1. Publishable summary – First Period

www.labmet.ntua.gr/ENEXAL

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1.1 Introduction

The primary aluminium production industry is the world's larger industrial consumer of energy and is ranked among the most CO_2 intensive industries. It also generates enormous quantities of wastes that further decrease the exergy efficiency of its production process. However, this industry is one of the most vital sectors from an economic and a social point of view, not only for EU but also for the entire world. In order to remain viable and competitive, primary aluminium industry has to operate in a smarter way, be more energy efficient and meet the environmental requirements of our times. This can be achieved only through radical new technologies and novel business strategies, which will enable the industry to maintain its competitiveness and fasten its viability in the world's markets, and explore new business opportunities.

1.2 Project objectives

The main goal of the EU funded ENEXAL project is to provide primary aluminium industry with "green" innovative technological and economical solutions, focusing on the

(i) significant improvement of energy and exergy efficiencies of the production process

(ii) substantial reduction of GHG emissions

(iii) ***complete elimination of its solid wastes*****.**

In order to achieve these goals, the ENEXAL project will demonstrate three novel technologies for the improvement of the primary aluminium production industry, which in sort are:

1. **The high temperature carbothermic reduction of alumina in an electric arc furnace (EAF),** which can achieve up to **10% energy savings a**nd up to **65% reduction in GHG emissions** compared to Best Available Techniques currently used in industry.
2. **The moderate temperature carbothermic reduction of alumina in a novel solar furnace** which can achieve up to **68% energy savings** and up to **65% reduction in GHG emissions** compared to Best Available Techniques currently used in industry.
3. T**he red mud treatment in an innovative EAF**, which will allow the **total conversion of the red mud waste** of the Bayer Process into valuable products, thereby increasing

by **10 percentage points the exergy efficiency** of the Bayer Process and **eradicating its substantial environmental footprint** (today approximately 2 kg of red mud are produced for every kg of primary aluminium).

All technologies, after laboratory scale optimizations, will be demonstrated in pilot scale and their products will be evaluated by appropriate industrial end-users.

Technologies (I) and (III) represent technological solutions that relay on mature manufacturing technologies (e.g. EAF) and can be utilized directly in industrial production. Therefore both will be demonstrated under actual industrial conditions in the facilities of Aluminium of Greece (ALSA), which is the sole primary aluminium industrial partner involved in the ENEXAL project. ALSA will construct an industrial pilot plant, equipped with a 1 MVA-EAF (batch capacity 3,500 kg), that will be used in both technology demonstrations. Each technology will be demonstrated in continuous operation over a 12 month period.

Technology (II) represents a 'future' technology utilizing concentrated solar radiation in an innovative solar furnace. As this kind of technology is still far from industrial applicability and its operation requires extensive optic facilities (a heliostat field and a solar tower), its demonstration will take place at the Weizmann Institute in Israel (WIS), which already posses unique optic facilities. The pilot testing of this technology will be conducted in smaller scale, batch experiments.

Following the demonstration and evaluation of these technologies a site optimization study will lead to the formation of **a new primary aluminium production schema**, integrating these novel technologies in current industrial practice and achieving **further reduction of energy and CO_2 emissions**, while **improving the energy and exergy efficiency of the whole process**.

In the end, it is expected that the novel technologies demonstrated in the ENEXAL project, will play a key-role i*n the* ***sustainability, competitiveness*** *and* ***viability*** *of primary aluminium production industry, so as to render it* ***a leader industry for energy-efficient technologies and products*** *in Europe and worldwide*.

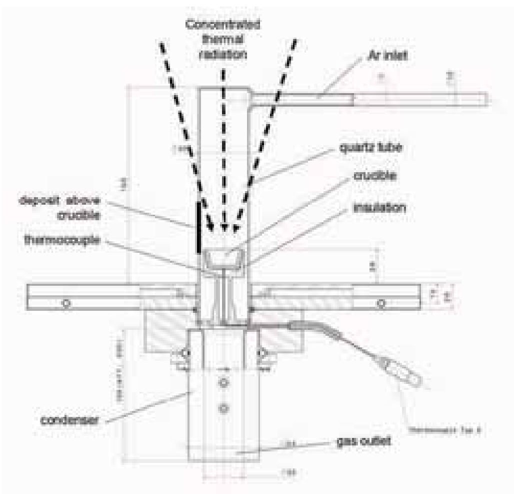
1.3 Work performed and main results achieved so far

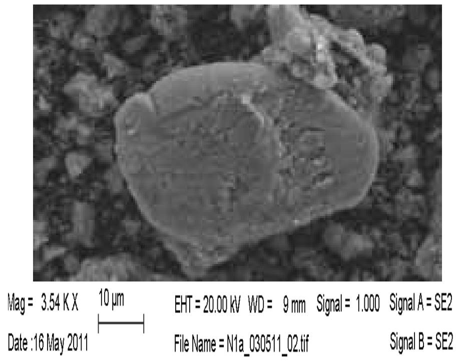
Since the beginning of the ENEXAL project, on June 1st 2010, the multimember ENEXAL Consortium has launched several research, demonstration and dissemination activities in parallel. Until the 31st of May 2011 the following results had been achieved:

(a) Detailed Analysis of current industrial practice (WP1): Prior to the demonstration and evaluation of any novel technology a detailed analysis of the current industrial practice was needed. To this end, utilizing the plant of ALUMINIUM S.A. as a case study, a detailed description of all production stages in the primary aluminium industrial plant with complete *identification of energy usage, exergy usage, GHG emissions and wastes generation* was performed by ALSA, NTUA, and DAPP. Additionally the impacts of this industrial practice was further evaluated through *a life cycle impact analysis* to asses potential impacts in the environment and the society. This study was concluded in November of 2010 and a relevant report has been sent to EC.

(b) Optimization of the high temperature carbothermic reduction of alumina (WP2): Prior to the industrial demonstration of this novel technology its laboratory scale development and optimization is required. To this end a detailed thermodynamic study was performed by NTUA which provided *a novel insight into the mechanisms responsible for aluminium* *volatilization and incomplete reduction at high temperatures*. These results, which are currently under publication in international referee journal, were verified in the first lab scale experiments performed by RWTH-Aachen. This first experimental campaign was conducted in the first semester of 2011 and has resulted in *a first proof of concept*. It is expected that in the following period of the ENEXAL project, utilizing the conclusions of the thermodynamic study the process will be further modified and optimized in order to achieve the goal of producing a viable industrial process.

Figure 1: EAF experiments for the carbothermic reduction of alumina and produced aluminium-carbon alloy (RWTH-Aachen).





Element	Weight%	Atomic%
O K	14.91	22.93
Al K	82.95	75.67
S K	0.53	0.41
Ca K	1.61	0.99

Figure 2: Scheme of the vacuum solar reactor by ETHZ and SEM –EDS analysis of deposited aluminium droplet by WIS.

(c) Optimization of the moderate temperature carbothermic reduction of alumina (WP3): Prior to the demonstration of this novel technology utilizing concentrated solar radiation its laboratory scale development and optimization is required. To this end WIS has developed a detailed thermodynamic model of the process which establishes the optimum conditions (temperature and pressure) for the conduction of the process in a solar furnace. ETHZ has conducted to set of experimental campaigns utilizing a high solar flux simulator, providing both a proof of concept as well as insight in the process kinetics mechanisms. Finally WIS has conducted experiments in a small scale in order to study the optimum aluminium condensation methods in relation not only to conditions but also to reactor design. In the next period of ENEXAL it is expected that the mechanisms of the process will be further investigated utilizing a novel "solar-driven" thermogravimeter reactor build in ETHZ while further advancements in the design of the prototype solar furnace by WIS will be made.

(d) Optimization of the red mud treatment (WP4): Prior to the industrial demonstration of this novel technology its laboratory scale optimization is required. To this end NTUA has developed a *detailed thermodynamic model of the reductive smelting process, through which the optimum conditions and material feed (carbon and fluxes) for the process were determined,* in order to achieve maximum iron recovery and a slag suitable for fiber production. Standards and specifications provided by TMF-Serbia and SIRMIUM for pig-iron production and by PEGASO for mineral wool production, helped in achieving this objective. *Experiments in laboratory inductive and resistance heating furnaces* where conducted in the first semester of 2011, *fully verifying the model predictions*. Additionally NTUA has launched a CFD modelling campaign in order to model with detail the novel slag fiberization process which will be used in the technology demonstration. It is expected that in the next ENEXAL period further experiments for the optimization of the process in Electric Arc Furnace will be conducted and the slag fiberization modelling will be concluded.

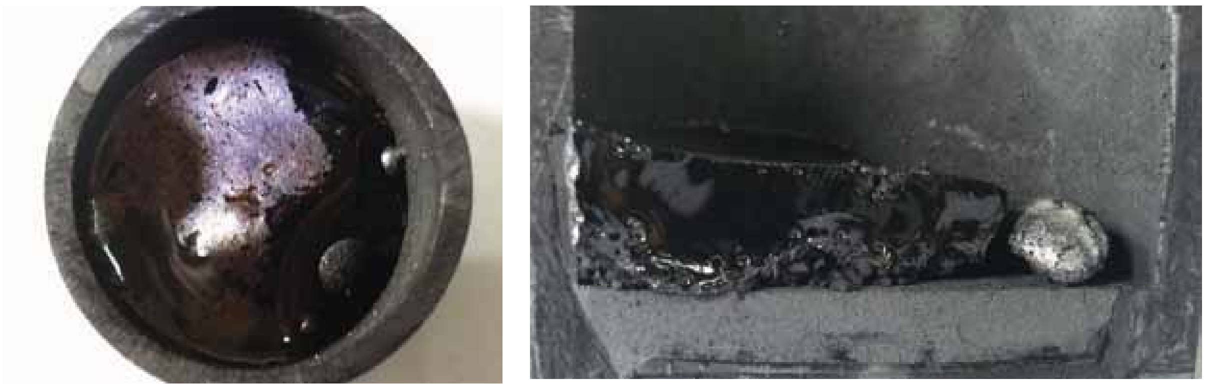


Figure 3: Top and section view of graphite crucible with glassy slag and pig iron produced from red mud reductive smelting (NTUA)

(e) Erection of the red mud treatment pilot plant (WP5-Task 5.1): To perform the industrial demonstrations of the red mud treatment and the high temperature carbothermic reduction of alumina, a pilot plant will be constructed in the industrial plant of ALSA. The heart of this plant will be a 1MVA AMRT-EAF, along with the necessary auxiliary systems and fiberization equipment. During the first year of the project ALSA in cooperation with LINDBERGH, PEGASO and SIRMIUM has designed this plant and ALSA has accordingly configured the industrial building which will house it. The EAF and all other equipment have been commissioned to appropriate technology providers and are currently in the final stages of manufacturing. It is expected that the pilot plant will be operational by November of 2011 as foreseen in the ENEXAL Description of Work document.

(f) Assembly of the prototype solar furnace (WP7-Task 7.1): The demonstration of the moderate temperature carbothermic reduction of alumina will take place in prototype solar furnace designed and assembled for this purpose in the facilities of WIS. Even though the design of this furnace is still in the research phase (paragraph c), some parts of the furnace associated mainly with vacuum creation as well as in line gas chemical analysis have already been assembled in WIS. It is expected that final prototype furnace will be created over the next ENEXAL periods through gradual upgrades and unit additions, in parallel with technology optimization efforts.

(g) Dissemination of project results (WP10-Task 10.1): Essential to the ENEXAL project objectives is also the dissemination of the project intentions, efforts and results in order to introduce the novel ENEXLA technologies and the overall proposed future view of the primary aluminium industry to the world. To this end project partners and especially the technology developers are committed in participating in targeted thematic European and International Conferences, thematic Industrial Workshops and Forums, as well as in publishing results in scientific European and International journals. During the first period of the ENEXAL project, a *dedicated web site has been launched* promoting the activities of the project and providing access to its results (Deliverable D10.1) Furthermore, scientific results from the first period of ENEXAL project are scheduled to be presented in *5 different international conferences* (from June 2011 to December 2011) while *3 paper publications* in international peer reviewed journals are currently in press.

1.4 Expected final results and potential impact

The ENEXAL project refers to the primary alumina/aluminium production industry which is currently responsible for more than 2.5% of the total anthropogenic GHG emissions, 7% of the total industrial energy consumption, and has a strong presence within EU member states, amounting to approximately 10% of global aluminium production. *The new technologies, which will be demonstrated in this project, are expected to reduce the total GHG emissions of this industry by a factor of 31% to 63%, reduce its total energy consumption by a factor of 17% to 55%, increase its total exergy efficiency by 3% to 33% and will include a prototype technology demonstration for the direct use of renewable energy sources in its production process.* Thus the new primary alumina/aluminium production schema that will be demonstrated and validated in pilot scale in the frame of this project, is well within the goals of EU's "20-20-20" policy and has a high potential for creating a sustainable primary alumina/aluminium industry.

The current practice of the electrolytic reduction of alumina to aluminium is one of the most energy intensive industrial processes globally. Large amounts of electricity usually produced from fossil fuel burning, are lost in electrolytic cells' overpotentials, while significant amounts of GHG are released both directly and indirectly from electricity production, by this process. To remedy this situation, this project will demonstrate two alternative technologies to reduce alumina using carbothermic reduction. By utilizing carbon to directly reduce alumina, significant amounts of energy are saved as the overpotentials of the Hall-Héroult process are eliminated, while electrical energy is needed solely to provide process heat. *When the carbothermic reduction is conducted at high temperatures using an electric arc furnace (EAF) energy savings from to 10% to 16% can be achieved, GHG emissions can be reduced from 35% to 65% while the exergy efficiency of the process, which in this case signifies the thermodynamic efficiency of energy utilization, can increase up to 3% or 5%*. This novel process utilizes a technological mature industrial furnace (EAF) and hence has the potential to be immediately applied in industrial practice with low technological risk.

An alternative carbothermic reduction process at moderate temperatures will achieve even greater energy savings (up to 68%) and similar GHG emission reductions (up to 65%), while it will offer the capability of utilising concentrated solar radiation for the production of the process heat needed. *The exergy efficiency increase when using such solar technology can be as high as 82%***,** as the sun will offer “free” and inexhaustible energy for the process heat. The demonstration and validation of this breakthrough technology is a major milestone in creating a truly sustainable industrial production. Further research into the development of a hybrid solar-electric furnace for continuous aluminium production will be necessary before industrial implementation of the technology is possible, but this is expected to be achieved within the next decade. This novel solar technology for aluminium production can be implemented in Southern European countries, like Greece, Italy, France and Spain, and will have an important impact on the solar industry in Europe. This technology could be also exported to other sites like in Africa, US and Australia where both Bauxite and solar energy are also readily available.

The substitution of the Hall-Héroult process with either technology for the carbothermic reduction of alumina ***will result in reducing energy consumption, reducing direct and indirect GHG emissions and increasing the efficiency of energy utilization***, ***as both technologies lead to lower carbon manufacturing processes***. The direct use of carbon as a reducing agent in the reduction of alumina proves to be more energy and exergy efficient than the electrolytic reduction of alumina. It should also be noted that carbon is the only reducing agent that can be used in industrial production as CO, CH_4, H_2 or Si thermodynamically cannot reduce the aluminium oxide. Therefore *a lower carbon manufacturing process in the primary production of aluminium can only be achieved by the direct use of carbon as a reducing agent.*

The exergy efficiency of a process is a direct measure for the sustainability of this process. The Bayer process, which is used to produce alumina from bauxite ores, has an exergy efficiency of 2.75% as it spends significant energy solely for process heat generation, in order to separate the bauxite ore into approximately equal amounts of alumina and red mud. The total of 35 million tonnes of red mud waste produced annually embodies significant chemical exergy and its disposal creates substantial economic and environmental problems. The red mud treatment technology that will be demonstrated in this project solves these problems and increases the exergy efficiency of the Bayer process by completely transforming this waste into valuable products. *In the new primary aluminium production industry proposed, pig iron and mineral wool will be co-produced in a solid-wastes free process, the exergy efficiency of which will be between 12% and 23% depending of the energy source used.*

The Bayer process coupled with the red mud treatment along with the carbothermic reduction of alumina will compose a new primary alumina/aluminium industry, which after a detailed site optimization to effectively recycle waste heat between this new processes, is expected to have *a total exergy efficiency between 16% and 59%, depending on the energy sources used.* ***Thus, this new production schema utilizes energy more efficiently both through novel production process like the carbothermic reduction of alumina and through waste utilization, like the red mud treatment for the production of pig iron and mineral wool***.

The integration of three production processes (aluminium, pig-iron, mineral wool) into one industry, offers a cross-sectoral efficiency in energy and resources utilization. Energy for producing all three products will be spent more concentrated thus producing in total, less entropy and less waste heat. Resources utilization will be substantially improved, as 100% of the bauxite ore will be utilized, while the massive production of glassy fibres will reduce if not eliminate basaltic ore mining for mineral wool production and pig iron production will reduce iron ore mining as well. Finally significant environmental protection will be achieved with the elimination of the red mud and all other solid wastes of the primary alumina/aluminum industry. This will end red mud landfill disposals, thus alleviating brownfield generation near alumina producing plants and reducing air, ground and underground pollution in the nearby regions (which are usually inhabited).

Additionally the new added-value products (pig iron and mineral wool) will give to the new alumina/aluminium industry an economic diversity and flexibility, necessary in the modern fast-changing global economy. The new primary alumina/aluminium industry will have a significant industrial advantage as it will have lower operating cost due to energy savings and therefore a lower aluminium production cost, while it will also be active in different markets, due to the production of new products. ***The combination of a sustainable use of resources and new market penetration will establish the new European primary alumina/aluminium industry as a world leader in this sector.***

EU in general has significant financial and social interests in promoting such changes, as although it possesses a large primary aluminium industry extending in 10 member states and 6 associate states, its production still does not cover the European aluminium demand. Therefore to secure aluminium supply, the European primary aluminium production must increase and this can only happen by creating new more profitable and sustainable production processes that will attract new investments in this field. Furthermore it should also be noted that only two member states (Greece and Hungary) are currently producing primary alumina, as exploitable bauxite ores exist only in the general south east region of Europe (and mainly in the Balkans). The red mud treatment technology can help increase this primary alumina production by providing additional market penetration, which in a growing EU economy translates into new business opportunities and new jobs creation. In both cases, ***it is clear that by supporting the new sustainable primary alumina/aluminium production industry, EU stands to gain significant benefits in terms of financial growth and unemployment decrease.***

In conclusion, the development of the new sustainable alumina/aluminium industry will open possibilities for further research and work as a case study example for the future direction of all European industrial activity. By adapting novel technologies which are designed to maximize energy efficiency and can utilize renewable energy sources and by creating new processes for in-situ recycling of waste material and waste heat into valuable products, a *new model of sustainable poly-producing industry can be created.* European Union has both the scientific and research capabilities and the social and political resolve needed, to realize such changes and proceed *into the era of a "green industrial revolution"*. This revolution seems to be the only answer to the main challenge of the 21st century: *economic development and environmental protection in a world with continuously growing population*. A waste free, low carbon, sustainable aluminium industry, developed within the European scientific community and operating within the European borders, will be a small step in this direction and serve as a testament to the benefits, the capacities and the potential of the European Union.