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# Redesign of secondary magnesium metallurgy in the complex Mg Serbien

The application of environmental thinking and the wider issue of sustainability into the business and management have unfolded over many years. The relationship between business and sustainability has become one of the central debates for the long-term future. Having in mind accelerating global development and associated increasing resource use, as well as environmental impacts, it seems increasingly apparent that business as usual is not an option for a sustainable future [1,2].

## 1 Introduction

In modern times the EU industry largely depends on the availability of critical raw materials, which significantly affects its growth, development and competitiveness. Particularly great importance it has in the implementation of an adequate, sustainable approach to the use of critical raw materials [2]. There is no primary production of magnesium in the EU, which is totally dependent on import of semi-processed materials: import of magnesium and magnesium alloys for die-casting represent respectively 63kt and 48kt in Mg content and according to the latest data of critical raw materials, magnesium is among the twenty the most critical elements [3].

Magnesium metal is of great strategic importance and its application is numerous and different in electronics, metallurgy, aerospace and automotive industries as well as in the production of nuclear energy. The use of magnesium increases in the car industry where requirements for efficient, recycling and sustainable technologies grow constantly [3]. As a structural material, magnesium is used as an integral element of alloys with other metals, which makes the basic area of its application. The modern techniques of magnesium alloys are applied primarily due to their low density, chemical resistance and good mechanical properties at the same time [4,5].

In order to use magnesium in auto industry instead of other light metal, this element has to be available, especially in the EU. All this is also supported by increasingly stringent regulations regarding environmental pollution and greenhouse gas emissions. Another indication why in the EU is no magnesium production are very poor recommendations in the BAT/BREF standards for its production. So it is necessary to make a sustainable model of production in accordance with ecological, technological and economic aspects.

The aim of this paper is to find a sustainable business model for the production of magnesium from economic, environmental, technological and supply viewpoint trought redesign of secondary magnesium metallurgy in the complex Mg Serbien.

## 2 Materials and methods

The main objectives of redesign of secondary magnesium metallurgy in the complex Mg Serbien is to expand its product range, improve quality and implement economically and environmentally sustainable production with the optimum use of existing financial and human resources. The methodology is based on the application of criteria for evaluation of investment decisions that do not only use the accounting methods of assessing the financial benefits of capital expenditure but also the method based on cash flows, or the issuance and receipt of cash.

Estimates are primarily based on static and dynamic indicators for which the most important are: the rate of return, net present value and payback period of funds.

For the reduction of future income and expenses, and net proceeds to the present value - base year of economic life of the project is used as a discount rate. The unified methodological approach UNIDO and the World Bank is used.

The basic products of the planned production program (with the planned quantity per year in t):

- Raw dolomite – 180.000 t,
- The calcined dolomite – 20.000 t,
- Magnesite – 30.000 t,
- Primary magnesium – 4.500 t,
- Mg alloy – 11670 t,
- Mg-Al granules – 1500 t.

Intermediate products from the process of production of calcined dolomite (quantity per year in t):

- Dolomite dust (fraction 0 - 5 mm) – 870 t,
- Dolomite grit (fractions 5 - 10 mm) – 2025 t,
- Dust of calcined dolomite – 1145 t.

Intermediate products from the process of production of primary Mg (quantity per year in t):

- Dolomite (fraction 0 - 5 mm) – 1020 t,
- Dolomite grit (fractions 5 - 10 mm) – 2386 t,
- Dust of calcined dolomite – 1357 t,

- The solid residue from the process reduction – 39830 t.

Intermediate products from the production process of Mg alloy from primary magnesium (quantity per year in t):

- Dolomite dust (fraction 0 - 5 mm) – 2460 t,
- Dolomite grit (fractions 5 - 10 mm) – 5751 t,
- Dust of calcined – 3272 t,
- The solid residue from the process – 93244 t.

The calculation of the cost of raw materials, energy and fluid production of primary magnesium is done for primary Mg and Mg alloy. For other products (raw dolomite, the calcined dolomite, magnesite Mg-Al granules) costs are set by market prices. It has been found that the project will need 120 employees, and average earnings are calculated according to the data of average earnings in the Republic of Serbia.

It is planned that the investment period lasts 3 years. From the fourth year it is planned to used full capacity and beginning of project exploitation. Economic life of the project is estimated at 20 years. Mineral annuity is 1-3% (adopted 2% in calculation). Deviations are possible due to currency conversion.

Now, within the company Mg alloys in ingots and magnesium from secondary metallurgy, from recycling are being produced. Through this investment in Brownfield, the trading activity is also shown.

The realization of production in Serbia requires the purchase of raw materials, energy and auxiliary materials. For production process crushed ferrosilicon and additives are used, as well as agents for reduction of Macedonia and Norway and FeSi granules form Germany, Poland, Czech, Turkey, Russia and China. The basic raw material for the production of magnesium in Serbia is dolomite, which contains about 23% MgO and is one of the best ore in Europe. Reserves at the mine "Lokve" in Serbia are estimated at around 30 million tons.

Technical gases: argon, oxygen, sulfur dioxide, propane-butane, acetylene are also provided in the domestic market and the production of compressed air and water vapor is carried out in the factory. Salt for melting and processing of magnesium, as well as other necessary equipment is provided from Germany and France [6].

Electricity for the project was provided on domestic market, along with other energy sources: coal, crude oil, etc. Utilization of oil or gas, as fuel in the production of magnesium instead of coal is recommended in c ases where the reliable distribution network to supply the fuel. Quantity of energy reserves in Serbia, such as oil and gas is symbolic and represents less than 1% of geological balance sheet and off reserves high level of exploration, while the remaining 99% of energy reserves are various types of coal, with the largest share of lignite from over 95% in balance reserves. Transport costs are a significant regulator of raw materials selection. A coal will be provided on the local market, as alternative it can be used cheaper coal from Ukraine.

## 3 Results and discussion

The structure of the needed investments is given in the table 1. Total investments are divided into investments in equipment, installation of equipment then the infrastructure investment, design and licenses, supervision of works and other intangible costs. Table 2 shows the volume and dynamics of companies funds per years and table 3 the calculation of depreciation.

Table 1. Overview of the estimated cost and structure of the necessary investment in $

| Description | Cost $ |
|---|---|
| Costs of equipment | 28.855.526 |
| **Equipment for mining operations** | 4.456.452 |
| Calcination | 4.456.452 |
| Homogenization and briquetting | 779.879 |
| Reduction | 12.812.299 |
| Melting, refining and casting | 3.342.339 |
| Secondary metallurgy | 3.008.105 |
| **Infrastructure investment** | 2.785.282 |
| **Design and licenses** | 1.671.169 |
| **Construction supervison** | 334.234 |
| **Other intangible assets** | 334.234 |
| Installation of equipment | 2.785.283 |
| Total cost | 36.765.728 |

Table 2. Volume and dynamics of total investments per years in $

| Structure of investment | 1 | 2 | 3 | Total cost $ |
|---|---|---|---|---|
| Fixed assets | 36.765.728 | 0 | 0 | 36.765.728 |
| Permanent assets | 4.456.452 | 7.798.791 | 8.912.904 | 21.168.147 |
| Total investment | 41.222.180 | 7.798.791 | 8.912.904 | 57.933.875 |

Table 3. Calculation of depreciation in $

| Description | Amount in $ | Depreciation rate in % | Depreciation in $ |
|---|---|---|---|
| Buildings | 2.785.282 | 0.025 | 69.632 |
| Equipment and installation | 28.855.527 | 0.07 | 2.019.886 |
| Intangible assets | 2.005.403 | 0.2 | 401.080 |
| Depreciation total | | | 2.490.598 |

In order to determine the cost prices of the products from the planned production program the method of the previous calculation is used on the basis of norms of consumption in production process. The aim of this calculation is that it determines the economic viability.

In the table 4 and 5 is shown the calculation of the cost of raw materials, energy and fluid production of primary Mg and Mg alloy, per year.

Table 4. Calculation of the cost of raw materials, energy and fluid production of primary magnesium per year

| - | Description | | Unit | Consuption per t/Mg | Price per t ($) | Cost per unit ($/t) |
|---|---|---|---|---|---|---|
| 1. | The calcined dolomite | | t | 5.076 | 64,61 | 327.96 |
| 2. | Ferrosilicon | | t | 0.984 | 1.225,52 | 1205.91 |
| 3. | Additives | | t | 0.4 | 222,82 | 89,128 |
| 4. | Electricity | | kWh | 1400 | 0.087 | 121,8 |
| 5. | Coal | | t | 3 | 72,41 | 217,23 |
| 6. | Liquid petroleum gas | | kg | 7.277 | 0.955 | 6.949 |
| 7. | Oils | | kg | 7.15 | 2,228 | 15,93 |
| 8. | Salts | | kg | 70 | 1.303 | 91,21 |
| 9. | Ar gas | | kg | 0.5 | 3.765 | 1.8825 |
| 10. | SO2 gas | | kg | 4.64 | 1.715 | 7,9576 |
| 11. | Borax | | kg | 1 | 0.891 | 0,891 |
| 12. | Talc | | kg | 0.5 | 0.0668 | 0,0334 |
| 13. | Technical water loss | | $m^3$ | 120 | 0.278 | 33,36 |
| 14. | Consumable materials | | | | | |
| | 14.1. | Retorts | piece | 0.05 | 445.64 | 22,282 |
| | 14.2. | Bodies for grind | kg | 0.25 | 38,99 | 9,7475 |
| | 14.3. | Pipes for maintenance | kg | 0.25 | 6,907 | 1.7267 |
| | 14.4. | Seals | piece | 0.0105 | 72,41 | 0.7603 |
| Cost per unit (t) of primary Mg | | | | | | 2.154,69 |
| Total for 4500 t Mg | | | | | | 9.696.105$ |

Table 5. Calculation of the cost of raw materials, energy and fluid production of Mg alloy per year

| - | Description | | Unit | Consuption per t/Mg | Price per t ($) | Cost per unit ($/t) |
|---|---|---|---|---|---|---|
| 1. | The calcined dolomite | | t | 4.56 | 64,61 | 294,62 |
| 2. | Ferrosilicon | | t | 0.885 | 1.225,52 | 1.084,58 |
| 3. | Additives | | t | 0.36 | 222,82 | 80,215 |
| 4. | Electricity | | kWh | 1400 | 0.087 | 121,8 |
| 5. | Coal | | t | 2.5 | 72,41 | 181,025 |
| 6. | Master alloys and alloying elements | | | | | |
| | 6.1. | Al | t | 0.07 | 1392,64 | 97,48 |
| | 6.2. | AlMn | t | 0.02 | 4.038,65 | 80,77 |
| | 6.3. | AlBe | t | 0.0002 | 41.222,1 | 8,244 |
| | 6.4. | Zn | t | 0.0075 | 2.618,16 | 19,63 |
| 7. | Liquid petroleum gas | | kg | 6.47 | 0.955 | 6,17 |
| 8. | Oils | | kg | 6.43 | 2,228 | 14,32 |
| 9. | Salts | | kg | 63 | 1.303 | 82,089 |
| 10. | Ar gas | | kg | 0.45 | 3.765 | 1,69 |
| 11. | SO2 gas | | kg | 4.17 | 1.715 | 7,15 |
| 12. | Borax | | kg | 0.9 | 0.891 | 0.801 |
| 13. | Talc | | kg | 0.45 | 0.0668 | 0.03 |
| 14. | Technical water loss | | m3 | 108 | 0.278 | 30,02 |
| 15. | Consumable materials | | | | | |
| | 15.1. | Retorts | piece | 0.045 | 445,64 | 20,05 |
| | 15.2. | Bodies for grind | kg | 0.23 | 38,99 | 8.97 |
| | 15.3. | Pipes for maintenance | kg | 0.23 | 6.907 | 1.58 |
| | 15.4. | Seals | piece | 0.01 | 72,41 | 0.72 |
| Cost per unit (t) of Mg alloy | | | | | | 2.142,43 |
| Total for 11.670 t Mg alloy | | | | | | 25.002.158 $ |

The total cost of the basic materials, energy and fluids in the full utilization of capacity for production of 4.500t Mg and 11.670t Mg alloy are 34.698.263$. The largest share in the cost structure have ferrosilicon and amounting to 18.083.748$. The value of energy costs is 1.971.160$.

Intangible costs are estimated at 1.997.113$. It is estimated that the project would require 120 workers of various profiles. For the purpose of this analysis average salary in the Republic of Serbia is used. Total company cost per employee is 913.248$/year. The costs of production for raw dolomite, calcined dolomite, magnesite and Mg-Al granules are by market prices. In the table 6 is shown total costs of production for these products.

Table 6. Total costs of production for other basic products of the production program

| Description | Quantity per year in t | The costs of production ($/t) | Production costs ($) |
|---|---|---|---|
| Raw dolomite | 180000 | 5,57 | 1.002.600 |
| The calcined dolomite | 20000 | 64,61 | 1.292.200 |
| Magnesite | 30000 | 20.05 | 601.500 |
| Mg-Al granules | 1500 | 2.004,60 | 3.006.960 |
| Total | | | 5.903.260 |

Revenue structure includes products from the basic program with intermediates. The planned structure of total revenue per year by type of product, starting from the fourth year when is planned the full use of available capacity. Total revenue for planned production program is 56.171.395 $/year.

Taking into account the study is based on certain assumptions in line with anticipated future developments, if there was a change of certain influence, initial assumptions would be changed. As a result, an analysis of project sensitivity to changes in selling prices, material costs, as well as analysis of the impact of these parameters on the dynamic indicators of profitability of the project [7].The project sensitivity analysis is shown in table 7. The project is most sen-sitive to price changes on market for primary Mg and Mg alloy, because they bring the largest part of revenue, and if there was a drop in revenues by 20% the project would be unprofitable, net present value is negative. Project is also sensitive on the increase of material costs, energy and fluids cost, and only if the increase will be more than 30%, project will be unprofitable.

Table 7. Project sensitivity analysis

| | | % | Internal rate of return | Net present value | Return period |
|---|---|---|---|---|---|
| Total revenue | - | 1 | 18% | 48.310.729 | |
| Total revenue | - | 10 | 12% | 14.991.692 | |
| Total revenue | - | 20 | 3% | -22.029.460 | |
| Costs of raw materials, energy and fluid | + | 3 | 17% | 44.809.315 | |
| Costs of raw materials, energy and fluid | + | 20 | 10% | 3.989.311 | |
| Investment in equipment | - | 15 | 23,4 % | 63.205.736 | 3,9 |

In addition, the use of gas as a fuel in order to minimize impacts on the environment by reducing energy consumption and using cleaner energy sources, which will cause a significant reduction in emissions of persistent organic pollutants with maximum conversion of the starting raw material into the final product [8]. Using gas as a fuel instead of coal will reduce OPEX for 8.4%.

Internal rate of return is the relative earnings of the project or project interest rate. By applying these rates the inflows and outflows are equated in the economic project, and the net present value is reduced to zero. It is believed that investment in the project is justified if the internal rate of profitability is higher than the chosen discount rate. In our case the chosen discount rate is 11.50%.

Number of years required for a return on investment is the period for which the net inflows generated by exploitation of the investment project repay its total invested assets. Investment in the project is justified if the period of return on investment is not greater than the economic life of the project. Net present value is the absolute value of the earnings on the project and represents the discounted value of the inflows and outflows in an economic project, including investments. The investment in the project is justified if the net present value is positive. Relative net present value is the ratio between the net present value and the present value of investments. The investment in the project is justified if the relative net present value is positive. Profitability index means that for every euro invested, project receive 2.201$ back. Dynamic indicators calculated based on the discounted cash flow of the project according to UNIDO methodology are shown in table 8.

Table 8. Dynamic indicators

| Dynamic indicators | Amount | Acceptability |
|---|---|---|
| Individual discount rate | 11,50 % | yes |
| Internal rate of return | 19 % | yes |
| Time of return | 3,11 years | yes |
| Net present value | 51.220.736 | yes |
| Unit present value | 0,91 | yes |
| Profitability index | 1,98 | yes |

Taking into account that the economic period of the investment is 20 years (and could be more) and based on the techno-economic analysis we came to the conclusion that the project is acceptable.

A preliminary techno-economic study of redesign of secondary magnesium metallurgy gives similar economic parameters of efficiency and profitability, as well as the studies Tami-Mosi in Nevada. Investment has projected capital cost per unit of $5,267/t, with unit OPEX of $ 1,395/t. Plants using Pidgeon process should have a capital cost per unit at least $2,500/t per year to make their production viable [9].

This redesign of secondary magnesium metallurgy is an integrated approach, starting from mine production of crude dolomite and magnesite, through production of calcined dolomite, to the primary magnesium production and its alloys with all intermediate products (dolomite dust, dolomite grit, calcined dolomite dust, the solid residue from the process of reduction), contributes significantly to the material flows management, waste minimization and cleaner production, as well as preventive measures for environmental management of which depends the speed of economic growth based on the principle of sustainable development [10]. The management of material flows and cleaner production is focused on good production planning, which provides energy and reduce emissions of persistent organic pollutants and, therefore, the preservation of natural resources. The final effects of the material flows management and cleaner production are reflected in the reduction of operating costs, increasing profitability and reducing negative impacts of both, the working conditions and on the environment.

By using gas as a fuel the impacts on the environment are minimized by reducing energy consumption, using cleaner energy sources, which will cause a reduction of persistent organic pollutants emissions with significant economic effects.

Minimization of environmental pollution is achieved through waste gas filtration in order to eliminate emissions of particulate matter (particles), using oxygen burners in the process of calcination to reduce emissions of gas pollutants, using regenerative burners in the process of reducing-distillation melting, by minimizing the quantity of waste generated, correct treatment or disposal of solid waste, complete recirculation system of industrial water, as well as cost-effective energy management [11].

The energy will be provided by using oxygen / gas burner which is recommended to reduce the total amount of the gases. Using pure oxygen instead of air mixture in combustion, increases the temperature of the flame. This allows for greater efficiency of heat transfer to the molten material, as well as reducing energy use. This technique reduces energy consumption and reduces emissions of NOx and CO2, through higher combustion temperature.

By using oxygen burners in combination with heat recovery up to 30% energy savings is realized. Heat recovery is used by the hot combustion gases that performs pre-heating and reduces the consumption of primary energy for melting [12]. The theory shows that 8% of the energy is saved for every 100°C of preheating, practically, heat can be utilized for pre-heating up to 400°C, which leads to the storage of energy as 25%.

Fuel and heating oil increase emissions of SOx and NOx, depending on the content of sulfur or nitrogen. The use of cleaner fuels such as natural gas or propane will not cause additional pollution, except for CO2, as in the case of all other combustion processes.

Additional contribution to energy efficiency and reducing emissions of pollutants into the atmosphere is achieved, as has been said, using a modified Pidgeon process using aluminum waste and ferro-silicon-aluminum as a reducing agents. During this process, ferrosilicon and aluminum, which has a lower melting point than ferrosilicon, generates a liquid / solid reaction. In addition, in comparison with the reaction of dolomite and ferrosilicon, the reaction between the dolomite and ferrosilicon and aluminum has a lower Gibbs's free energy, resulting in higher vapor pressure and consequently, in increasing the speed of the reduction reaction [13].

Finally, in this way, it is an additional contribution to energy efficiency and reducing emissions of pollutants into the atmosphere.

The use of aluminum waste or ferro-alumunium as a reducing agent would lead to lower process costs than using ferrosilicon. On the other hand, the production of ferrosilicon within the plant as an integrated part of the production is significantly reduced, which in this case increases the capital thereby reduce the operating cost of production.

At present, only a small amount of magnesium alloy is recycled while the rest is burned or buried in the ground as landfill [3]. Fine fractions of different classes of scrap based on magnesium represent a big recycling and recovery challenge, caused by a very large specific surface covered with MgO [14]. Reaction of this waste with humidity leads to a considerable oxidation, resulting in a high loss of metal. Slag, as an inevitable by-product in the production of magnesium and its alloys, also represent a particular problem in the metallurgy of magnesium. This slag has characteristics of hazardous waste and usually contains oxides and chloride salts of alkali and alkaline earth metals (K, Na, Mg, Ca, Al, Fe, etc.). The most efficient process for the treatment of different classes of waste (fine fractions of different classes of scrap and slag – fraction -3mm, obtained by the process of melting in a specially constructed induction furnace, without the use of flux) is the vacuum-distillation process [15]. Apart from the possibility of production of highly pure magnesium (about 1 ton per day) various by-products such as oil, slag, metallic oxides and non-metallic impurities are obtained. Slag and non-metallic impurities can be used as additions in asphalt and oil can be used as a fuel. The obtained MgO can be re-used as a refractory material, as an agent for stabilizing of dissolved, migratory, heavy metals, for treatment of wastewater, etc.

The Al-alloy from the vacuum-distillation process can be used for steel desulphurization. In this way and through the introduction of a innovative "green" technology for recycling and valorization the useful substances from waste materials, multiple effects are achieved: Production of highly-pure magnesium, by processing of different classes of waste (fine fractions of different classes of scrap and slag – fraction -3mm) to useful components the material flow cycle closes, the amount of waste which originates from the process is reduced to the minimum, its disposal is avoided, waste becomes a resource, a significant increase in recovery of magnesium from the waste (up to 94%), a significant increase of the production capacity, ensuring a long-term market benefit and eliminating environmental issues (an emission of harmful pollutants into the air is prevented). Finally, the development of the plant for the treatment of magnesium scrap by vacuum distillation procedure ensures the adequate management of material flow and gives positive effects of a cleaner production, which is reflected in the reduction of operating costs, increased profitability and a minimum of negative impacts of production to the environment.

## 4 Conclusion

In the current study it has been concluded that production of magnesium is only feasible by principles of closing the production cycle through optimization and synergy between primary and secondary magnesium production in order to generate as least as possible waste, emission and pollution in the Pidgeon process. The time of return of investment in redesign of secondary magnesium metallurgy was concluded to be 3.11 years which is the shortest time for this kind of projects. The parameters as the individual discount rate 11.50%, internal rate of return, period of return 19%, positive net present value and profitability index 1.98 are acceptable. The unit capital cost per unit of $ 5,267/t and unit OPEX of $ 1,395/t were indicative of the economic success of this project and the most appropriate parameters have been achieved. Also, using gas as a fuel instead of coal will reduce OPEX for 8.4%. With this model waste substances are converted into highly profitable resources along with the promotion of sustainability and a cleaner production strategy, which is the ultimate goal for company and society.

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