, representing the definition of E3 categories of the E-axis of UNFC. The flotation technique is considered for the project, but further data is required to develop the technical feasibility evaluation. The lack of data is subject to further evaluation and meets the definition of F2 categories of the F-axis of the UNFC. In decision-making, the obtained data and calculations are considered to have low confidence levels (G3).

Covas has sizable waste volumes (100,000 to 150,000 m^3) and ore grades (1.9% Tungsten). Still, due to the lack of recovery rate data, it is too early for the project to determine its environmental, socio-economic viability (E3) and technical feasibility (F3). Moreover, E3 and F3 are estimated primarily on indirect evidence (G4).

However, Vale das Gatas has a waste volume of 100,000 m^3 and a notable ore grade (0.68% Tungsten and 0.11% Tin). The extracted Tungsten and Tin might generate around 127 million USD in revenue (Tungsten price in April 2023) or 174 USD/Mt, much higher than the comparable average expenditure (10.25 USD/Mt). In addition, the high As, Pb, Cd, Zn and Cu content in the tailings needs careful environmental consideration because of the possibility of leaching into surrounding water streams. Although the project's development and operation are not yet established, there are reasonable chances for environmental-socio-economic viability based on realistic assumptions (E2). The reprocessing procedures of flotation, gravity separation, high-intensity magnetic separation, and chlorination separation are suitable, but more information is needed to improve the technical feasibility

evaluation (F2). The gathered data and calculations are regarded as having low confidence (G3) in E2 and F2's decisions.

Several scenarios have been examined to evaluate the social perception, where acceptance of secondary production from abandoned mines is considered the dependent variable. Age, gender, employment opportunities, company trust, government trust, and sustainable techniques are the independent variables. The regression model with an acceptable percentage of error shows that people's acceptance depends on employment opportunities and sustainable techniques that could alleviate environmental pollution.

5. Discussion

Due to its extensive activities and significant presence in developing nations, the mining industry has close links to the issues addressed in each of the 17 SDGs. [17]. In Portugal, abandoned mines pose radiological hazards to public health, being a source of acid mine drainage, arsenic, and toxic materials combined with soil and water [11,12]. The study shows in Table 1 that abandoned mines in Portugal violate KPIs-11 and 15, and at the same time, responsible secondary production can help achieve KPIs-7, 8, and 9. It is crucial to distinguish between the positive and negative consequences of mining to adjust the SDGs indicators to current sustainability performance metrics for the mining sector.

UNFC provides a clear definition of its categories but lacks guidelines for a systematic assessment of anthropogenic resources, notably specifying the methodology for assessing project-specific parameters, level of uncertainty, and minimum allocated categories [15]. Table 3 summarizes parameters, sub-parameters, and methods considered in the E, F and G axes of the UNFC during the classification of abandoned mines and tailings in the study. The approach might be regarded as a contribution to developing a complete framework for secondary resource characterizations.

Given the present reasoning of environmental conservation and economic expansion through the effective utilization of resources, piles and tailings containing abandoned mining sites in Portugal should be considered secondary sources of raw materials [10]. The study has applied the UNFC to five of the 40 abandoned Tin and Tungsten mines in Portugal to determine the responsible resourcing potential of the metals. Table 4 shows that the five sites can be categorized as prospective, non-viable and potentially viable projects. Nevertheless, data acquisition, gathering and implementation throughout the decision-making process are primarily based on indirect evidence or in low-level confidence, requiring further, more in-depth study of the classified findings.

6. Conclusions

The study has identified the KPIs of the SDGs that can be related to the secondary production from abandoned mines in Portugal and proposed and implemented the parameters and sub-parameters with relevant methodologies in classifying the abandoned mines using the definition of the UNFC axes. In addition, after evaluating social perception, it concludes the viability of the secondary production of Tin and Tungsten from five abandoned mines in Portugal using the UNFC framework. Secondary production from abandoned mines in Portugal may be a realistic alternative for the EU to meet the rising market demand for Tin and Tungsten while enhancing the security of the supply of such metals.

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