A Techno-Economical Study Comparing the Bayer and Pedersen Processes for Alumina Production and Bauxite Residue Treatment

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Abstract

The objective of this paper is to investigate Mo i Rana as a possible site for the improved Pedersen process based on the results of the EU funded ENSUREAL project which investigated this process as an alternative to the Bayer process for producing alumina to the aluminium industry without producing bauxite residue deposits. A techno-economic study has been performed on several case studies: Keeping the Bayer process as it is today with a case study of a new-establishment of the Bayer process in Greece; Building the Pedersen process in its entirety in Mo i Rana; Building the Pedersen process for treating bauxite residue only; Building the Pedersen process connected to an existing Bayer refinery to avoid bauxite residue deposits and building a new Bayer process in Mo i Rana with and without the Pedersen process. The conclusion of the techno-economic study is very clear when it comes to revitalizing the Pedersen process: It is not economically feasible and cannot be recommended as a realistic competitor to the Bayer process. However, an economically feasible alternative is to treat the bauxite residue from the Bayer process, with the Pedersen process to access the iron and alumina raw materials present in the material that is now deposited. The techno-economic study performed in this work shows that this is an alternative that should be investigated further

Keywords: Techno-economic study, Bayer vs. Pedersen, Alumina production, Bauxite residue treatment, Valorising bauxite residue.

1. Introduction

The EU funded ENSUREAL project aimed at investigating a modification and optimisation of the Pedersen process to determine if it can be a true alternative to the currently dominating Bayer process for industrial production of aluminium oxide (also known as alumina or metallurgical/smelter grade alumina) from Bauxite. In the Bayer process a significant amount of the bauxite raw material is lost as a landfill called bauxite residue. This residue is highly alkaline and consists mainly of iron oxide but typically with 15-25 wt% alumina in addition. For every kg of alumina produced, approximately two kg of bauxite residue is generated with the feedstock today. Bauxite residue storage practices vary significantly; historically lagooning or even direct disposal were commonplace, however the industry is adopting more environmentally friendly practices such as dry stacking or farming. Nevertheless, the bauxite residue tailings present an environmental risk and historically major incidents have occurred with significant impacts on the surroundings and environment. The high content of Al_2O_3 in the bauxite residue represents a loss of raw material that could have been utilized with a more efficient process. In addition, there have been several severe incidents with bauxite residue lakes flooding towns, e.g., Hungary in 2010 killing several people and controversy regarding heavy rain claimed to be causing flooding of bauxite residue deposits in connection with the Alunorte plant in Brazil in 2018. Investigations after the incident, however, reported that no direct release/overflow occurred: the release was caused by some "not fully treated effluent" that ended up in the nearby Para River [1]. The major advantage of the Bayer process is that it produces alumina with a significantly lower energy consumption compared to the Pedersen process. However, from a circular economy perspective, where all raw materials should be utilized it makes sense to work towards reducing landfill materials.

Figure 1 shows a very general overview of the Bayer and the Pedersen processes. The most obvious difference between the two processes is the electric arc furnace which produces pig iron from the iron oxide in the bauxite. Pig iron is produced by carbothermic reduction when bauxite is smelted with burnt lime as the flux and coke as the reduction agent. A calcium aluminate slag is formed, and this is further treated by hydrometallurgy to extract alumina. The slag disintegrates during cooling and is then pulverized. The powder is then digested using sodium carbonate solution in the leaching phase, and the reactions are summarized in Equations (1)-(3) [2]. Figure 2 shows a more detailed flowsheet of the Pedersen process [3]. The process can also be performed using bauxite residue as raw material [4, 5].

$$CaO \cdot Al_2O_3(s) + Na_2CO_3(aq) \rightarrow Na_2O \cdot Al_2O_3(aq) + CaCO_3(s) \quad (1)$$
$$3CaO \cdot Al_2O_3(s) + 3Na_2CO_3(aq) \rightarrow 3Na_2O \cdot Al_2O_3(aq) + 3CaCO_3(s) \quad (2)$$
$$12CaO \cdot 7Al_2O_3(s) + 12Na_2CO_3(aq) \rightarrow 7Na_2O \cdot Al_2O_3(aq) + 12CaCO_3(s) + 10NaOH(aq) \quad (3)$$

In the classification step, grey mud is separated from the sodium aluminate solution. Grey mud is the non-soluble residue. The grey mud mainly consists of $CaCO_3$, but also some CaTi-oxides and SiO_2. The grey mud can possibly be used for cement production, in lime fertilizer production or be reused in the Pedersen process. In the precipitation step, CO_2 is used to precipitate gibbsite ($Al(OH)_3$) from the sodium aluminate solution. The sodium carbonate solution that is left in the solution is recycled into the leaching/digestion step. Gibbsite is further calcined to form smelter grade alumina, mainly comprising of transition alumina phases such as γ-Al_2O_3. The calcination step in the Pedersen process is identical to the calcination step in the Bayer process and is a well-established industrial technology.

In the present study several case studies have been investigated when it comes to techno-economic feasibility for handling of the bauxite residue issue to make alumina production more sustainable.

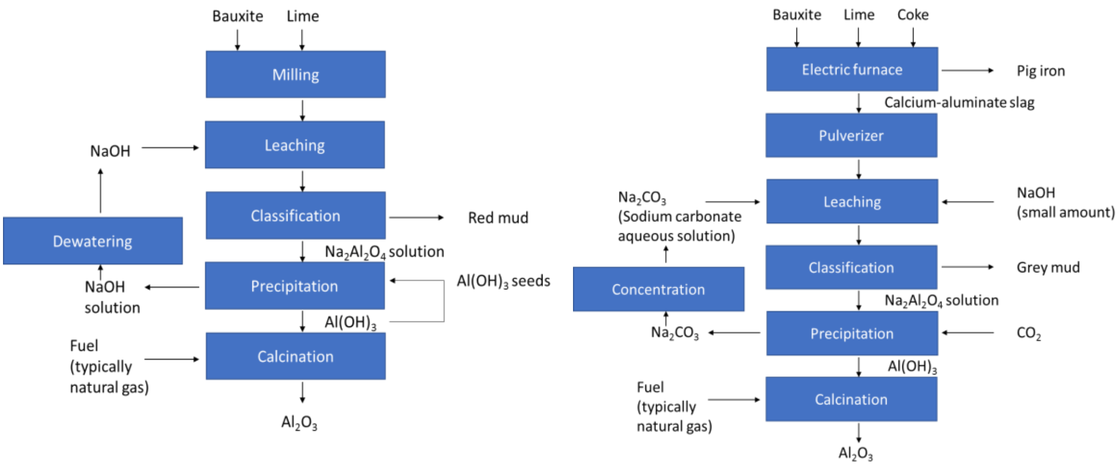

Figure 1. Overview of the Bayer process (left) and the Pedersen process (right). adapted from [2].

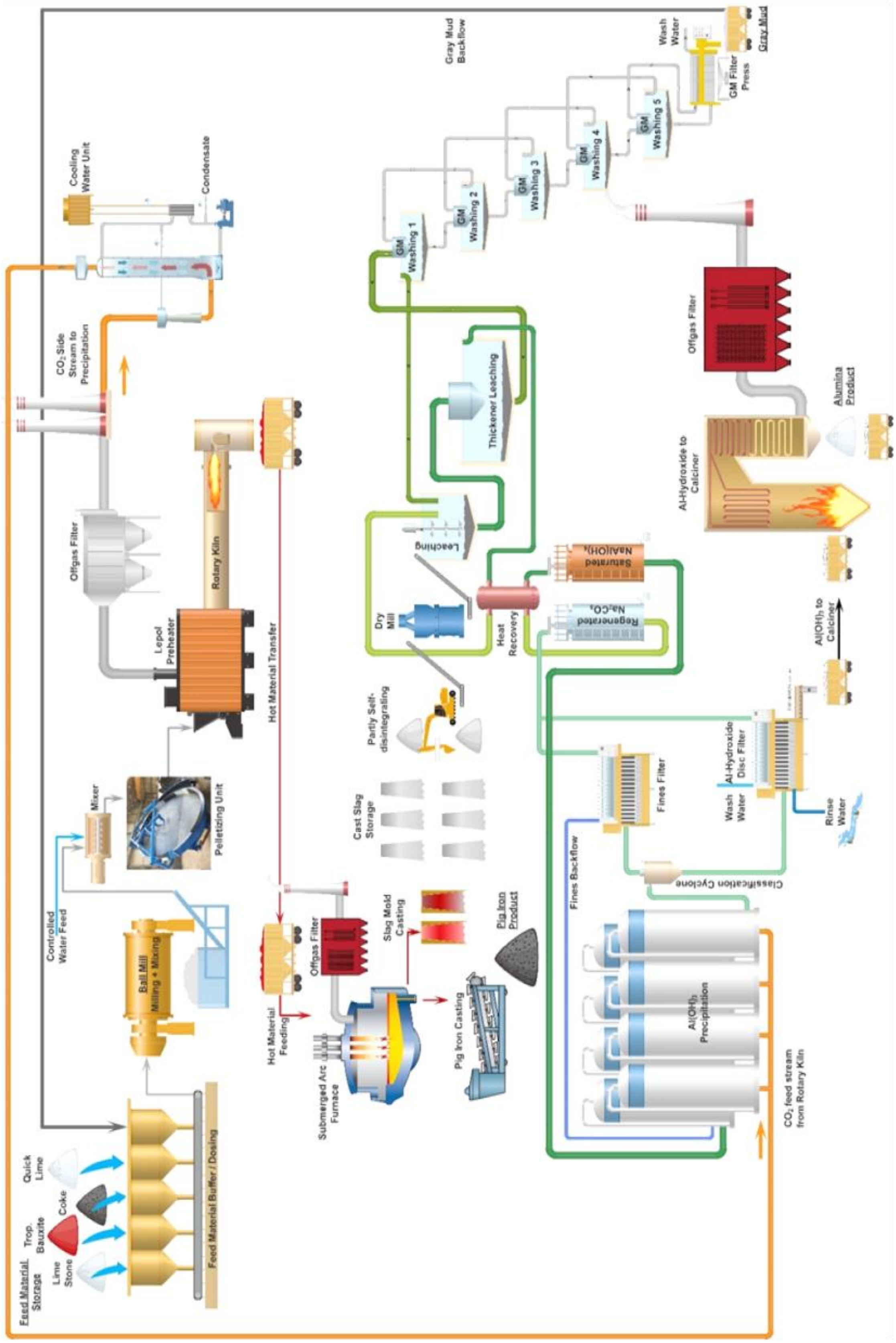

Figure 2. Flowsheet of the Pedersen process. Adapted from [3].

2. Methodology and Assumptions

In all case studies, an output production rate of 500 kt/year of alumina which equals 60 t/h of alumina is used as benchmark. The case studies that have been investigated are:

- Bauxite Residue Pedersen (BRP): Treatment of bauxite residue using the Pedersen process at the Aluminium of Greece site in Greece, where there is an existing bauxite residue deposit.
- Greece Bayer: Establishing a new Bayer processing plant in Greece without bauxite residue treatment.
- Greece Bayer + Pedersen: Alumina production at the Bayer plant in Greece with a scaled down Pedersen process in series, to treat the bauxite residue by producing pig iron and accessing the remaining alumina in the bauxite residue for alumina production. In this case a separate calciner for alumina from the Pedersen process is assumed. In a real process it is more likely that the calciner for alumina from the Bayer and the Pedersen processes will be the same.
- Norway Pedersen: Pedersen process placed in Mo i Rana, Norway inside Mo Industrial Park using Jamaican bauxite and recirculating grey mud in the process.
- Norway Bayer: Installing a new Bayer plant in Mo i Rana, Norway with state-of-the-art technology, without bauxite residue treatment.
- Norway Bayer + Pedersen: Installing a Bayer plant in Mo i Rana, Norway with state-of-the-art technology, with a scaled down Pedersen process in series, to treat the bauxite residue by producing pig iron and accessing the remaining alumina in the bauxite residue for alumina production.

When calculating the techno-economic feasibility of these case studies, the CAPEX and OPEX costs have been estimated and adjusted according to the necessary scale of the required industrial site. Two reports from the ENSUREAL project have been used as basis for these calculations: Technology scale-up study - Deliverable D4.2 for CAPEX [3] and Life Cycle Cost Analysis – Deliverable D6.4 for OPEX calculations [6].

OPEX is calculated based on:
- Energy cost
- Raw material cost
- Maintenance cost
- Employee costs and number of employees
- Utilities cost

CAPEX is calculated based on the total installed cost:
- Equipment cost
- Bulk material and mass balances
- Installation contracts
- Engineering
- Administration and procurement
- Commissioning
- Contingency

The yearly capital cost is calculated based on Equation (4):

$$Yearly\ capital\ cost = \frac{\left(\frac{CAPEX \cdot \sum_{n=0}^{n=c} 1/(1+p)^{\wedge}n}{c}\right)}{\sum_{n=c+1}^{n=m} 1/(1+p)^{\wedge}n} \quad (4)$$

Here, c = numbers of construction years. In this work this number has been set to two years. For the net present value calculations (NPV) the rate of return = p and has been set to 7.5 %. n = year number. m = maximum period. The maximum period has here been set to 25 years. It is important to keep in mind that there is a difference in installing a so-called "first of a kind" vs. an "n^{th} of a kind" processing plant. The first of a kind processing plant will always be more expensive than an n^{th} of a kind plant. In these calculations an n^{th} of a kind processing plant has been assumed, however, with conservative assumptions.

Table 1. Price list of raw materials, energy, and utilities. Negative numbers are selling price. The background for the numbers is found in [6].

Input	**Unit**	**Greece**	**Norway**
Greek bauxite	EUR/t	77	0
Jamaican bauxite	EUR/t	0	52
Bauxite residue	EUR/t	-3	0
Calcined lime	EUR/t	97	97
Limestone	EUR/t	0	0
Coke	EUR/t	230	199
Sodium carbonate	EUR/t	300	220
Hydrogen	EUR/t	2500	2500
Caustic soda	EUR/t	150	150
Carbon dioxide	EUR/t	-30	-30
Fresh water	EUR/m^3	0.18	0.74
Cooling water	EUR/m^3	0	0
Processed air	EUR/kg	0	0
Electricity	EUR/GJ	11.1	2.2
Natural gas	EUR/GJ	12.9	8.2
Steam	EUR/GJ	5.6	0.9
Output	**Unit**	**Greece**	**Norway**
Grey mud	EUR/t	-2.4	-2.4
Pig iron	EUR/t	-390	-390
Carbon dioxide	EUR/t	30	30
Wastewater	EUR/t	0	0
Bauxite residue	EUR/t	30	30
Air emission	EUR/kg		
Alumina	EUR/t	-420	-420

Aluminium of Greece operates an integrated Bayer plant and aluminium reduction plant in Greece. They are placed near a bauxite mine and cover the entire value chain from bauxite to alumina to aluminium. There is also a bauxite residue deposit site next to the Bayer plant. Aluminium of Greece is a partner in the ENSUREAL project and is also used as a case study in this work. The other case study is Mo Industrial Park in Norway. Mo Industrial Park is placed 80 km away from Alcoa Mosjøen which is an operating aluminium plant where they consume approximately 500 kt/year alumina. Mo Industrial Park host various industries today and has some available brown field land that could be utilized for the Pedersen or the Bayer process. There is also available electricity, cooling water and other industrial infrastructure which makes establishing new industries easier, and cheaper. Table 1 shows the price list of raw materials, energy and utilities that lay the foundation for the OPEX calculation of the technoeconomic calculations. The report on Life Cycle Cost Analysis was used to identify the numbers in the table [6]. Negative numbers are selling price for produced goods. The negative number for CO_2 in the input list is due to produced CO_2 being used as a raw material in the precipitation step. The negative number for the bauxite residue is due to removal of waste handling which represents a modest fee today when it is deposited, however, when the handling of this residue starts, you would expect to be paid a small fee to clean up waste. Norway does not have any bauxite residue; this is the reason for this value being set to 0. It is not obvious to us why coke is more expensive in Greece compared to Norway and why fresh water is more expensive in Norway compared to Greece. However, these numbers are not decisive for the final result of the calculations.

3. Results and Discussion

3.1 CAPEX Calculations

Table 2 shows CAPEX calculations for the four cases:

1. Full-scale Pedersen process with recirculation of grey mud,
2. Traditional Bayer process,
3. Pedersen process on bauxite residue only, and
4. Traditional Bayer process with bauxite residue treatment using the Pedersen process.

CAPEX is considered the same for both geographical cases in Norway and in Greece. It is important to keep in mind that the Greek case is considering building an entirely new plant. It is not comparing building a new site in Norway to the existing site in Greece. The CAPEX values for the Pedersen are taken from [3]. The values for the Bayer process are calculated based on equipment from the Pedersen process and the cases for the Pedersen process on bauxite residue and Bayer + Pedersen processes have been linearly scaled according to necessary size of the equipment compared to the case that Konlechner et al. reported [3].

Table 2. CAPEX calculations for four case studies. CAPEX is considered the same for both geographical cases in Norway and in Greece. The unit for the numbers is mill EUR for a plant production capacity of 60 t alumina per hour [3].

Equipment	Case studies			
	Pedersen with grey mud recirculation	Bayer process	Pedersen process on bauxite residue	Bayer + Pedersen processes
Storage raw materials	106	106	212	150.3
Milling and mixing	32.9	32.9	65.8	46.6
Lepol preheater + rotary kiln	54.8	-	109.6	22.9
Offgas, cleaning and cooling	10.5	10.5	21	
Submerged arc furnace	350	-	420	87.7
Pig iron casting and handling	6	-	18	3.8
Slag casting	24.8	24.8	24.8	30
Dry mill	8.3	8.3	8.3	10
Leaching	10.6	10.6	10.6	12.8
Grey mud thickening	27.6	27.6	27.6	33.4
Storage products	7.9	7.9	7.9	9.6
Hydroxide filtration	10.5	10.5	10.5	12.7
Cyclone	0.5	0.5	0.5	0.7
Precipitation	30	30	30	36.3
Calcination	49	49	49	59.3
Roads, infrastructure	28.5	28.5	28.5	34.4
Total sum	758	347.2	1044.2	565.3

There are several things to notice in Table 2. Slag casting was added to the Bayer process, this is not a necessary production step but was kept there as part of a conservative approach for the CAPEX calculations to avoid underestimating the CAPEX cost. For the Bayer + Pedersen process case, the Bayer process has not been scaled down accordingly to account for the alumina production volume of the Pedersen process. This was also done as part of the conservative approach during the calculations. Another aspect of the Bayer + Pedersen case is that both these processes are considered independent of one another in the CAPEX calculations. It could perhaps be possible to treat the aluminium rich slag from the submerged arc furnace (SAF) as feedstock into the existing Bayer process, but this has not been considered here. If it is possible from a technical point of view is also not certain. The EU funded HARARE project is now studying novel methods for treatment of bauxite residue where the SAF is replaced with a shaft furnace, and hydrogen is used as the reduction agent instead of carbon. This way a purer iron would be produced increasing the selling price of the metal produced and reducing the CAPEX cost of the reduction furnace. In the present CAPEX calculations, it has been assumed that it would be necessary to build a small scaled-down Pedersen process to treat the slag from SAF to produce alumina from bauxite residue. The bauxite residue is assumed to contain 13 % accessible alumina; however, this number varies a lot in literature and numbers up to 25 % is frequently reported. A higher output of alumina will likely increase the profitability of the attached Pedersen process.

One case study that has not been considered but one that is very likely is to dimension the Pedersen process to start cleaning old bauxite residue deposits along with treating the ongoing bauxite residue flow from the Bayer process. This way, it is possible to avoid bauxite residue deposits from growing and start cleaning up existing deposits.

The CAPEX cost for the Pedersen process is approximately twice as much compared to the Bayer process. The SAF alone represents almost entirely the increased cost of the Pedersen process compared to the Bayer process. The Pedersen process on bauxite residue only with a production rate of 500 kt/year alumina, would have to treat a very high flow of bauxite residue and consequently produce a larger amount of pig iron. This in turn would need SAF to be scaled accordingly (or a need for two furnaces) which in turn increases the CAPEX cost noticeably.

3.2 OPEX Calculations

When doing a techno-economical study it is important to consider both the CAPEX and the OPEX costs, and usually OPEX is the true cost driver. OPEX costs consist of raw materials, energy, and utility prices.

For the present six cases the raw material, energy and utility prices were calculated for a plant producing 500 kt/year alumina which equals to 60 t/h based on the numbers in [6]. 500 kt/year alumina is the benchmark production rate in this work. The results are summarized in Table 3. One important take-away from Table 3 is that the "Bayer + Pedersen"-case will need less bauxite raw material compared to the Bayer process alone as more of the alumina is recovered from the bauxite. Today, this alumina is part of the bauxite residue. In these calculations it is assumed that 13 % of the bauxite residue contains accessible alumina through the Pedersen process. This is a conservative assumption and the amount of wasted alumina in the bauxite is most likely several percentages above this number. In Table 3 it is assumed a yearly production time of 8000 hours. Further on, the yearly OPEX costs were calculated as EUR/t, and this is summarized in Table 4. In both Tables 3 and 4, negative numbers represent income/selling price of produced goods. It is worth noting that the selling price of grey mud is set to a very conservative estimate as the use of this product is still questionable. For the "Bauxite residue + Pedersen" case there is a will to pay to clean up the bauxite residue and this is accounted for in the calculations indicated in the negative number for Bauxite residue. The Pedersen process also consumes CO_2 and reduces the CO_2 tax as reflected in the negative CO_2 numbers. It is also worth noting that the Greek bauxite is more expensive than Jamaican bauxite that is assumed used in a Norwegian alumina production site. Another difference that affects the OPEX costs and the final calculated profit for the cases (Table 5) is the difference in natural gas prices between Greece and Norway.

In Table 3 the -201 600 kEUR represents the total selling price for a total production volume of 500 kt/year alumina. This is equal to an alumina price of 420 EUR/t as shown in Table 5. This is comparable, but also a conservative estimate compared to the selling price at London Metal Exchange (dated March 2022) where the current selling price is 450 EUR/t. Worth noting in both tables is also the pig iron price which clearly reflects the total tonnage of pig iron produced in the various cases involving the Pedersen process. A larger production of pig iron also required a larger Pedersen processing plant with a larger submerged arc furnace as reflected in the CAPEX costs in Table 2 SAF is a major CAPEX and OPEX cost driver of the Pedersen process and at a certain size the CAPEX price will become so high with the consequence of making the Pedersen process non-competitive compared to the Bayer process. For the "Bauxite residue + Pedersen" case it is assumed that bauxite residue is the only raw material for producing the 500 kt/year alumina and this requires a large amount of bauxite residue. This in turn produces a large amount of pig iron which is reflected in the large income of pig iron. This industrial setup would also require a very large preheater, rotary kiln and SAF or perhaps a parallel production unit. This setup would be very vulnerable to fluctuations in pig iron price, and this is also reflected later in Figure 3.

Table 3. The calculated OPEX costs at a production rate of alumina equal to 60 t/h of alumina and assuming a yearly production time of 8000 hours (leaving 760 h for maintenance). This equals a production rate of 500 kt/year.

		Greece			Norway		
Input	Unit	BRP	Bayer	Bayer + Pedersen	Pedersen	Bayer	Bayer + Pedersen
Greek bauxite	kEUR	-	79 686	70 484	-	-	-
Jamaican bauxite	kEUR	-	-	-	62 575	53 814	47 600
Bauxite residue	kEUR	- 8 727	-	-	-	-	-
Calcined lime	kEUR	9 917	1 397	2 381	37 807	1 397	2 381
Limestone	kEUR	-	-	-	-	-	-
Coke	kEUR	65 026	-	7 509	8 883	-	6 497
Sodium carbonate	kEUR	10 080	-	1 164	5 491	-	854
Hydrogen	kEUR	-	-	-	-	-	-
Caustic soda	kEUR	-	3 456	3 057	-	3 456	3 057
Carbon dioxide	kEUR	-10 570	-	-1 221	-10 714	-	-1 221
Fresh water	kEUR	248	310	303	733	1 275	1 245
Cooling water	kEUR	-	-	-	-	-	-
Processed air	kEUR	-	-	-	-	-	-
Electricity	kEUR	83 201	2 667	11 966	6 400	533	3 939
Natural gas	kEUR	132 715	54 938	63 919	45 995	34 988	40 707
Steam	kEUR	19 733	-	2 279	1 901	-	353
Output	Unit	BRP	Bayer	Bayer + Pedersen	Pedersen	Bayer	Bayer + Pedersen
Grey mud	kEUR	- 4 332	-	-500	-2 583	-	-500
Pig iron	kEUR	-342 946	-	-39 602	-62 524	-	-39 602
Carbon dioxide	kEUR	31 190	6 062	8 964	10 008	6 062	8 964
Wastewater	kEUR	-	-	-	-	-	-
Bauxite residue	kEUR	-	11 390	-	-	11 390	-
Air emission	kEUR	-	-	-	-	-	-
Alumina	kEUR	-201 600	-201 600	-201 600	-201 600	-201 600	-201 600

Table 4. OPEX costs in EUR/t for producing 500 kt/year alumina.

		Greece			Norway		
Input	Unit	BRP	Bayer	Bayer + Pedersen	Pedersen	Bayer	Bayer + Pedersen
Greek bauxite	EUR/t	-	166	147	-	-	-
Jamaican bauxite	EUR/t	-	-	-	130	112	99
Bauxite residue	EUR/t	-18	-	-	-	-	-
Calcined lime	EUR/t	21	3	5	79	3	5
Limestone	EUR/t	-	-	-	-	-	-
Coke	EUR/t	135	-	16	19	-	14
Sodium carbonate	EUR/t	21	-	2	11	-	2
Hydrogen	EUR/t	-	-	-	-	-	-
Caustic soda	EUR/t	-	7	6	-	7	6
Carbon dioxide	EUR/t	-22	-	-3	-22	-	-3
Fresh water	EUR/m^3	1	1	1	2	3	3
Cooling water	EUR/m^3	-	-	-	-	-	-
Processed air	EUR/kg	-	-	-	-	-	-
Electricity	EUR/GJ	173	6	25	13	1	5
Natural gas	EUR/GJ	276	114	133	96	73	85
Steam	EUR/GJ	41	-	5	4	-	1
Output	Unit	BRP	Bayer	Bayer + Pedersen	Pedersen	Bayer	Bayer + Pedersen
Grey mud	EUR/t	-9	-	-1	-5	-	-1
Pig iron	EUR/t	-714	-	-83	-130	-	-83
Carbon dioxide	EUR/t	65	13	19	21	13	19
Wastewater	EUR/t	-	-	-	-	-	-
Bauxite residue	EUR/t	-	24	-	-	24	-
Air emission	EUR/kg	-	-	-	-	-	-
Alumina	EUR/t	-420	-420	-420	-420	-420	-420

Table 5. Calculated profit for the six cases. EUR/t alumina.

	Greece			**Norway**		
	BRP	**Bayer**	**Bayer + Pedersen**	**Pedersen**	**Bayer**	**Bayer + Pedersen**
Variable cost	-178	-177	-177	-241	-125	-128
Energy	-491	-120	-163	-113	-74	-91
Fee income bauxite residue	18	-	-	-	-	-
Cost of CO_2	-43	-13	-16	1	-13	-16
Fee bauxite residue	-	-24	-	-	-24	-
Products grey mud	9	-	1	5	-	1
Products pig iron	714	-	83	130	-	83
Products alumina	420	420	420	420	420	420
Capital cost	-175	-58	-95	-127	-58	-95
Maintenance	-87	-29	-47	63	-29	-47
Manning	-108	-36	-58	78	-36	-58
Profit	81	-36	-52	-65	62	69

Table 5 shows the calculated profit for the six case studies. A negative profit number means a non-profitable case, while a positive number reflects a case study where it is possible to make a profit. The number is a variable of +/- 450 EUR/t alumina which was the selling price of alumina at the time of doing these calculations. A profitable case may turn into a non-profitable case if the alumina selling price drops and from these calculations it is evident that the margins in these calculations are not great. Regarding the Greek Bayer case, the capital cost is not necessary to account for since this plant is already built and in operation. When removing this number (- 58) then the Greek Bayer case becomes profitable. It is also worth mentioning that the capital costs calculations (CAPEX) for the Bayer cases are highly uncertain since they are calculated based on equipment meant for the Pedersen process. In future work, this calculation should be made specifically on the Bayer process. Another cost that can be reduced in times when running with lower margins, is the maintenance cost. This can be reduced while waiting for increasing alumina (and/ or pig iron) prices.

Variable costs (as shown in Table 5) include all raw materials. Fee income bauxite residue represents what you would be paid per tonne bauxite residue to start cleaning up old bauxite residue deposits. There is likely an income to be made for the cases with an attached Pedersen process to an existing Bayer processing plant too, if the bauxite residue treatment facility (Pedersen) is scaled up a bit to both treat the constant flow of bauxite residue but also reprocess an amount of bauxite residue from existing deposits with the aim of reducing the deposit size and eventually clean it up entirely. Cost of CO_2 is the cost in CO_2 tax to emit this gas. The Pedersen process both consume and produces CO_2. The bauxite residue fee represents the cost of deposition. The income of grey mud is set low, due to a very uncertain cost estimate for this product. The "Bauxite residue – Pedersen (BRP)" case would produce a very large amount of pig iron and hence give a large income. However, this income is highly sensitive to fluctuations in the pig iron prices as is illustrated in Figure 3 (orange column). With a reduction in pig iron prices with 50 % the case with bauxite residue treatment using the Pedersen process to produce an alumina tonnage equal to 500 kton/year is not feasible. The pig iron income is also contributing to the "Bayer + Pedersen" plant cash flows. The maintenance cost is calculated as 4 % of the total CAPEX cost and this is accordance with common practice when calculating maintenance cost for techno-economical calculations as it is normally set between 2-6 % of CAPEX costs. The manning need is based on calculations in [3] and has been linearly scaled up and down with the size of the production site. For the original Pedersen processing plant, the manning was set to 500 people.

Figure 3 sums up all the results in this work including CAPEX and OPEX costs for all the six cases. This is shown in the blue bars. It also shows what happens with the production cost if:

- the pig iron selling price drops with 50 % (orange bars),
- the electricity prices increase with 50 % (grey bars),
- the natural gas price increase with 50 % (yellow bars),
- the CAPEX costs increase with 50 % (light blue bars),
- the need for manning increase with 50 % compared to the assumed amount (green bars),
- the rate of return increase with 50 % (dark blue bars)

When comparing these bars, it is obvious that attaching the Pedersen process to treat bauxite residue from Bayer plants (Greek and Norwegian cases) will not increase the production cost of alumina to a large degree. This means that the Pedersen process can be established next to existing Bayer plants to continuously treat the bauxite residue produced in the Bayer process without increasing the production cost of alumina significantly.

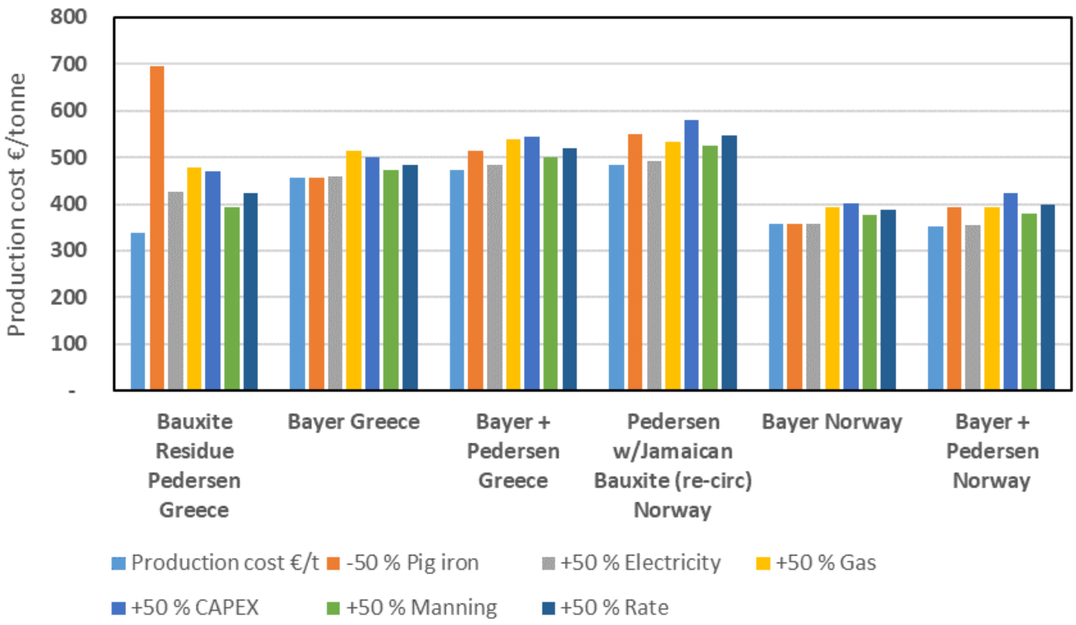

Figure 3. Production cost in EUR/t alumina for the six cases including cases with decreased pig iron prices and increased costs for electricity, gas, CAPEX, manning, and rate of return.

Establishing a new Bayer plant in Norway is cheaper than establishing a new Bayer plant in Greece and the reason for this is the difference in bauxite and natural gas prices. However, the distance from the bauxite mine to the Bayer plant will most likely be a showstopper for alumina production in Norway as the transportation cost of bauxite to Norway would be too high. It makes more sense to transport alumina as a finished product. Producing alumina through the Pedersen process with bauxite residue as the raw material is highly sensitive to the pig iron price due to the large volume of pig iron produced. The Pedersen process is not competitive to the Bayer process or the Bayer + Pedersen process case. This is obvious when comparing the three case studies to the right in Figure 3. Hence, the Pedersen process **cannot** be recommended to replace the Bayer process for production of alumina. The investment cost in CAPEX is too high.

4. Conclusion

The task of this report was to investigate the possibility of establishing the Pedersen process inside Mo Industrial Park. This work is conclusive: it is not recommendable to place the Pedersen process there. A full-scale Pedersen process is too expensive in terms of CAPEX compared to the Bayer process. Transportation cost of bauxite to Norway would also be too expensive. It is more reasonable to produce alumina close to the bauxite mines and as the work in this report has revealed, it is highly feasible that bauxite residue can be treated using the Pedersen process as a waste treatment plant. Installing a smaller Pedersen processing plant at existing Bayer plants would solve the bauxite residue problem, producing iron from the iron deposits in bauxite residue and accessing all alumina from bauxite. The calculations in this report are based on prices and mass balances done for a full-scale Pedersen process. There have been made many assumptions that make the calculations quite uncertain, and better calculations should be made especially on Bayer + Pedersen cases close to existing Bayer sites with better mass balances, studies on synergies that can be made between Pedersen and Bayer processing steps (like flotation, calcination etc.) and better sensitivity calculations that combine series of events (e.g., the combination of lower pig iron price and higher electricity prices). Despite these short comings, the result in this paper is very interesting concerning bauxite residue treatment and better utilization of the bauxite raw material without adding extra cost to the alumina manufacturers.

A fluctuating alumina price will always affect the business case for alumina producers, and the resulting alumina price in this report is perhaps a bit high in today's alumina market. However, the cost calculations in this report are based on very conservative assumptions and it is hence likely that the CAPEX and the OPEX costs are overestimated.

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