

1. Publishable summary – Second 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 CO₂ 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 and 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. **The 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 rely 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 1,500 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 possesses 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 CO₂ 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 in *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

In the third period of the ENEXAL project, from June 1st 2012, the multimember ENEXAL Consortium has continued several research, demonstration and dissemination activities in parallel. Until the 31st of May 2013 the following results had been achieved:

(a) Optimization of the high temperature carbothermic reduction of alumina (WP2): In the third period of ENEXAL the feasibility of Al-Si master alloy production through carbothermic co-reduction of alumina and silica in a 25 kW EAF was established. In parallel the concept of producing pure aluminium in a carbothermic reduction of alumina process which avoids liquid phase formation was proven, through experiments in specially modified hollow electrode EAF with a customized water-cooled copper condenser.

(b) Optimization of the moderate temperature carbothermic reduction of alumina (WP3): The carbothermic reduction of alumina under vacuum and moderate temperature has been

proven already from the previous ENEXAL period and it was fully optimized and verified both through CFD modelling and experiments. Detailed designs for the optimal solar reactor furnace to be used in the technology demonstration activities were delivered during this period.

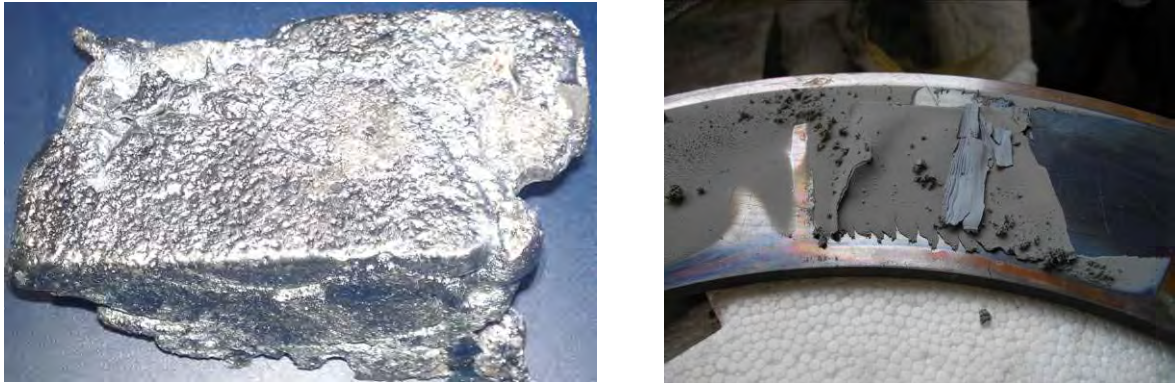


Figure 1 Left: Al-Si alloy phase produced. **Right:** Al deposits in the copper condenser (RWTH-Aachen).

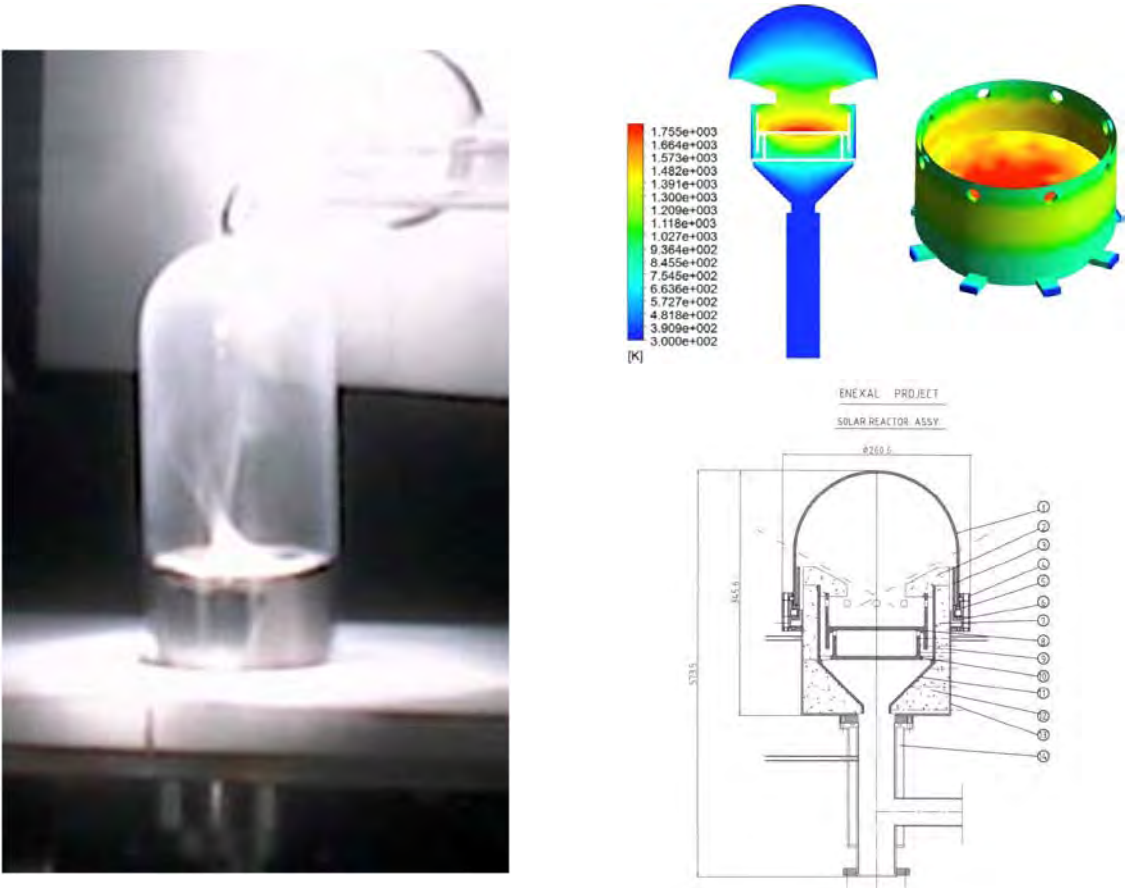


Figure 2: Solar simulation experiments (ETHZ) and solar reactor modeling and designs (ETHZ-WIS).



Figure 3 - Above: Red mud treatment process pilot plant in operation (ALSA); **Below Right:** produced pig-iron ingots; **Below Left:** End product, white cast iron balls 70mm, produced using pig-iron from the ALSA plant as scrap substitute.



End-User



(e) Demonstration of the red mud treatment (WP5): The industrial demonstrations of the red mud treatment began in the third period of ENEXAL. In the course of the period close to 25 tons of red mud have been processed producing 5 tons of pig iron and 16 tons of slag. This operation has resulted to the significant optimization of the process in order to achieve both good quality pig iron and the proper slag composition for producing mineral wool fibers. Two tons of the produced pig iron have been sent to the Serbian end-user and were used as substitute raw material for white cast iron production.

(f) Demonstration of the moderate temperature carbothermic reduction of alumina (WP7): The demonstration of the moderate temperature carbothermic reduction of alumina began in the prototype solar furnace designed and assembled for this purpose in the facilities of WIS. In the third period of ENEXAL six solar tests were performed at different process conditions leading to productions of metallic aluminium with up to 90% yield .

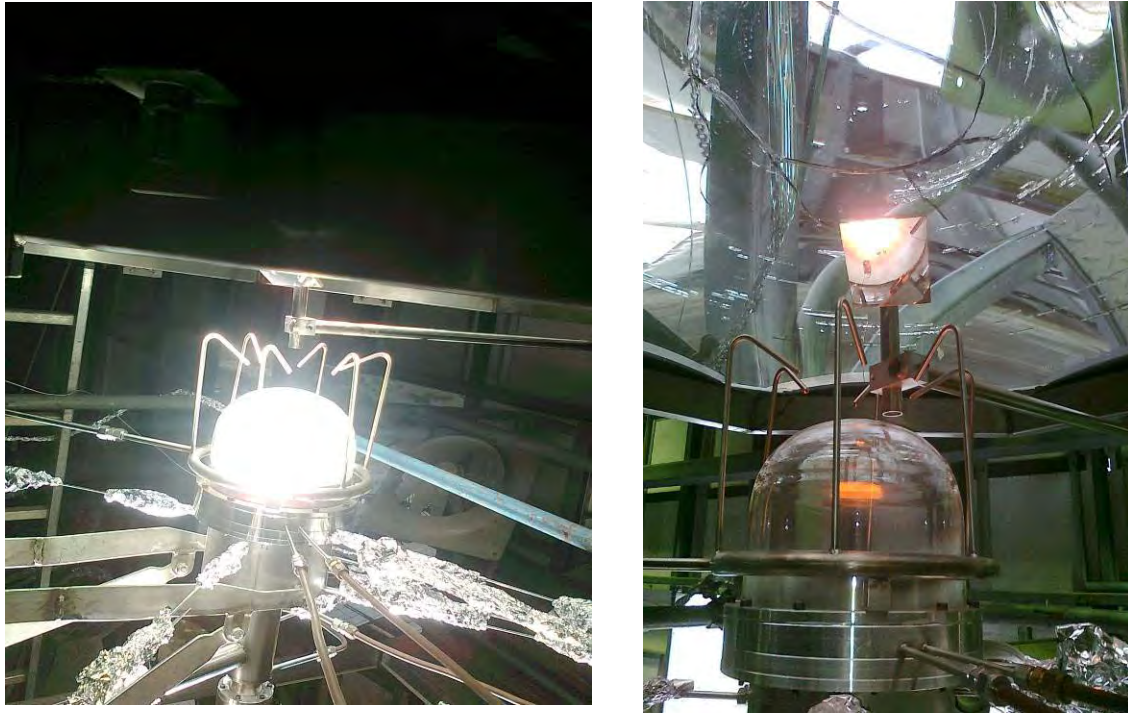


Figure 4: The Solar Furnace in WIS; **Left:** in operation; **Right:** just after end of operation

(g) Dissemination of project results (WP10): Essential to the ENEXAL project objectives is also the dissemination of the project intentions, efforts and results in order to introduce the novel ENEXAL 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. Up until the end of the third period of the ENEXAL project, 23 scientific papers in journals and conference proceedings have been published by members of the ENEXAL consortium, while the ENEXAL project was also featured in the “International Innovation Journal” (pp123-125, December 2013). The results of the project are featured in the ENEXAL project web site: www.labmet.ntua.gr/ENEXAL.

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 co-reduce alumina and silica, 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. The final product of such a process is not pure aluminium but rather aluminium-silicon master alloy, an alloy used in all casting applications which amount to approximately 30% of all aluminium demand. Compared to the conventional aluminium production technology, *this carbothermic co-reduction in an electric arc furnace (EAF) can achieve energy savings from 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 of pure alumina at moderate temperatures and under vacuum 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, CH₄, H₂ 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 120 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.