REPORT OF THE

LITHIUM WORK GROUP

Created by

Order No. 15040/2016 of the Secretary of State for Energy

Published in the D.R. 2nd series, of 13 December 2016

INTRODUCTORY NOTE

*This version of the Lithium Working Group **Report** incorporates the assessment arising from a public consultation of the document on 27 March 2017.*

*Bearing in mind the principles of transparency in the production of the work under review and according to the recommendation in this document, based on relevant stakeholders, such as the academia and the companies, the **public consultation** held in the period from 08 June 2017 to 08 July 2017 expanded the scope of participation, thus pursuing the objective of enriching the debate on this topic of evaluating the potential of the lithiniferous mineral resources of the country.*

Lisbon, 22 September 2017

EXECUTIVE SUMMARY

In response to the momentum generated in our country with exploration and exploitation for applications for lithium mineral deposits, leveraged by the global pursuit of this metal for its respective use in batteries for the automotive industry, the Lithium Working Group (WG) was created by Order No. 15040/2016 of the Secretary of State for Energy, published in the D.R., 2nd series, of 13 December 2016).

This Executive Summary condenses succinctly the results of the Working Group as a response to the mission defined above, with the following terms of reference:

- Identifying the occurrences of lithium mineral deposits and the economic activities of identification and utilisation associated with it.
- Establishing a hierarchy of priorities and trends for the industrial use of this resource, seeking to maximise the economic benefit;
- Defining a programme for the valuation of lithium mineral occurrences in Portugal, supported by the assessment of the "state of the art" of the existing knowledge in the country regarding the technical viability of processing and on the metallurgy aiming at the valuation of national ores with a view to the production of Li compounds;
- Proposing measures that serve as the basis for the creation of a processing unit and specific beneficiation of these minerals.

The **Lithium Market** and its compounds have direct application on a broad and diversified spectrum of industries, including ceramics and glass, industrial lubricants, medical applications, batteries, aluminium metalworking, among many others, contributing to the production of a broad range of tradable goods. The most common unit of measurement when referring to the lithium market is the Lithium Carbonate Equivalent ("LCE").

Lithium carbonate (Li_2CO_3) is the most common product in the market trading of this metal, having reached in 2015 around 90kt of LCE, which corresponds to approximately 50% of the volume of the overall market. The second most marketed lithium product is lithium hydroxide (LiOH), with a 20% share, followed by the concentrates of lithium minerals normally used in the ceramics and glass industry, with sales volumes of 14%. The remaining products represent more or less 13% of the market (Deutsche Bank, 2016).

A **Legal and Regulatory Framework** that is fair, transparent, clear and predictable is a determining factor for investment decisions and on the respective contribution to economic development, a situation with increased importance in the case of activities of revelation (Identification) and benefitiation of the geological resources.

In this context, Portugal is an example of stability in the legal framework of the mining industry. Indeed, the mining legislation of 1930 (Decree No. 18713, of 01-08-1930) remained in effect for 60 years, and then in 1990 (Decree-Law No. 90/90, of 16-03), which remained in effect 25 years until current Law No. 54/2015, of 22-6 (LBRG), which is in the stage of preparation of the law regulation Besides the fact that Portugal is a country with stable and long-lasting mineral legislation, there is also the constitutional (Art. 84 of the Constitution of the Portuguese Republic) and legal (Art. 5 of Law No. 54/2015, of 22-6) on the public ownership of the mineral deposits; thus, there is in our country a public interest underlying this integration of the mineral deposits in the public domain of the State.

In the context of the regulation being prepared it is expected that a sustainable exploration should be ensured of the geological, social, environmental and territorial resources, aware of the values of transparency and security in attracting investment of public interest in the geological resources integrated in the public domain of the State and the fact that they are scarce and cannot be replaced or relocated, encompassed in the **principle of coexistence** with other uses of the soil and in the **principle of parity** of the values of these natural resources with the environmental and territorial values.

In regards the **Geological Setting and Mining Potential**, the WG worked with a large databank of archived and published documentation related to the occurrences of lithium minerals.

Lithium is the lightest metallic element known and occurs in nature, as part of various mineral species, the most common being spodumene, lepidolite, petalite, amblygonite-montebrasite and triphylite-lithiophilite. These minerals are generally associated with pegmatite-aplite or hydrothermal ore deposit that are formed in the final stages of consolidation of granitic magmas.

Since the 1990s, institutions such as the National Geological Service, or those that included it, were giving increasing priority to activities of the mineral inventory and research and the technological characterisation of the occurrences of lithium minerals and, more intensively in the last 15 years, seeking to anticipate a better strategic use of these ore types:

- In a first phase, up to the year 2000 and taking advantage of the opportunity to disclose the results of internal prospecting and research projects in the regions of Guarda – Seixo Amarelo/Gonçalo and Barroso Alvão, an important compilation of this work was published in a special volume of the Publication *Estudos, Notas e Trabalhos*, an historical and traditional magazine of the Mining Geological Survey. Thus, these projects and the publication of the results achieved made an important contribution to the awareness of our territory and its lithiniferous mineral resources. During this period, although still dominated by the use of the lithium ores only for the internal ceramics market, the first steps were taken to show the importance of a technological stage to upgrade the lithium ores leading to the production of concentrates, as a national strategy to take full advantage of this important resource. At the time, this strategy was part of the so-called "technological paradigm"; as opposed to the "supply paradigm" which until then had guided the definition of the objectives for public projects, based on the asssumption that the primary resources should be explored, to take advantage of their added value to the fullest extent possible. Even for the ceramics industry, they claimed the importance of this technological step as a means to offer the market quartz-feldspar mixtures with a controlled level of lithium, to increase the melting power of those mixtures by reducing energy consumption in the baking process;

- Later, , in 2011 with the full recognition of the importance of lithium compounds in more advanced technologies, the LNEG, DGEG and ADI, in the context of the Ibero-American development programme CYTED (IBEROEKA), promoted an important meeting around the topic "Valuation of Lithiniferous Pegmatites", attended by all of the national research groups on lithium and was attended by foreign, Brazilian, Spanish and Argentine specialists;
- Both publications enhanced the evolution of the geological, mining and technological knowledge of the lithiniferous potential in Portugal, and certainly contributed unequivocally to the increase in investment in the prospecting and research of this resource, capturing international interest, as it is happening right now when this report is being presented to the public.

In metallogenetic terms, the North and Centre regions of Portugal are part of the tungsten- tin Province of the NW of the Iberian Peninsula, known worldwide, which is characterised by the occurrence of pegmatite-aplite and hydrothermal structures that appear locally enriched in minerals of those metals, as well as in lithium minerals. These occurrences are genetically associated with syn-tarditectonic granite intrusions related to the third phase of the Variscan Orogeny, dated from 320 to 290 million years ago.

Eight regions are described with occurrence of lithium mineralisations in Portugal. They occur from Caminha, in Alto Minho, to Idanha-a-Nova, in Beira Baixa and are presented in this geographic order in the report, and therefore not reflecting any hierarchy of importance among them.

- Serra de Arga
- Barroso – Alvão
- Seixoso – Vieiros
- Almendra – Barca de Alva
- Massueime
- Guarda (including Seixo Amarelo – Gonçalo, Gouveia, Sabugal, Bendada and Mangualde)
- Argemela
- Segura

The mineralised structures are hosted in granitic rocks, as is the case with the ore deposits in the Guarda region, or in metasediments from Neoproterozoic to Silurean ages for the remaining cases, although in some cases both situations were found (Serra de Arga, Argemela and Massueime). In general, they correspond to:

- tabular pegmatite-aplite structures, organised in a sub-horizontal (sills) or sub-vertical (dikes) ;
- In some specific situations, the mineralised structures correspond to hydrothermquartz veins, in the case of Argemela, or a transition between pegmatite and hydrothermal, in the case of Massueime;
- Thickness is quite variable, from a few centimetres to more than a dozen metres, but generally around 1 metre;
- The extension of the outcrop of these structures is also quite variable, from a few dozen metres to over 1 km;
- The orientation of these structures varies from region to region and even within the same ore deposit, where it is common to find a local distribution in vein swarms; the contact with the surrounding rock is generally sharp, with a small contact metasomatic selvage varying from a few centimetres to several decimetres.

In metallogenetic terms, the mineralised structures correspond mostly to pegmatites from the LCT family (Li, Cs, Ta), subtypes spodumene, petalite and lepidolite:

- The parageneses vary from region to region and even within each of the ore deposits considered:
- In a very generic terms, the main minerals correspond to quartz, orthoclase, albite, muscovite, biotite and lithium minerals (spodumene, petalite, amblygonite e lepidolite);
- Also, generically, accessory minerals include tourmaline, beryl, garnet, columbite-tantalite, cassiterite, among others, including lithium minerals when they do not belong to the main paragenesis;
- Often the pegmatite-aplites are zoned, and it is possible to distinguish bands in which the aplite or pegmatite facies are predominant and also zoning in the concentration of lithium minerals.

As to the known resources in the different ore deposits, the existing data is scarce:

- For the Barroso – Alvão region, 14 million tonnes of lithiniferous ore are reported, with an average grade of 1% Li_2O, corresponding to the sum of various pegmatite-aplite structures, that may be part of the category Inferred Mineral Resources;
- For the pegmatite-aplite ore deposit of Seixo Amarelo – Gonçalo, in the Guarda region, there is an estimated resource of 1.4 million tonnes with an average grade of 0.42% Li_2O, classified as Measured Mineral Resources.

- For the Argemela region, with an Inferred Mineral Resource (upper part of the ore deposit) of 20.1 million tonnes with 0.4% Li_2O, it is estimated however, the for all of the ore deposit a total of over 200 million tonnes of ore with an average grade of 0.4% Li_2O for which there is not yet complete data that would allow to be safely officially classified as a Mineral Resource;
- From the information provided by the DGEG based on the technical reports of five companies, with rights granted for exploration and exploitation, it is possible to estimate a mineral total lithium mineral resourcel of (million tonnes) 29.74 Mt@0.81% Li_2O, with 16.80 Mt@0.88% Li_2O, classified as inferred, 12.30 Mt@0.68% Li_2O as indicated and 0.64 Mt@1.50% Li_2O as measured.

It should be noted that the levels mentioned refer to various types of ores, and that the very specificities of each one condition the profitability of possibly using them in the production of lithium.

The **Economic Activities** developed in Portugal for research, exploration of granitic pegmatites had as their primary objective the production of quartz, feldspar and, in addition, lithium. The productions reported by the concessionaires of feldspars for lithium are relatively low and reflect only to the exploration carried out by five companies.

The lithium minerals occurring in Portugal, namely petalite, spodumene, lepidolite and lithium phosphates, have been used on ceramics materials, benefiting the industrial melting process, and added value for the production of ceramic pastes, since the melting point is lower in the presence of the lithium, thus allowing decreased energy consumption. The exploration and prospecting of pegmatitic resources in Portugal should also aim to make use of the metal contained therein, besides lithium, also tantalum, niobium and tin, from the perspective of making full use of those mineral deposits toward to the production of nearly zero waste.

Recently (2015-2016) a sharp increase has been observed on lithium prices in the international market, and it is predicted that there will be soon an exponential increase in electrical vehicles (EVs), resulting in a higher demand for lithium worldwide. Thus, it is expected that research and prospecting for this mineral resource, as well as its exploitation and beneficiation will deserve a substantial development, namely in countries with geologically recognised lithium mineral resources, as in the case of Portugal.

Confirming this expectation, there is a well-known growing interest by foreign companies in Portuguese lithium minerals. Just in 2016, the DGEG received 30 exploration applications, with lithium as the main mineral commodity, corresponding to a total proposed ivestment of around 3.8 million for a total area of 2,500 km^2 (including the overlapping of some poligons).

There are also other cases at the DGEG of other with lithium being an acessory commodity.

There are holders of mineral rights rights that are aware of the economic potential of the deposits evaluated and are expressing their interest in exploring lithium ores and proceeding with their beneficiation aiming at the production of concentrates, and thus will present to the DGEG the necessary request for concession.

The DGEG mapped the locations of the areas corresponding to the applications and the signed contracts (for prospecting, research and exploitation), using as a reference all the geological information provided in the different application and contracts signed for lithium, and it was possible to define 11 "ore districts", that outline zones of potential interest for the companies.

For each "district", the land use status has been listed which could potentially condition the start and/or ongoing exploration and research projects and/or future possible mining.

The “technological beneficiation paradigm” described above, is based on the assumption of the **Technical Viability of the Production of Mineral Concentrates** as a focal point of economic added value, a topic that deserved the attention of the WG to compile the experience gathered in Portugal on the processing technologies applicable to Portuguese lithium ores, which reached the following main conclusions:

- The Portuguese lithium ores are technologically recoverable, through the single or combined application of the separation processes of Dense Media, Optical Separation and Foam Flotation. There is experimental evidence on the application of these technologies to all types of national lithiniferous ores to produce concentrates designed for the following:
  - Lithium compounds industry, producing concentrates of high level lithium minerals;
  - Ceramics industry, ensuring level “constancy”;
- The beneficiation of mineralised structures that are not very thick depends on the technical viability of a pre-concentration operation with a rough gauge (10 mm) that allows the elimination of host barren rock in the early stages of the processing diagram;
- Experience has shown that, in certain cases, it was not possible to obtain fluctuation concentrates at a level as close to the stoichiometric value of the minerals as desired, because in some parageneses there are micrometric occlusions (in ranges < 10 μm) of other minerals, such as quartz and albite, inside the crystals of larger lithium minerals, which led to collecting in the concentrates particles not yet fully released;
- The effects of metasomatism on the surrounding rock generally lead to the dissemination of the lithium contacts of the mineralised structures. This situation should be safeguarded since it exaggerates the results of the chemical analyses and may lead to less encouraging lithium recovery values that, in this case, are not attributable to inefficiencies in technological processing.
- Finally, it should be noted that the delay verified in adopting processing technologies for the recovery of lithium ores, through the production of high level concentrates, is not due to any lack of knowledge regarding applicable technologies or any other less positive aspects of national

lithium ores, but rather to market conditioning factors that, until very recently, would have precluded the respective investments or made them less attractive.

The topic of **Metallurgy** deserved a special focus from the WG, given the importance of this phase of beneficiation of the mineral resource to produce the lithium compounds that reach the highest listings on the market, from mineral sources or from concentrates obtained from upgrading their mineral sources or from concentrates obtained from metallurgic upgrading.

The most common final metallurgical product is lithium carbonate, with lithium hydroxide as an alternative. Therefore, the production, costs and technical and economic ratios are often expressed by equivalent unit of lithium carbonate, as mentioned previously.

The two principal mineral sources of lithium are from the brines (essentially, salt lakes) and the minerals hosted in pegmatites, mainly silicates such as spodumene, lepidolite and petalite:

- For several decades, most lithium has been extracted from the brines, due to the lower operating costs compared with extracting from pegmatites;
- Although production costs vary according to the region, with levels and other productive factors, the following values may be indicated as typical production costs, to explain the metallurgical option of the last few years:
  - 2000 US$/t CLE for production from brine;
  - 5000 US$/t CLE for production from pegmatites;
- However, the growing demand for lithium in the market has allowed the launching of some mining projects from pegmatites and sedimentary deposits, seeking innovative solutions to reduce production costs.

By looking at the manufacturing processes corresponding to the two types of mineral sources, we can see that the cost differences result from the relative complexity of these processes: while lithium in the brines is already in a soluble form in water, requiring merely operations of concentration (evaporation, commonly using solar energy) and purification, in minerals from pegmatites a series of mining operations must be performed, such as physical concentration, thermal conversion and chemical reaction, until we obtain the lithium in a soluble form. Thus, there are, in this case, added costs in the consumptions of chemical reagents (commonly the most important cost) and of energy.

The classic methods for metallurgical processing, already tested in laboratories for some ores from Portuguese ore deposits, are:

- Calcination process followed by acid digestion;
- Process of roasting with lime;
- These processes are commonly fed by a concentrate with levels in the 4.5-6% Li_2O range;

- Thermal conversion is done at a high temperature (>900ºC). In recent developments, there has been an attempt to reduce the temperature of the conversion process as well as the consumptions of reagents, either by altering or improving the reactive processes, or by introducing unit operations aimed at more efficient management of the procedural flows;
- Projects referenced in the bibliography and publicised seek new processes for the metallurgical recovery of lithium from pegmatites, namely in Canada, Australia and Finland.

With the growing search for lithium, the recycling of end-of-life products, namely Li-Ion batteries, is essential in order to implement a circular economy system for this metal. With the development of the electric vehicle, this issue will become strategic. Most of the recycling processes for this type of battery, currently in use, are more focused on recovering other valuable metals present in the batteries (such as cobalt and nickel), but future processes will have to deal with the recovery of lithium as a priority objective.

"SWOT Analysis"

Based on the analysis of the most significant points of all the chapters included in the report, a **SWOT Analysis has been prepared**, in which the following points were highlighted:

I) **Strong Points**:

a) **Mineral potential**, with various and extensive pegmatite-aplite fields bearing the different lithium minerals.

b) **High attractiveness** for investments in the mining sector, due to the legal framework, institutional support and excellent infrastructure, embodied in several dozen exploration and mining applications for lithiniferous mineral resources.

c) **High know-how** in research, exploration and processing lithiniferous mineral resources in research institutions, universities and in private companies.

II) **Weak Points**:

a) Inequality in the degree of existing knowledge regarding the various deposits, supported namely by robust data, especially in-depth, that is reflected in a **severe weakness in estimating resources/reserves** on a national scale and that arise from a reduction of public investment and the almost total negletibility of the drilling costs in the budgets of national and European I&D programs.

b) **Increasing weaknesses in human and financial resources** of the governmental institutions related to the mining sector and slowness in granting **research and exploration rights**, especially when there are overlapping requests, thus loosing investment opportunities.

c) **Lack of incentives to companies in the sector**, without any benefit in taxes and/or related to reducing energy costs, in an activity that requires substantial investments, but generates employment and wealth.

As well as the following opportunities/threats:

III) **Opportunities**:

a) Development of a programme of "mining promotion", designed to **evaluate** the lithiniferous mineral **resources** in Portugal, from the standpoint of total valuation of the pegmatite-aplite resource, with zero waste production and that allows it to be inventoried and characterised, bearing in mind the respective use as raw material, metal, or on the ceramics industry.

b) Implementation of an **Experimental Mining-Metalurgic Unit** for f developing a knowledge basis and testing technologies for the entire value creation chain of the lithiniferous mineral resources.

c) Setting up a **Demonstration Pilot Unit** of a decidedly industrial nature, the primordial objective of which will be to demonstrate the economic viability of the value chain. If the economic results appear promising, this Demonstration Unit will evolve into an industrial investment phase.

IV) **Threats**:

a) **Lack of specific financial programmes** which hinders the development of these "Opportunities".

b) **Sterilisation of important lithiniferous mineral resources**, due to wrong decisions in policies and plans for **territorial planning**. To avoid this potential sterilisation, it is essential to prepare a **sectorial programme** for the mineral resources, including them in the territorial management instruments**, as provided in Article 40 of Law No. 54/2015, of 22 June, so that the regulation of this basic law shall ensure their safeguarding and parity with other** natural resources.

c) **sectorial programme** for the mineral resources included in the territorial management instruments and that will serve as the basis for the legislation that will allow it be safeguarded, in parity with other natural resources.

d) The enthusiasm and experience of inter-company cooperation, if not strongly encouraged, could **compromise the viability of a project of producing carbonate and/or lithium hydroxide on a country-wide scale**, potentially leading to the production of non-economic projects.

Recommendations and **Proposals**

Based on the extensive gathering and compilation of data and the conjectures elaborated on them that are described in the respective chapters of the WG report, with the development considered suitable to be useful to the economic promoters that are interested in the potential of the lithium ores in Portugal, the WG put together the **Recommendations** and **Proposals** explained below.

I) **Recommendation** to develop a programme of "mining promotion", to **evaluate** the **lithiniferous mineral resources** of Portugal, from the standpoint of the total valuation of the pegmatite-aplite resource, with zero waste production and that allows it to be inventoried and characterised, bearing in mind the respective use as a metallic raw material for the ceramics industry.

II) **Recommendation** to set up two Technological Units with different goals:

1. **Experimental Mining-Metallurgic Unit** for the purpose of developing a knowledge basis and testing technologies for the entire value creation chain of the resources:

    a) Geology and mineralogy of the ores

    b) Mining planning, including selectivity of the mining

    c) Processing ores to obtain concentrates of lithium minerals

    d) Metallurgical processes to obtain lithium compounds

    Using the brand and structure of Cluster Portugal Mineral Resources, recently recognised by the government and loans available to strengthen the existing means and competences at the LNEG and the Universities, a Partnership shall be set up, physically distributed in various locations, that will also have occasional participation from operating companies. The objective would be to hold study "campaigns" of samples from different ore deposits.

2. **Pilot Demonstration Unit** of a decidedly industrial nature, which will have as primary objective of to demonstrate the economic viability of the value chain. If the economic results appear promising, this Demonstration Unit will evolve into an industrial investment phase.

    This Pilot Unit would receive ores or concentrates to be treated as a function of the market demand and evaluate the respective production costs, applying and developing the processes that were studied in the Experimental Unit and, cumulatively, developing the qualification of specialised human resources.

    This Pilot Unit would necessarily be the target of a Consortium among companies wishing to value its ores up to the metallurgical phase, meaning that an individual company would not have sufficient production alone to support its own metallurgy (a situation that is indeed quite common). It would also include governmental and academic institutions that can significantly support its work, namely in the application of the concept of **cluster** and **circular economy**, that includes the entire value-added chain of the primary resource and recycling, also keeping in mind the possibility of introducing secondary resources in to the processes.

Proposal to welcome applications for the creation of both the Experimental and Pilot/Demonstration Units at available co-financings – COMPETE (or other in the context of Portugal 2020) or, for example, the recent INTERFACE and/or Collaborative Laboratories programmes that favour the formation of "clubs" of producers or suppliers – in the following possible frameworks:

- The development of a "mining promotion" programme, with the goal to **evaluate** the lithiniferous mineral **resources** of the country, would be set up through a consortium of the Cluster Portugal Mineral Resources, among companies, universities and governmental institutions;
- The **Experimental Mining-Metallurgic Unit** would be supported by a "knowledge-based society" – LNEG and Universities, with the companies being the "interested parties", taking advantage of the Cluster Portugal Mineral Resources (its "brand" and structure), recently recognised by the government.
- The **Pilot Demonstration Unit** would clearly be a "producers' club, predominately business in nature, seeking to extend as far as possible the value chain of the extraction activity of the lithium ores.

With regards to the opportunity to launch a technological course for lithium, the Working Group recommends that continuation is given to the definition of the models of **Industrial Development**, focused on consolidating the various economic parameters and, consequently, creating quantitative scenarios that allow an estimate of the economic viability of extending the technological process to longer value chains.

The Working Group also recommends that this Report be disclosed first-hand, even before it is made public, by the group of national entities that make up the "interested parties", namely, the university groups that have most dedicated themselves to scientific and technological works and companies that are already directly linked to the valuation of the lithium ores in Portugal, for the purpose of receiving a first indication on the impact of the document and, perhaps, providing an opportunity for possible significant contributions.

Lisbon, 27 March 2017

Working Group