RESEARCH REPORT

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PCC from steelmaking slag – case study

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Summary

In this work, a preliminary assessment for producing PCC from Outokumpu steelmaking slag for use at Veitsiluoto paper mill was made. The work was performed as a desktop study, using available experimental data. The framework and boundaries for the study were first assessed. It was found that although the current generation of slag suitable for the process is not enough for supplying the amount of PCC needed (130,000 t/a), future expansions are expected to provide enough slag, although the margin will be small. Various alternatives for implementing the process were screened. The option, where PCC is produced at the steel mill site and transported to the paper mill by truck was found to be the cheapest way for implementation, since it had the lowest transportation costs (3-10 euro/t PCC). This option was selected as the base case for concept evaluation to determine a coarse estimation of the investment costs and operational costs for the facility. The feasibility analysis of the case studied showed that the investment costs are relatively high – 76 M€. With an estimated annual revenue of 6.1 M€, the payback time would be 20 years. A large part of the investment costs is due to the demanding filtration requirements. A conventional PCC plant requires only one stage of filtration, while the PCC process evaluated here would require three stages. However, the filtration performance is largely based on assumptions and real experimental data is missing. Therefore, future works should concentrate on determining the filtration requirements for the process.

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Preface

This evaluation was performed as a commission from Stora Enso and Tapojärvi during June 2012 – January 2013. The target of the project was to preliminary assess if a process for producing PCC from Outokumpu steelmaking slag is a competitive alternative to the current PCC production at Veitsiluoto and at what the prerequisites for its competiveness are. The work was performed as a desktop study, using available experimental data. The progress of the evaluation was monitored and directed by Raino Kauppinen, Reijo Vapa and Jouko Pakarinen, with whom several fruitful meetings and discussions were held. Jouko Pakarinen also assisted with cost estimations for certain parts of the process.

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Sebastian Teir

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1 Introduction

Synthetic calcium carbonate, commonly known as precipitated calcium carbonate (PCC), is used as a filler and coating pigment in papers and plastics. Filler material is needed in paper to improve the whiteness, opacity, brightness and printability of the paper. Since PCC is synthesized, the production process allows for control of the particle shape and the size distribution, which makes it a more flexible filler material than ground calcium carbonate. The use of PCC has doubled in the last decade and nowadays 14 Mt of PCC is annually consumed worldwide (Roskill, 2012).

Most PCC is made by direct carbonation of hydrated lime. In this process, high purity calcium carbonate rock (limestone) is mined, crushed and some of the impurities removed. The rock is calcined at 1000 °C, forming lime (CaO) and carbon dioxide (CO_2).

$$CaCO_3 + Heat \rightarrow CaO + CO_2 \quad (1)$$

The lime is transported to a so called satellite plant located at the paper mill, where the lime is mixed with water in a "slaker" to form "slake" or calcium hydroxide:

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (2)$$

Additional impurities can be removed from the slaked lime. The slurry is then led to a “carbonator” tank where the slaked lime is reacted with gas containing carbon dioxide (CO_2).

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

Calcium carbonate is formed, and since it is insoluble in water, it precipitates out. After careful screening, the PCC slurry is delivered to the paper mill. If the PCC is to be used as a dry product, the slurry can be dewatered, dried and milled.

Although the production of PCC binds CO_2, even more CO_2 is emitted when the rock is calcined, since CO_2 is also generated from the fuel used (typically fossil oil). In addition, the lime is transported hundreds of kilometres to the paper mill. The pure limestone needed in conventional PCC processes is becoming more rare and expensive and is currently imported from Norway. In a new process concept, calcium is extracted from steelmaking slag using ammonium salt solutions, from which PCC can subsequently be precipitated using CO_2 (Teir et al., 2009).

Steelmaking slags in large quantities are being produced annually from stainless steel production at Outokumpu steel mill at Tornio, which is located 40 km away from Veitsiluoto paper mill. According to recent studies the Outokumpu steelmaking slag seems suitable for producing PCC using the aforementioned concept (Rinne, 2008). Therefore, there could be an opportunity to utilize the steelmaking slag from Tornio steel mill as a raw material for producing PCC for Veitsiluoto paper mill. However, there are many challenges when implementing a new industrial process and careful assessment must be made in order to determine the feasibility of the case.

2 Goal

The goal of the project was to preliminary assess if a process for producing PCC from Outokumpu steelmaking slag is a competitive alternative to the current PCC production at Veitsiluoto and at what the prerequisites for its competiveness are. The work was performed as a desktop study, using available experimental data.

3 Definition of boundary conditions

First, the boundary conditions and the frame of the case were identified. This was done by discussing with the parties involved regarding their interest and current operations. Also, further background information was collected by literature review of relevant publications and previous reports related to the concept.

The following main boundary conditions were identified:

- PCC requirements of the paper mill
  - PCC demand (130,000 t/a, reliable supply needed)
  - PCC quality requirements (high brightness, narrow particle size distribution, scalenohedral particle shape, low impurity level, high pH stability, low abrasiveness)
  - PCC costs competitive to current costs
- Slag production and use at the steel mill
  - Annual slag production (about 200,000 t/a net suitable for PCC use)
  - Residual slag quality requirements (options for utilisation of residual slag)
- Main limitations of the new PCC process for slag
  - Maximum extraction ~60%, average extraction 50% (assumption)
  - Needs a continuous CO_2 supply (70,000-80,000 t/a CO_2)
  - Needs 250,000 t/a steel slag (assuming an average CaO content of 58%) for producing 130,000 t/a PCC.

The boundary conditions are examined in more detail below.

3.1 Veitsiluoto paper mill

Veitsiluoto mill in Kemi is an integrated production facility manufacturing fine paper, magazine paper and timber products. The direct fossil CO_2 emissions in 2011 from the plant was 341,000 t and the direct biogenic CO_2 emissions were 1,160,000 t. While the plant uses annually 130,000 t PCC, also ground calcium carbonate is used, amounting to a total of 224,000 t/a.

3.1.1 Current PCC production

The current PCC plant at Veitsiluoto is owned and operated by Omya and supplies the PCC required by the paper mill. The PCC plant uses flue gas from the lime sludge reburning kiln at the paper mill. The flue gas originates from heavy and light oil, and has a CO_2 concentration of roughly 20-25%. About 75% of the CO_2 in the flue gas is utilized, which means that the theoretical minimum requirements for producing 130,000 t/a PCC would be a flue gas stream containing 76,000 t/a CO_2. When the lime kiln is not operational, flue gas from the recovery boiler is used as well as liquid CO_2. The plant uses the common process for carbonation of hydrated lime (described in the Introduction), and uses calcined limestone. The lime is imported by ship tankers to Veitsiluoto harbour. The amount of waste water from the plant is small and treated in the paper mill's water treatment plant. The PCC is currently pumped to the paper mill and stored in tanks at as a slurry (18-20 wt-% solids).

3.1.2 PCC requirements

Filler pigments are used in paper, as they improve certain paper properties, such as opacity, brightness, dimension stability and printability, and they are cheaper to use than pulp (Vapa, 2012). Except for PCC also clay, ground calcium carbonate (GCC) and titanium oxide (TiO_2) can be used. PCC is gaining popularity as it gives a high brightness, opacity and bulk. The particle structure can be tailored to suit specific paper qualities. The particle size distribution of PCC is narrow and the abrasiveness is quite low. The PCC used in Veitsiluoto paper mill has preferably a scalenohedral particle shape, median diameter of a few micrometers, and brightness higher than 95%.

3.1.3 CO_2 sources

The paper plant at Veitsiluoto has several sources of CO_2-containing flue gases that could be suitable for use with a new PCC plant (EMV, 2004). The most promising are:

- Black liquor boiler (187 MW)
- Solid fuel boiler (246 MW)
- Lime sludge reburning kiln (26 MW, flue gases already used by the current PCC mill)

3.2 Tornio works steel mill

Tornio Works is one of the largest stainless steel mills in the world. Its main products are cold rolled and hot rolled stainless steel coils and sheets. The steel plant uses lime and dolomite as slag formers for removing impurities at various stages during steel production, causing about 300,000 t of steel slag annually (Figure 1).

Different process stages produce different types of slag. Tapojärvi Oy processes the slags from Tornio Works on-site further into products that can be utilised, for instance, in road construction. Argon-oxygen decarburization (AOD) slag and ladle slag have very high Ca-concentrations (40-60 %), making these slags potential raw materials for PCC production (Table 1). A portion of these slags (18 kt/a) is already in internal use for neutralisation purposes (Figure 2). Otherwise, AOD and ladle slag is very little utilized, since it is considered too soft for road construction purposes. While electric arc furnace (EAF) slag and chrome converter (CRK) slag have relatively high Ca-concentrations, also impurities are easily extracted, making these more difficult raw materials for PCC production.

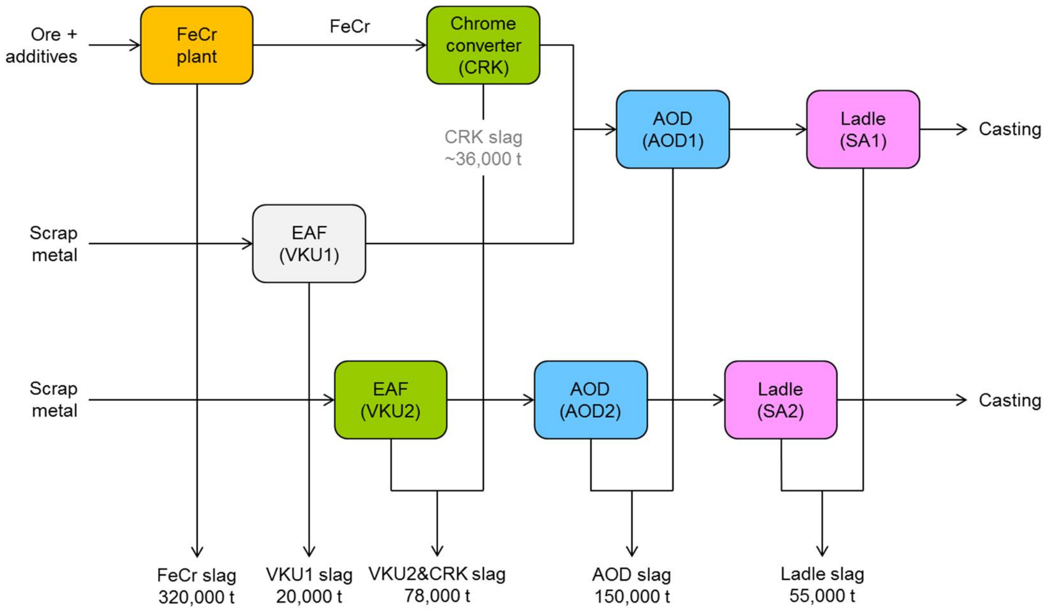

Figure 1. Current slag production at Tornio works (numbers based on the annual slag production in 2011).

Table 1. Chemical composition of the steel slags at Tornio works (Maikkula, 2009; units wt-%).

	CaO	MgO	Al_2O_3	SiO_2	Fe_2O_3	Cr_2O_3	TiO_2	MnO	Mo	F
FeCr	1.4	23	28	28	6.5	13				
CRK	39	17	3.5	36	0.5	1.4	1.9	0.3		
VKU1	40	11	5.8	26	1.6	7.6	3.9	2.3	0.04	
VKU2	43	5.6	7.1	27	0.9	2.2	7.6	1.4		
AOD1	56	8.3	1.2	30	0.3	0.5	0.7	0.4	0.04	
AOD2	57	7.5	1.5	29	0.2	0.5	1.5	0.3	0.04	
SA1/2	60	7.1	2.0	26	0.5	0.2	0.9			5.6

The ferrochrome production plant produces also slag, ferrochrome slag (320,000 t/a). However, ferrochrome slag has a very low Ca-content (<2%) and has therefore no practical potential for PCC production. Ferrochrome slag is also currently utilised successfully in construction projects (e.g. road construction instead of stone aggregate).

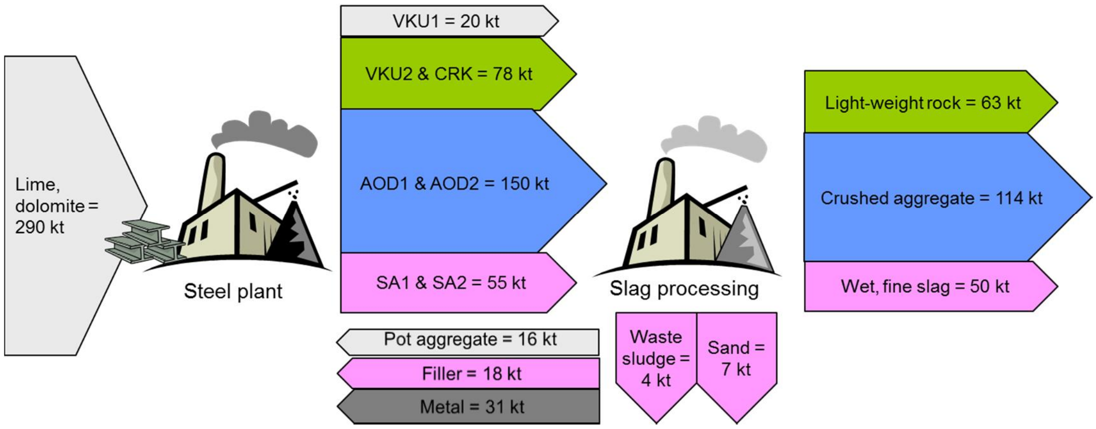

Figure 2. Slag processing and use at Tornio works in 2011.

Considering the current utilisation of slag, most of the AOD and ladle slag, in total about 170,000 t/a, is readily available for PCC production purposes. However, new investments are currently being made that will double the ferrochrome output of the steel mill. Also, as a part of the company strategy the steel production from the plant will be increased. Current facilities allow for a 40% increase in steel production, which directly leads to a similar increase for the steel slag output.

3.2.1 CO_2 sources

The direct fossil CO_2 emissions from Tornio Works were 590,000 t in 2011. There are several CO_2 emission sources at the steel mill, of which at least the boiler plant is likely to be suitable for PCC production (Figure 3).

However, SMA's lime kiln, producing burnt lime from limestone, is located at the same industrial site. The lime kiln emits up to 168,000 t CO_2/a (typically 100,000 – 140,000 t CO_2/a) and the flue gases have a concentration of about 22% CO_2. The lime kiln is a shaft kiln design, resulting in the flue gases having a very low sulphur content and the flue gases a relatively low temperature. This makes the lime kiln the most potential CO_2 source at Tornio Works for PCC production.

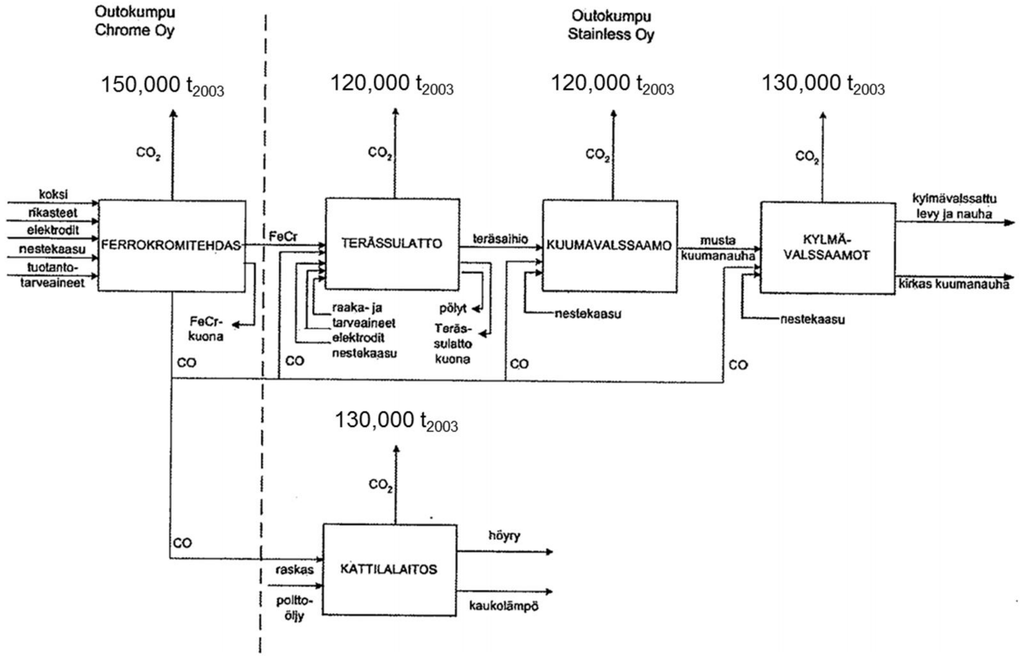

Figure 3. CO_2 emission sources at Tornio Works (EMV, 2005).

3.3 New PCC production concept from slag

In the new PCC production concept, calcium is extracted from steelmaking slag using ammonium salt solutions, from which PCC can subsequently be precipitated using CO_2 (Teir et al., 2009). As the PCC precipitates the solvent is regenerated, and can be returned to the extraction reactor for reuse in the process (Figure 4).

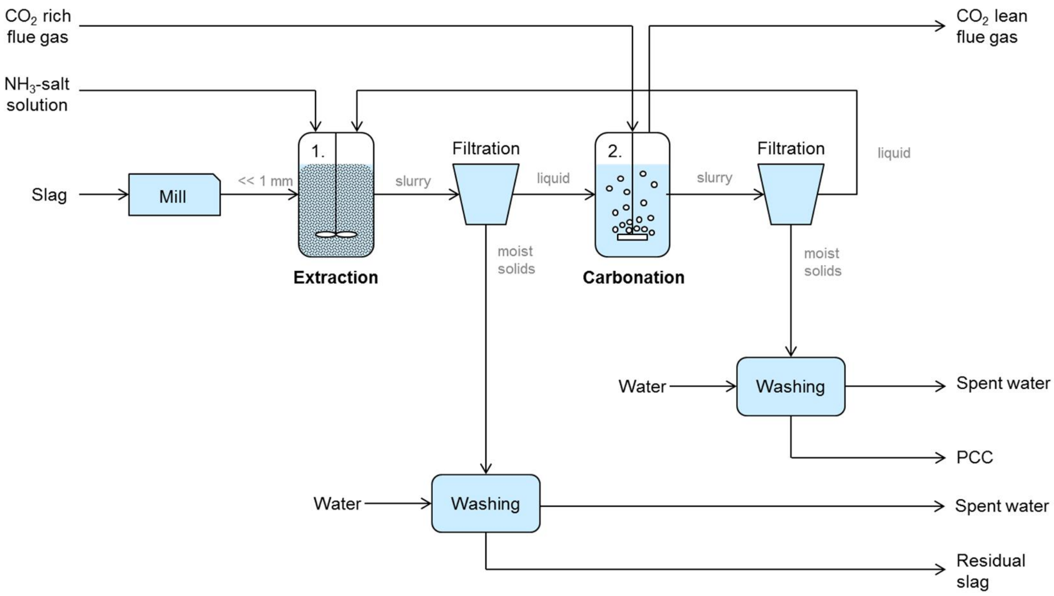

Figure 4. Process concept for producing PCC from steelmaking slag.

There are several benefits from this new process concept (in comparison with conventional PCC production processes):

- No virgin raw materials are needed. Also, slag is much cheaper than lime, which is required by conventional PCC plants.
- Lime is produced by calcining limestone, which emits more CO_2 than is bound in conventional PCC plant. The new PCC production process has negative net CO_2 emissions, since PCC is produced from a carbonate-free material (slag).
- Emissions from transportation should be minimal, since slag is produced close to the paper mill. Lime for existing PCC plants is imported from abroad in tanker ships.

However, there are also a few drawbacks of the new process:

- The PCC precipitates in the ammonium solvent, and needs extensive filtering and washing in order to remove the ammonium solvent from the product and recover as much as possible of the solvent.
- Ammonia vapours form in the process and some of these escape with the flue gas used in the carbonation reactor. Therefore, it is possible that a flue gas scrubber is needed to remove the ammonia vapours from the flue gas.
- After calcium has been extracted from the slag, a residual slag is formed, which must be separated from the solvent. The residual slag is likely to require washing to remove solvent remnants. Also, the usability and properties of the residual slag is rather unknown.

In order to produce 130,000 t/a PCC using AOD and ladle slag at least 250,000 t/a slag would be needed (calculated assuming an average concentration of 58% CaO in slag and 50% extraction conversion). The current annual slag production is not enough for covering this, but the planned increase in steel production (40% increase) would increase the net slag output to 240,000 t/a. The missing 10,000 t/a could possibly be covered for by using stockpiled slag.

4 Screening of case alternatives

Next, various alternatives for implementing the new PCC process for slags at the Veitsiluoto – Tornio area were identified. Four main alternatives were identified:

- Retrofit of existing PCC plant at Veitsiluoto
- New PCC plant at Veitsiluoto
- New PCC plant at Tornio
- Split process – plants at Tornio and Veitsiluoto

4.1 Retrofit of existing PCC plant at Veitsiluoto

The seemingly simplest solution would be to retrofit the existing plant at Veitsiluoto. However, the PCC process for slag is very different from the conventional (different raw material, mass flows & volumes, washing requirements and solvent recycling), and building a new plant was considered a cheaper option than retrofitting the current plant. Therefore, the option to retrofit the existing PCC plant at Veitsiluoto was not further considered in this project.

4.2 New PCC plant at Veitsiluoto

One option is to build a new PCC plant at Veitsiluoto. This allows PCC to be produced on-site for Veitsiluoto paper mill, using CO_2 in the flue gases from the mill. However, 250,000 t/a slag has then to be transported from Tornio Works to Veitsiluoto and residual slag (~190,000 t dry weight, but will be wet after processing) is likely needed to be transported back to Tornio, since the slag processing facility is currently located at Tornio Works industrial site.

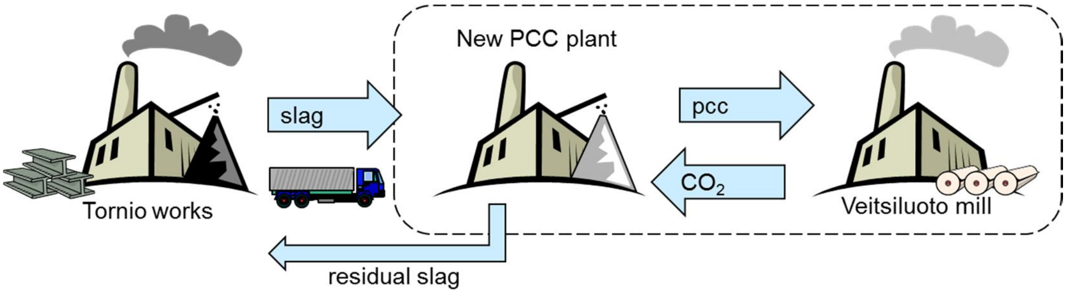

Figure 5. New PCC plant at Veitsiluoto – main material streams.

4.3 New PCC plant at Tornio

Another option is to build a new PCC plant at Tornio Works industrial site. This allows slags to be processed on-site, while PCC (130,000 t/a, dry weight) is transported to Veitsiluoto mill. Flue gases from the lime kiln at the Tornio site would be used for providing CO_2 for the PCC plant.

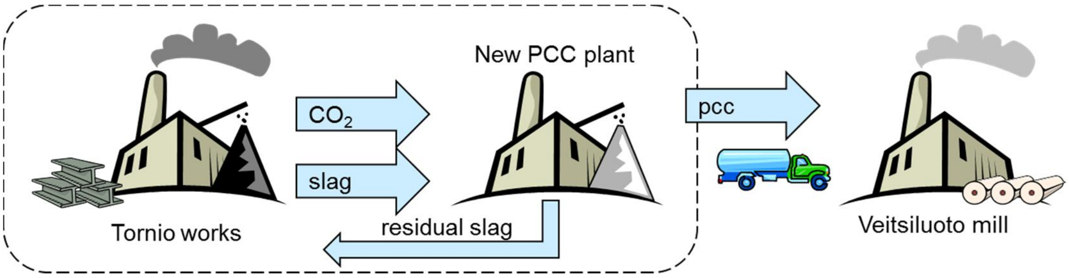

Figure 6. New PCC plant at Tornio – main material streams

4.4 Split process – plants at Tornio and Veitsiluoto

The new process concept allows for a third implementation alternative: splitting the PCC plant into two – one plant performing the extraction part and another plant performing the carbonation part. The main advantage of this case is that slag can be processed on-site at Tornio Works, while PCC can be produced on-site at Veitsiluoto mill. The main disadvantage is the transportation requirements: 2,500,000 t/a Ca-rich ammonium solvent needs to be transported from Tornio to Veitsiluoto and roughly the same amount of Ca-lean solvent back for reuse.

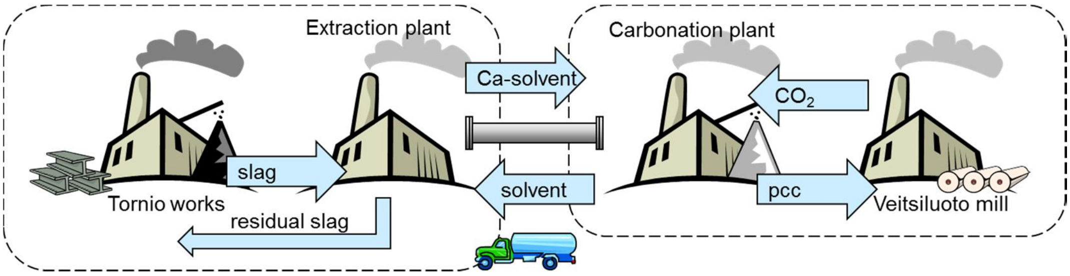

Figure 7. Split process – main material streams.

4.5 Logistics

As the case alternatives identified above shows the main difference is in the amount of material and type of material transported between the sites. Therefore, the costs from handling and transportation determines in practice which of the cases above can be selected for further study.

4.5.1 Handling and transportation of material

Different materials are transported depending on how the concept is implemented. Slag can be transported, either dry (crushed or milled) or wet (residual slag). PCC can be transported either dry or as slurry. In the split plant – case the ammonium salt solvent is transported. Also, intermediate storage facilities will be needed at both sites for storing either slag, PCC or the Ca-solvent. In addition, terminals need to be modified or constructed in order to be able to handle the loading and unloading of material.

4.5.1.1 Transportation and handling of slag

The PCC case option presented in Section 4.2 requires transportation of slag and residual slag between the two industrial sites. Coarse slag would be easy and cheap to transport and handle as a bulk rock material. Transport options are for instance dump trucks, bulk train wagons, or barges used for sand transportation. However, slag contains also a fine portion (20-40% < 1 mm particle size), which would cause a dust problem. Also, the residual slag is likely to be wet and silting. Therefore, sealed containers are a better alternative, since these could be used for transporting both fresh slag and residual slag. However, in order to maximize the calcium extraction slag needs to be dry-cooled and milled, which produces mostly fine particles (< 1 mm in size). For this, pneumatic transportation would be the most ideal solution. But pneumatic transportation is not possible to use for residual slag, unless the residual slag is dried. Therefore, the transportation of slag is probably the most complicated one, logistic-wise.

4.5.1.2 Transportation and handling of PCC

The PCC case option presented in Section 4.3 requires transportation of PCC from Tornio to Veitsiluoto. Transportation of PCC slurry can be performed by transportation in tanks both on rail and road. However, ordinary tanker ships built for liquids cannot handle PCC slurry, since it has a higher density than liquids. Tanker ships transporting PCC have custom built reinforced tops. In theory, lean PCC slurries could be transported using pipelines as well, but it is likely that the pipeline would require regular maintenance to avoid clogging from build-up of solids. However, transporting PCC as a slurry means also that water is transported, which more than doubles the amount of material that is transported.

Pneumatic transportation could also be an option to use for dry PCC transportation. Dry PCC would also require less storage space and could be stored for a longer period of time without losing pH stability. However, calcium carbonate powders have a low bulk density, 0.4-0.8 tonnes per cubic meter (Tegethoff et al., 2001). Therefore calcium carbonate powders need still a relatively large storage and transport volume. Also, pneumatic conveying systems are relatively expensive in terms of energy use. Therefore, high solids slurries are favoured.

4.5.1.3 Transportation and handling of ammonium salt solvent

The PCC case option presented in Section 4.4 requires transportation of the ammonium salt solvent between the industrial sites. The ammonium salt solvent is a water-based, clear liquid, with the Ca-rich solvent having a pH of about 11 and the Ca-lean a pH of about 8. This could be transported in tanks or pipeline. Transporting the ammonium solvent requires the highest amount of mass to be transported and depends on what solid-to-liquid ratio is used in the extraction reactor. It is possible that the solid-to-liquid ratio could be doubled, but then the extraction efficiency is likely to be lower or at least require longer residence time in the extraction reactor (several hours). Therefore, a solid-to-liquid ratio of 0.1 is a quite realistic approximate.

4.5.2 Means of transportation

Except for handling of material different means of transportation can be selected. Tornio works and Veitsiluoto mill are located 40 km apart by road (Figure 8) and are also connected by railroad. Both industrial sites are located on the shoreline and each has its own harbour. Therefore, the main transportation alternatives are truck, train and ship.

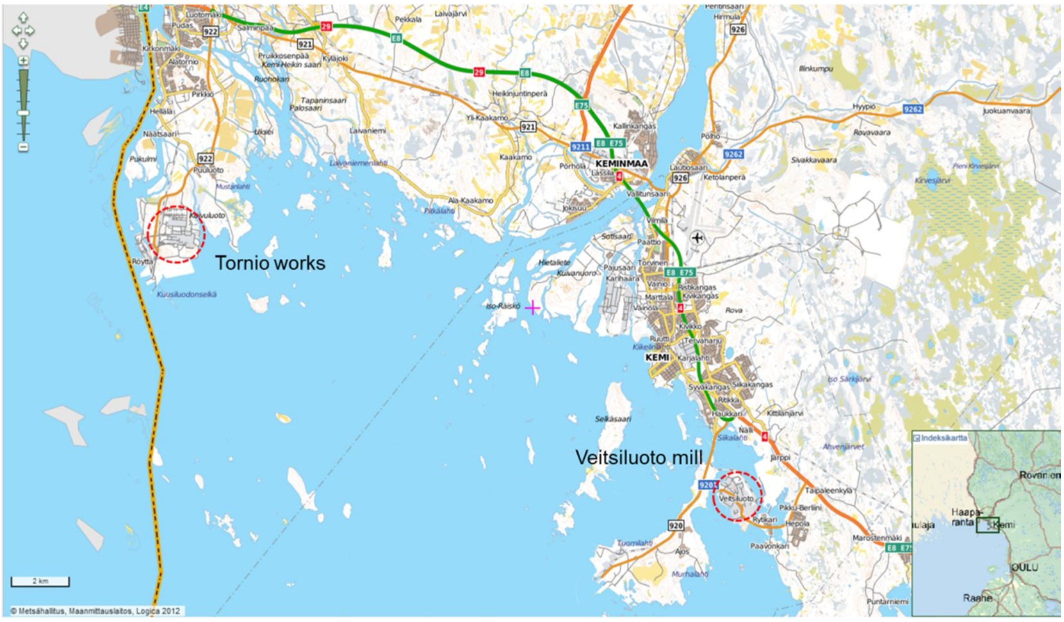

Figure 8. Map of the location of Tornio works and Veitsiluoto mill.

4.5.2.1 Truck transportation

Truck transportation is a flexible alternative, but there would be fairly large operations from continuous loading/unloading: 9-18 truck loads a day, 3-7 trucks & drivers needed (for the single plant cases). The costs for truck transportation was assessed together with Jarkko Lehtinen, VTT. The assumptions are listed in Table 2. Extra operational costs for loading or unloading were not included, neither investment costs for terminal expansions or intermediate storage silos/tankers.

Table 2. Assumptions used in truck transportation calculations.

Rental for truck and driver	150,000 – 250,000	€/year
Driver working hours	8	h/day
Truck capacity	40	t
Loading/unloading time	30	min
Driving time (one way)	40	min

4.5.2.2 Train transportation

Railroad transportation is also one feasible solution. The railroad transportation would also be ordered as a service and the costs were therefore assessed by asking for preliminary tenders from both VR and Proxion. Tank wagons were suggested for use for dry PCC, slurry or ammonium salt solvent. Detachable containers were suggested for in the case of transportation of slag/residual slag. One train load is about 400-1000 t, two return trips can be performed in 24 h, loading is assumed to take 4 h. Service contract time spans from 5 years and upwards were preferred. Investment costs for terminal expansions and temporary storage silos were not included.

4.5.2.3 Ship transportation

Ship transportation was assessed by discussion with Arto Nokelainen (VTT) as well as with shipbrokers ESL Shipping and Helsinki Chartering. Ship transportation was not seen as an economic option for the cases under assessment here. Since the distance is very short for ship transportation, most costs would arise from port and pilot fees, weekend stops, and loading/unloading. Unpredictable ice conditions could also cause serious delay, requiring intermediate storage capacity at both plants that could cover for over 1 month of transportation halt. Container usage was considered unfeasible. Also, PCC tanker ships are specialised tankers that would require large investments. Some form of truck transportation would still be needed to transport the cargo between harbour and plant. Pusher-barges for uncovered solid bulk cargo, such as sand (in this case coarse slag), was considered the only viable solution. Barge capacity is up to 15,000 t per barge. Although ship transportation was considered to be a very unlikely solution, cost calculations were performed assuming rental of existing ship (barge or tank ship: 4.5 euro/t per return trip), including loading/unloading costs using Kemi harbour prices: 3 euro/t (Sjölund, 2012). Operational costs for loading, transport, and unloading between plant and harbor (trucks) were not included. Neither were investment costs (terminal expansions, temporary storage silos).

4.5.2.4 Pipeline transportation

In the PCC case option presented in Section 4.4 pipeline transportation is the most likely form of transportation, due to the high volume flows involved. For this, two pipelines are required: one for bringing the Ca-rich solvent from Tornio to Veitsiluoto and one for returning the Ca-lean solvent to Tornio from Veitsiluoto. For a pipeline, the operational costs (mainly pumping power) are expected to be very low in comparison to the investment costs. Cost estimates for pipeline construction and assembly was acquired from KWH pipe and Uponor. Although the material costs for the pipelines are relatively low, the installation costs are very high (Table 3). The high installation costs are due to a challenging environment: in order to prevent frosting in winter time, the pipeline must be installed 2 m underground (Kalliokoski, 2012). For this, soil test drilling would be required. There are also several rivers in the transportation path, which would require the pipe to be installed on the bottom of the river. In addition, there would be costs due to acquisition of land rights, but these have not been taken into account. In order to be able to compare the transportation costs with those for the other means for transportation (consisting mainly of operational costs), the annuity for the investment was calculated using 5% rate on the loan, and 20 years of payback time.

Table 3. Cost for pipeline construction.

PE pressure pipe PN10, DN 315	40 – 80	€/m
Pumping stations (15-20 stations required)	2000	€/station
Installation costs (estimate)	1000 – 2000	€/m

4.6 Results and case selection

The results from the transportation cost assessment are summarized in Table 4. To put the transportation costs into perspective, the costs are compared to the total production cost for PCC using the conventional process, which is coarsely about 100 €/t. The cost for lime in a conventional PCC plant is typically about half the production costs. Therefore, the transportation costs need to be well below this in order for the new PCC process to be feasible.

As can be seen from the table, the transportation costs for the split plant –case (Section 4.4) are considerably higher than the other two cases (that require transportation of slag or PCC). Therefore, the split plant –case can be ruled out. In addition, the calculations verified that ship transportation is too costly and can be ruled out.

Considering whether to transport slag or PCC, the results show that transportation of PCC is cheaper than transportation of slag, even though the transportation vessels return empty. Even the transportation of slurry containing 50 wt-% PCC is slightly cheaper than transportation of slag/residual slag. Considering additionally the additional logistics difficulties of having to handle both dry, fine slag solids and wet residual slag in containers (see Section 4.5.1.1), the placement of a new PCC plant at Tornio seems to be the best alternative. This case was therefore selected for the feasibility study.

Table 4. Results from the transportation cost assessment.

	Slag		PCC		Ca-solution
	crushed	milled	dry powder	slurry (50%)	
Truck	8-14	?	3-5	6-10	80-130
Train	10-29	?	8-16	13-26	52
Ship	31-33	"Not feasible"	"Not feasible"	>20	75
Pipe	N/A	N/A	N/A	?	26-53

Note 1: Although the cost for transportation of milled slag/residual slag was not assessed in detail, they are expected to be higher than those for crushed slag.
Note 2: Although the feasibility of transporting a PCC slurry in pipeline was not assessed, the installation cost would be similar to that of the Ca-solution.

5 Feasibility of the selected case

In order to determine whether or not the new PCC process concept studied here is a competitive alternative to the existing PCC supply at Veitsiluoto, a coarse feasibility study of the most promising case was performed. The selected case studied here is new a plant producing PCC from slag, located at Tornio works industrial site, and supplying PCC for use at Veitsiluoto mill. The feasibility of the case was calculated on a coarse plant component level using Excel. Process parameters from experimental results have been used where available.

Very recently, a model of the new PCC production process from slag was made and the process economics for a generic case preliminarily assessed (Kotiranta, 2012). Information from that report has been applied to this case where applicable and where experimental data has not been available. Also, solutions differing from Kotiranta are highlighted and motivated. In order to ease the comparison of results, the layout of Sections 5.1 to 5.3 are identical to Kotiranta (2012).

5.1 Description of process calculations

In this chapter, the process calculations are explained and calculations for each process component described. The flow sheet of the process is laid out in Figure 9. The extraction, carbonation and filtration will be operating as batch processes, since the particle shape and size of the produced PCC is more easily controlled in a batch process. The solvent used in the calculations was ammonium chloride, since it is the cheapest alternative, but also ammonium nitrate and ammonium acetate perform similarly.

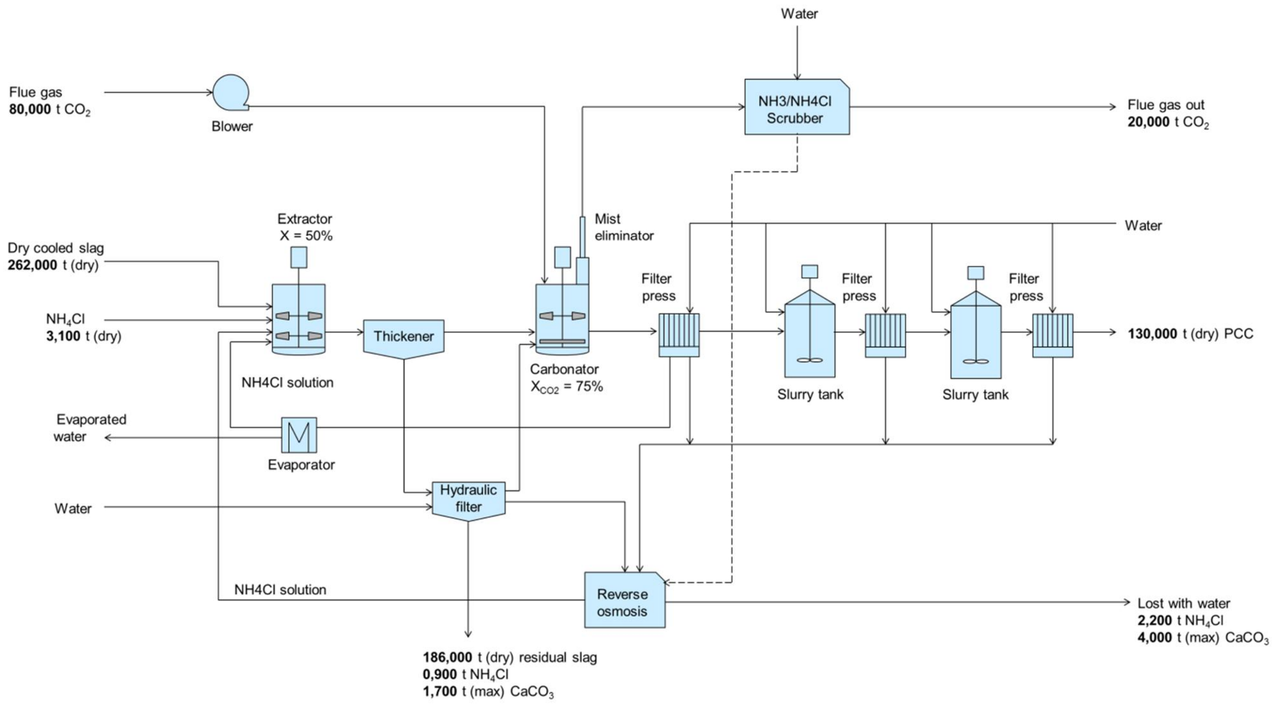

Figure 9. Flow sheet of the case study on the PCC production process for slag (mass flow unit: tonne per year).

5.1.1 Table of assumptions and input data

The input data and assumptions used in the calculations have been summarized in Table 5.

Table 5. Summary of input data and assumptions used in the calculations.

Parameter / **equipment**	Value		Comment
Extractor			
Slag composition	58	% CaO	Average
Solvent strength (NH_4Cl)	4	M	
	214	g/L	
Extraction efficiency	50	%	Rinne (2008)
Solid-to-liquid ratio	0.1		
Thickener & hydraulic filter			Treated in the calculation as a single unit
Cake moisture before washing	10	%	Kotiranta (2012), Pakarinen (2012)
Washing efficiency	80	%	(i.e. 20% of impurities remain)
Carbonator			
Temperature	25	°C	
CO_2 utilisation	75	%	of feed (assumption)
Vapor losses	0.5	%	Eloneva et al. (2011)
PCC production (net)	130,000	t/a	
Cooling requirements	3.9	MW	Kotiranta (2012)
Filter presses and PCC washing			
Filter units per washing stage	8	units	Kotiranta (2012)
Washing stages needed	3	stages	Kotiranta (2012)
Moisture of filter cake	20	%	Kotiranta (2012)
Washing efficiency	80	%	Kotiranta (2012)
Flue gas feed			
CO_2 concentration	22	%	Pakarinen (2012)
Flue gas temperature at carbonator	25	°C	
Flue gas temperature at entrance	80 – 120	°C	Pakarinen (2012)
Scrubber efficiency	99	%	
Reverse osmosis unit			
Concentration of recovered solution	214	g/L	
Recovery efficiency	80	%	
Evaporator			
Need for water removal	32.4	t/h	Kotiranta (2012)
Steam consumption	10.8	t/h	Kotiranta (2012)

5.1.2 Feed material

It is assumed that dry-cooled AOD and ladle slag is supplied to the PCC plant from the on-site slag processing facility. The cost for pre-processing of the slag (dry-cooling and milling) is therefore not included in the case study. Since previous work has shown that extraction of calcium from AOD and ladle slag is very selective, a slag composition approximate of 58 % CaO is used for the calculations. With the assumptions used in these calculations, 262,000 t/a slag is required for producing 130,000 t/a PCC. The number is slightly higher than presented in earlier chapters, since the calculations have assumed that a small part of the leached calcium is lost with washing of residual slag and PCC.

5.1.3 Extractor

Previous experimental work has shown that it is possible to extract 50% of the calcium in AOD slag (Rinne, 2008). The extracted calcium ions is carried with the ammonium solution to the carbonation reactor, while the residual slag is separated using a thickener and a hydraulic filter. The residue is washed for removing ammonium solvent remnants and the ammonium is recovered from the spent water from the reverse osmosis unit.

5.1.4 Carbonator

The PCC is precipitated in the carbonator, by bubbling flue gas through the calcium-rich ammonium salt solution. It is assumed, that 75% of the CO_2 in the flue gas stream reacts and form carbonate, while the remaining 25% exits with the flue gas stream. 0.5 % of the ammonium salt solvent is lost as vapours with the flue gas. Since the carbonation reaction is exothermic, the temperature rises unless the reactor is cooled. In order to maintain the reactor at 25 °C the reactor needs 4.0 MW of cooling. Note: the required precipitation parameters have not yet been mapped. It is possible that precipitation needs to take place at another temperature in the ammonium salt solution in order to form scalenohedral PCC.

5.1.5 PCC filtration and washing

The dimensioning of the PCC filters are based on filtration requirements for a PCC plant case producing 100,000 t/a PCC (6 units required) and assumptions related to the washing requirements (Kotiranta, 2012). It is not certain how high concentration of NH_4Cl can be allowed in the PCC, but it is likely that a very low concentration limit is necessary. By mixing the filter cakes with water and refiltering, twice, the ammonium chloride content can be brought down to 20 ppm. Therefore, two steps of slurrying and refiltering are added. After filtration the moisture of the filter cake is 20%, i.e. the solid contents is 80%. According to Skuse (2002) it is normal to prepare calcium carbonate slurries at 78% solids. However, in this case it is assumed that the solids concentration is kept at 50% after the final filtration stage, since the PCC will be applied as a slurry containing only 20% solids.

5.1.6 Flue gas supply

The flue gas would be supplied from the lime kiln at the site, emitting 100,000 – 140,000 t CO_2 per year. The flue gases have a concentration of about 22% CO_2. The lime kiln is a shaft kiln design, resulting in the flue gases having a very low sulphur content. After the particle filter the flue gases have a temperature of about 80 – 120 °C (Pakarinen, 2012). A pipeline would need to be constructed to transport the flue gases to the site for new PCC plant, assumed to be located at a distance of about 600 – 1 200 m from the lime kiln. This distance would be enough to bring the flue gas temperature down close to ambient temperature. A blower is likely to be needed to avoid backpressure towards the kiln.

5.1.7 NH_3 recovery

Since 0.5 % of the ammonium solvent (or 3,000 t/a NH_4Cl) is lost with the flue gas, a flue gas scrubber is needed to reduce the ammonia emission down to allowed emission levels (<100 mg/Nm^3). Kotiranta (2012) assumes that the emissions are mainly gaseous ammonia and calculates the option for using a HCl scrubber. While this is likely to be an effective solution, HCl is highly corrosive and chloride emissions are possible. Water is also efficient for scrubbing ammonia emissions and a scrubbing efficiency of 99% is achievable. Scrubbing with HCl would produce ammonia chloride that could be directly led to the extraction reactor. Scrubbing with water produced water with a small ammonia chloride content that needs to be led to the reverse osmosis unit for purification. It is possible that this water could replace some of the water used in the first PCC filtration stages or for washing the residual slag.

5.1.8 Evaporation

Kotiranta (2012) used evaporation for managing the water balance in the system. Although it should be possible to manage the water balance without using evaporation, the water balance was not calculated in this study. Therefore, an evaporator is used and the evaporation requirements have been scaled up linearly from Kotiranta’s calculations. According to these assumptions, 25.0 t/h water needs to be removed, which would require 8.3 t/h steam.

5.1.9 Reverse osmosis unit

Since the process produces a lot of spent washing water that contain low concentrations of ammonium salt, a reverse osmosis unit is needed for concentrating the ammonium salt to purify the spent washing water and recover as much ammonium salt as possible. However, as Kotiranta (2012) notes it is not certain that a reverse osmosis unit would be suitable for this process, because the membranes used in these units are very sensitive to clogging. It was assumed that the concentration of the ammonium salt can be brought back to that of the fresh solvent.

5.2 Mass balance of water

The mass balance for the water usage was not calculated. Since a reverse osmosis unit is used for purification of the water, it is expected that a large part of the spent water can be reused in the process. The use of water is expected to be similar to that of Kotiranta (2012), but the main difference is the use of water in the ammonia scrubber, which adds to the water circulation in the system.

5.3 Costs and investment payback

The investment costs and commodity costs were evaluated on a very coarse level and the results are only an approximate of the level of cost for the process. The commodity costs give an approximation of the operational cost minus the labour cost and maintenance costs. The investment costs have been estimated only for the main equipment of the process and exclude costs for intermediate storage and handling of raw materials and products. Unfortunately, no investment and operational costs for conventional PCC plants were available for head-to-head comparison.

5.3.1 Investment costs

The investment costs for the equipment were taken from Kotiranta (2012). Kotiranta's cost estimates are for a continuous process and the costs are expected to be slightly higher for a batch process, due to the need for larger volumes and intermediate storages. However, a plant with a higher production capacity has typically a lower unit cost. Therefore, the costs listed in Kotiranta (2012) were scaled linearly according to the production capacity of the plant.

The cost for site construction, pumps, piping, automation, buildings etc. and other installation costs were approximated by using a factor of 3 for the main equipment and a factor of 2 for the pressure filters[1]. The reverse osmosis unit and evaporator are typically purchased as complete operational units, and therefore a cost factor of 1 was used for these.

Table 6. Investment costs for the base case.

Equipment	Amount	Unit cost	Investment factor	Total cost
Filters	25	0.93	2	47 M€
Reactors			3	10.1 M€
Thickener			3	2.5 M€
Flue gas scrubber			3	2.5 M€
Reverse osmosis			1	3.7 M€
Evaporator			1	3.9 M€
Flue gas supply			1	1.2 M€
Flue gas cooler			3	5.1 M€
Total investment				75.7 M€

The investment cost for the flue gas supply was calculated in more detail based on actual unit costs and an estimate for labour costs (Pakarinen, 2012). The calculations were based on constructing a flue gas channel of 1200 mm diameter with a weight of 200 kg/m. A flue gas blower is included in the cost, since it is likely to be required to minimize the risk for pressure build up in the lime kiln. It was assumed that the new PCC plant would be located next to the current slag processing facility, in which case a pipeline length of 1200 m would be required. The costs include installation of the pipeline on ground level, connection and pipe branching at the lime kiln, blower station, power supply to blower station and instrumentation (mass flow and temperature).

[1] Kotiranta (2012) used a factor of 3 for the pressure filters, although a factor of 2 should be enough, since the filters are semi-complete operational units.

The investment costs are presented in Table 6. The filter presses are the most expensive equipment of the process. These make up a significant share of the total investment costs.

5.3.2 Operational costs

The operational costs have been coarsely estimated by calculating the main commodity costs and including estimates for the other operational costs, such as electricity consumption for pumps, blowers and stirrers, personnel costs and maintenance costs. The cost estimate for electricity use, maintenance and personnel is based on industrial experience with slag processing facilities (Pakarinen, 2013). The transport unit cost is a mean value of the results, presented in Table 4, for transportation of PCC slurry (50% solids) by truck. Rough average values for CO_2 emission allowances and the produced PCC has been included in the balance to estimate the annual revenue.

The operational costs are presented in Table 7. As can be seen, the largest single cost is the need for evaporation of excess water. This is responsible for 27% of the total operational costs. The second largest cost is the assumed cost for slag.

The main difference in unit cost assumptions used in this study and that of Kotiranta (2012) is for the NH_4Cl cost – costs reported in public literature was under 200 €/t, so a cost of 200 €/t NH_4Cl this was used in this study. Kotiranta (2012) used a price of 650 €/t NH_4Cl, which would lower the annual revenue to 4.86 M€/a. Otherwise, the unit costs have been kept similar to facilitate comparison between the studies.

Table 7.Operational costs for the base case.

Cost/revenue	MW	t/a	€/t, €/MWh	M€/a
NH_4Cl make-up		3075	200	-0.62
Reverse osmosis unit (1 €/t input)		585903	1	-0.59
Carbonator reactor cooler (at 25 C)	3.9		20	-0.61
Evaporation (steam mass flow)		72949	30	-2.01
Electricity use (stirrer, pumps, filters)	0.5		60	-0.27
Slag		262208	5	-1.31
Total commodity costs				-5.40
Maintenance (coarse est. 2-2.5 €/t PCC)		130000	2.25	-0.29
Personnel costs (three-shift, weekend stop, 4 persons/shift)				-0.75
Transportation costs (6-10 €/t PCC)		130000	8	-1.04
Total operational costs				-7.48
Value of CO_2 emission allowances		59660.7	10	0.60
Value of produced PCC		130000	100	13.0
Annual revenue				6.11

5.3.3 Investment payback

The investment payback was calculated for a loan based on constant payments and a constant interest rate of 5%. In order to account for uncertainties in the commodity costs, the investment payback was also calculated for lower annual revenues. The results from the calculations can be found in Table 8. According to the calculations with the estimated revenue above (6.24 M€/a) the payback time for the investment would be 20 years. The table also shows an alternative payback time for a lower expected revenue (5.0 M€/a).

Table 8. Investment payback calculated for an interest rate of 5%

Revenue (M€/a)	Total investment (M€)	Payback (years)
6.11	75.7	20
5.0	75.7	29

5.4 Sensitivity analysis

5.4.1 Alternative placement of PCC plant

An alternative placement for the PCC plant was also calculated. In this alternative, the PCC plant would be located 600 m from the lime kiln, in which case the pipeline would only be 600 m long. This would reduce the investment cost for the pipeline and blower assembly to 860,000 euro, but it would require transportation of slag to the PCC plant, which was estimated to cost roughly 1 euro/t slag. The total investment costs would be reduced to 75.3 M€, but the annual revenue would also be reduced to 5.85 M€/a.

5.4.2 Alternative PCC requirement

All costs and assumptions in this report has been related to the PCC requirement of 130,000 t/a. In order to assess the impact of the scale on the costs, the case was recalculated for a production amount of 90,000 t PCC per year. In this case the current slag availability (170,000 t/a) is almost enough to meet the requirements (182,000 t/a). The requirements could be met if part of the internal slag use (currently at 18,000 t/a) could be diverted to slag production. Alternatively, the production requirements could be met using the current slag availability if the extraction efficiency was increased from 50% to 54%. For the sake of easing the comparison with the base case, it is assumed in the calculations that 182,000 t/a slag is available for the PCC process. The other process mass flows are shown in (Figure 10).

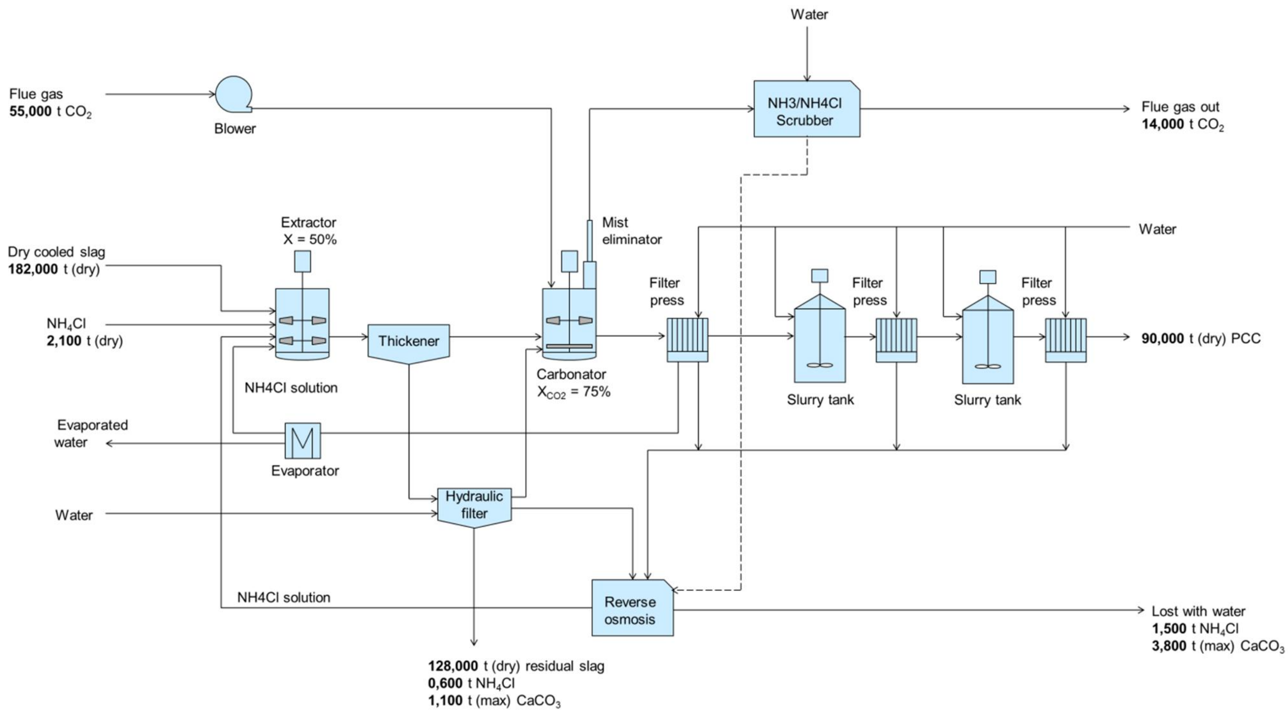

Figure 10. Flow sheet of the process with mass flows calculated by assuming an annual production of 90,000 t PCC.

The investment costs for the filters were recalculated using the available pressure filter prices, while the other investment costs have simply been scaled linearly (Table 9).

Table 9. Investment costs for the alternative case.

Equipment	amount	unit cost	factor	total cost	
Pressure filters	19	0.93	2	35	M€
Reactors			3	7.0	M€
Thickener			3	1.8	M€
Flue gas scrubber			3	1.8	M€
Reverse osmosis			1	2.6	M€
Evaporator			1	2.7	M€
Flue gas supply			1	0.8	M€
Flue gas cooler			3	3.5	M€
Total investment				55.6	M€

The costs for NH4Cl make-up, reverse osmosis unit, and slag have been recalculated according to commodity use, while the other commodity costs have been scaled linearly. Since no changes have been made to the process, it is assumed that the same amount of personnel is needed as in the base case. For this case, a higher solids content (65%) of the PCC is desired. The transportation costs have therefore been recalculated for this solids content. The largest change in comparison to the base case is therefore also the cost for the PCC transportation (Table 10). Still, the change is relatively small and therefore the investment payback with an interest rate of 5% is in this alternative case 21 year, which is close to the base case. The slightly higher payback time is due to the personnel cost, which is higher per tonne produced PCC in this alternative case, since four persons per shift is also assumed here.

Table 10. Operational costs for the alternative case.

Cost/revenue	MW	t/a	€/t, €/MWh	M€/a
NH4Cl make-up		2129	200	-0.43
Reverse osmosis unit (1 €/t input)		405626	1	-0.41
Carbonator reactor cooler (at 25 C)	2.7		20	-0.43
Evaporation (steam mass flow)		50503	30	-1.39
Electricity use (stirrer, pumps, filters)	0.35		60	-0.19
Slag		181529	5	-0.91
Total commodity costs				-3.74
Maintenance (2-2.5 €/t PCC)		90000	2.25	-0.20
Personnel costs (three-shift, weekend stop, 4 persons/shift)				-0.75
Transportation costs (3-5€/t PCC)		90000	4	-0.36
Total operational costs				-5.05
Value of CO2 emission allowances		41304	10	0.41
Value of produced PCC		90000	100	9.0
Annual revenue				4.36

6 Conclusions and future work

The results from the work show that producing PCC from Tornio Works' steelmaking slags could cover for the PCC requirements at Veitsiluoto mill. Although the current annual slag production is not enough, the expected production expansion in the near future is expected to also increase the slag output just enough to match the demand for PCC.

Investigation of the various implementation options for the PCC production concept showed that the most feasible alternative in this particular case is to produce PCC at the Tornio Works industrial site, since it allows for processing of the fresh slag and residual slag on-site and minimize the requirements from transportation and handling. The new PCC plant would utilize the flue gases from the lime kiln at Tornio Works site, which are currently not being utilized for other purposes.

The feasibility analysis of the case studied showed that the investment costs are relatively high – 76 M€. With an estimated annual revenue of 6.1 M€, the payback time would be 20 years. A large part of the investment costs is due to the demanding filtration requirements. A conventional PCC plant requires only one stage of filtration, while the PCC process evaluated here would require three stages. However, the filtration performance is largely based on assumptions and real experimental data is missing. If one stage could be removed from the filtration system (i.e. 2 filtration stages instead of 3) the investment costs would be reduced to 60 M€, reducing the payback time to 14 years. On the other hand the filtration may be demanding on the filter equipment, due to the ammonium chloride-based solution in use, which may require more expensive materials in the filter.

The water balance in the system needs also to be optimised. The water usage in the current calculations has not been optimised, which makes evaporation of excess water necessary. The evaporation unit is currently responsible for 5% of the investment costs and evaporation causes 27% of the operational costs.

Finally, means for utilisation of the residual slag is also important and affects the feasibility of the PCC concept. These issues will be investigated during FP3 in CCSP.

References

Eloneva, S., Mannisto, P., Said, A., Fogelholm, C.-J. 2011. Ammonium salt-based steelmaking slag carbonation: Precipitation of $CaCO_3$ and ammonia losses assessment. Greenhouse Gases: Science and Technology, Volume 1, Issue 4, Pages 285–350. DOI: 10.1002/ghg.37.

EMV, 2004. Kasvihuonekaasujen päästölupa. Stora Enso Oyj, Veitsiluodon tehtaat. Energiamarkkinavirasto, Päätös Dnro 251/311/2004, 20.12.2004.

EMV, 2005. Kasvihuonekaasujen päästölupa. Outokumpu Chrome Oy ja Outokumpu Stainless Oy, Tornion tuotantolaitokset. Energiamarkkinavirasto, Päätös Dnro 336/311/2004, 11.02.2005.

Kalliokoski, A. 2012. Phone conversation with Arto Kalliokoski, Uponor, September 2012.

Kotiranta, T. 2012. PCC saostusprosessin mallinnus. Internal deliverable from the Carbon Capture and Storage Program (CCSP), Deliverable 502.

Maikkula, P. 2009. Selvitys ruostumattoman teräksen valmistuksessa muodostuvan kuonafraktion nykytilasta. Oulun Yliopisto, Prosessi- ja ympäristötekniikan osasto, Kandidaatintyö 86.

Pakarinen, J. 2012. Discussions with Jouko Pakarinen, Tapojärvi, May 2012-December 2012.

Pakarinen, J. 2013. Phone conversation with Jouko Pakarinen, Tapojärvi, January 2013.

Rinne, J. 2008. CO_2 Sequestration potential of industrial by-products and waste materials in Finland. Master Thesis, Department of Energy Engineering, Helsinki University of Technology.

Roskill, 2012. Ground & Precipitated Calcium Carbonate: Global Industry Markets & Outlook, 1st edition 2012. Online summary. http://www.roskill.com/reports/industrial-minerals/ground-and-precipitated-calcium-carbonate-1 (3.9.2012)

Sjölund, H. 2012. Phone conversation with Henrik Sjölund, Helsinki Chartering 28.8.2012.

Skuse, D. R. 2002. Speciality Chemicals in Mineral Processing. Royal Society of Chemistry. 143 p.

Tegethoff, F.W., Rohleder, J., Kroker, E. 2001. Calcium Carbonate: From the Cretaceous Period Into the 21st Century. Springer, 342 p.

Teir, S., Eloneva, S., Revitzer, H., Zevenhoven, R., Salminen, J., Fogelholm, C.-J., Pöyliö, E.Method of producing calcium carbonate from waste and by-products. International application published under the patent cooperation treaty (PCT), WO 2009/144382, PCT/FI2009/050455.

Vapa, R. 2012. PCC quality requirements for paper making. PowerPoint presentation, CCSP, WP 5.2 Internal meeting, 13.2.2012.