Architecting an Electro-Chemical Separation Platform:
from the business case to the first commercial product

by

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Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

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Director of David H. Koch School of Chemical Engineering Practice

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ABSTRACT

Electrosorption technology is currently gaining significant tractions as a viable separation technique due to its low energy consumption, its intrinsic reversibility and its reagent free nature. As most companies thrive towards a more sustainable approach, electro-chemical based process become more and more attractive. The group of Prof. Hatton of the Chemical Engineering department at MIT has improved further the state of the art of electro-chemical technologies by using functionalized metallocene-based pseudo-capacitors. Their research demonstrates that the technology they developed can selectively remove specific compounds such as carboxylates, sulfonates, phosphonates and potentially heavy metals. The aim of this thesis is to help the technology find a first market fit and build the foundation for a successful scale-up by defining its positioning within the treatment train of the production of the identified markets.

Two main markets were identified. The selection of each market was based on the price of the end-product, the size and growth of the market and the numbers of applications and potential customers. The lactic acid and the lithium carbonate markets were selected. Both are growing markets sustaining a real demand over the years to come with very promising and diversified applications. We collected real-life feedbacks and identified the pain points in each respective industry by conducting interviews with professionals in the field. Several unmet needs and possible alignments with the benefits brought by the selective electrosorption technology were identified thanks to this endeavor. New potential production lines were proposed. The new innovative treatment line allows for the simplification of the process train, a reduction of the chemical and reagent needed and a likely decrease in solid waste and wastewater volume.

Thesis Supervisor: T. Alan Hatton
Title: Ralph Landau Professor of Chemical Engineering and Director of David H. Koch School of Chemical Engineering Practice
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Introduction

The separation field has evolved significantly in the past 5 years. Separation technologies have traditionally been used to remove and isolate problematic compounds from a value stream or a waste stream before discharge. As such, distillation and membrane technologies are by far the main separation techniques used in the industry due to their low costs and high scalability potential. Nowadays, as the concept of circular economy has started growing, the demand for technologies allowing the valorization of specific compounds increases resulting in a need for the development of selective separation technology. The Group of Prof. Hatton (Chemical Engineering Department at MIT) has developed an electro-chemical technology that allows the selective separation of specifics compounds. The work performed during this thesis can be considered a practical follow-up to the PhD work of Xiao Su (Su, 2017). The aim of this thesis is to help the technology find a market fit and build the foundation for a successful scale-up.

As with any chemical-based, hardware technology, we are facing numerous constraints. As we are evolving in a conservative market, it is difficult to collect quick constructive market feedback and traction before having built a product at a relevant scale. It is therefore likely that further demonstration would need to be realized past this first effort.

The first part of this thesis recapitulates the fundamentals of electro-chemistry with a focus on the specificity of the technology developed at MIT. We will then map the available markets for the technology and prioritize them. Finally we will work on understanding the positioning of the technology in each selected market in order to underline the potential alignment between the market needs and the offered solution.

Description of the technology

The aim of this first section is to recapitulate briefly the basic principles of electrosorption, the current technologies on the market and their main characteristics, and finally to introduce the technology developed at MIT, its differences with the current state of the art in electro-chemistry and its main benefits.

Electro-chemistry fundamentals

Electro-chemical processes and especially electrosorption are technologies based on the surface binding process promoted by the presence of an electrical field. Electrosorption is used to remove
and target charged compounds, i.e. ions and charged colloids. The basic principle of the technology is that charged species of opposite polarity are attracted to each other. Charged surfaces attract oppositely charged compounds which can then be extracted from the liquid phase. The major advantages of such a technology are:

- A limited energetic cost
- No need for chemical reagents
- Reversibility of the binding. Charged compounds can be bound and discharged with very little loss of efficiency of the medium surface.

The principle of adsorption is usually explained by the Gouy-Chapman-Stern theory and the formation of an electrical double layer at the interface between a charged surface and an electrolyte (Figure 1) (Stern (1924), Smirnov (2011)). The theory explains that in the Stern layer, charged particles interact with the charged surface in an orderly manner as a function of their finite sizes. Outside the Stern layer, ions can be treated as point-charges and behave according to the Gouy-Chapman model. In this model the charge distribution of ions is a function of the distance from the charged surface and the electric potential decreases exponentially as the ions are further away from the considered surface.

![Diagram of the Gouy-Chapman-Stern model](image.png)

*Figure 1: Gouy-Chapman-Stern model for electrical double layer. (Xu, 2017, adapted from Stern (1924))
Current electrosorption methods

There are currently two major technologies using electrosorption fundamentals:

- Capacitive deionization (limited deployments)
- Pseudo-capacitive deionization (small-scale units)

A schematic view of the basic principle of capacitive deionization and the different operating mode is presented in Figure 2.

![Figure 2: Flow-diagrams adapted from Porada et al. (2013) showing the various operating modes of the CDI process (a) flow-by mode, (b) flow-through mode, (c) ion-pumping and (d) batch adsorption and discharge. Reprinted with permission and courtesy of Su et al. (2017).](#)

Capacitive deionization is a technology where charged species are adsorbed onto polarized electrodes. The fluid to be treated flows in-between the electrodes and charged particles and ions are attracted to their respective counter-charges. The technology has been proven successful for low salinity effluent purification and is routinely implemented for brackish water desalination. Pseudo-capacitive deionization is Faradaic surface process that uses a redox mechanism to increase ion uptake and separation efficiency. This technology is extensively used in energy storage and new applications are currently investigated in other area due to the potential selectivity of the technology in diluted solutions (Wee et al. (2006)).

The main material used as electrode is carbon due to its low price, easy manufacturability and strong chemical and mechanical resistance and stability. Examples of carbon-based materials used
for capacitive deionization include carbon aerogels, carbon nanotubes, graphene and carbon nanofibers (Su (2017)).

The major advantages of capacitive deionization (or any electrosorption based technology) can be found in the combination of its significantly lower energy consumption over thermal or membrane based technologies, especially for low salinity effluent, and the reversibility of the electrosorption process allowing for repeatable separation without the need for chemical reagent. Both effects allow for the development of more sustainable options (potentially) compared to traditional separative techniques.

However, it is still important to notice that significant roadblocks need to be addressed in order to allow for the wide spread deployment of electrosorption technology outside of its current niche applications. Mechanical and chemical stability need to be improved especially with regards to the electrode fouling potential. Furthermore, scale-up and process intensification need to be addressed for the technology to become competitive in high flow applications.

Specificity of the technology developed at MIT

Basics principle

The Hatton group of the Chemical Engineering department at MIT has developed an innovative electrosorption-based technology. The main difference with current capacitive deionization technologies that can be found on the market is that the electrodes are “treated” in order to make them selective to specific compounds.

The MIT technology uses pseudo-capacitive electrodes functionalized with ferrocene-based redox polymers. Ferrocene is an electrochemically responsive coordination complex composed of a Fe(II) center located in between two cyclopentadienyl rings. When oxidized, the Fe(II) center can behave as an electrophilic center that can be used for reversible sorption of specific anions. While other electrosorption technology relies on ion accumulation in the electrical double layer as the main separation mechanism, metallocene-based pseudo-capacitors can adsorb organic anions selectively in the presence of excess electrolytes. Su et al. (2017) demonstrated ferrocene functionalized electrodes are selective towards organic functional groups such as carboxylates, sulfonates and phosphonates. The research work of Su (2017) also showed strong evidence that redox-enhanced hydrogen bonding with the cyclopentadienyl rings was likely the underlying
mechanism responsible for the adsorption of the arboxylate functional group (schematic view presented in Figure 3).

![Schematic view of the electrosorption process using ferrocene and its binding mechanism. Courtesy from Xu (2017)](image)

A schematic view of the electrosorption cycle with ferrocene is presented in Figure 3. Firstly, a fresh electrolyte solution is introduced to the reactor. A potential is then applied to activate the ferrocene (oxidation mechanism). Once the ferrocene is activated, specific adsorption can occur. Excess solution can then be rinsed and adsorbed species can be released in a solution of choice by reversing the potential. Fresh solution can be brought in again and the cycle can be repeated as needed.
Performance assessment

The electrosorption capacity of different available electro-chemical technologies as a function of the initial charged compound concentration is presented in Figure 4. The bench test realized by Achilleos and Hatton (2016) for different compounds are those with the name allocations. It can be observed that the electrosorption capacity of the pseudo-capacitive technology using functionalized ferrocene is one order of magnitude higher than current values reported in the literature for state of the art technology. While most of the technology presented electrosorption capacity between 0.1 and 20 mg/g (the state of the art in capacitive deionization), the MIT technology demonstrated electrosorption capacity between 100 and 500 mg/g. The difference is likely due to the fact that in conventional technology like capacitive deionization the electrosorption capacity is correlated with the structure of the carbon electrode (morphology and capacity limitation of the diffuse part of the electrical double layer) and the exposed surface area available while in the case of the MIT technology, each ferrocene molecule represents one potential site of adsorption.
Electrosorption technology is currently gaining some traction as a viable separation technique due to its low energy consumption, its intrinsic reversibility and its chemical free requirement. As most company thrive towards a more sustainable approach, electro-chemical based process become more and more attractive. The group of Prof. Hatton at the Chemical Engineering department of MIT has improved further the state of the art of the technology by using functionalized metallocene-based pseudo-capacitors. Their research demonstrates that electro-chemical process can also be used to remove selectively specific compounds, namely carboxylates, sulfonates, phosphonates and potentially heavy metals. While still in its infancy, it is interesting now to investigate potential market to try to figure out where this breakthrough can be more readily applied.
Market research: Finding the right niche

The aim of this section is to present the procedure that has been chosen to evaluate potential markets, the selected markets and their main characteristics and potentials.

Protocols, metrics and selection process

The market research first approach was based on the patent application (Su et al., 2017). We used the document to determine the potential molecules (carboxylates, sulfonates and heavy metals) that can be selectively adsorbed and be extracted by the technology. The list of the selected molecules identified in a first pass are recapitulated in Table 1. These molecules were selected in a first approach to due the strong confidence of Prof. Hatton group that the technology could selectively remove them from an effluent stream.

Table 1: List of the selected potential market (first pass)

<table>
<thead>
<tr>
<th>Potential target market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyruvate</td>
</tr>
<tr>
<td>Acetate</td>
</tr>
<tr>
<td>Formate</td>
</tr>
<tr>
<td>Lactate</td>
</tr>
<tr>
<td>Benzoate</td>
</tr>
<tr>
<td>Perchlorate</td>
</tr>
<tr>
<td>Hexafluorophosphate</td>
</tr>
<tr>
<td>Heavy metals (i.e. Lithium)</td>
</tr>
<tr>
<td>Sulfonates</td>
</tr>
<tr>
<td>Phosphonates</td>
</tr>
<tr>
<td>Proteins</td>
</tr>
<tr>
<td>viral clearance</td>
</tr>
<tr>
<td>Specific pharmaceuticals</td>
</tr>
</tbody>
</table>

The metrics used to segment the different potential molecule candidates were:

- Price ($/ton),
- Size of the market,
- Diversification into different area (number of application of the molecule).
Price was picked as a first criterion because from our professional experience, it is always easier to drive new technology adoption in markets that are not completely commoditized. Furthermore, people tend to be willing to spend more money on new technologies on their most expensive asset or the asset that deliver them the best revenue stream. The size (and growth) of the market was selected as the second criterion because we wanted to make sure that the market is large enough to support a new entrant in the technology space. Basically, checking the size of the market helped us assess the total addressable market and therefore evaluate if we will be able to make sufficient money to create a profitable company. Diversification and potential customers were chosen as the third criteria for a couple of reasons. The first one is related to the scaling of the business. Once the technology is successful for one application, it is considered now a de-risked technology. As such, it is very easy to expand in adjacent markets using the same product for different applications. The second reason is that if there are several producers competing for different applications, each of them is likely to be interested in a differentiating technology allowing it to gain a competitive advantage and edge in the market.

A Pugh matrix was used to compare the different markets based on the defined metrics. A selected part of the Pugh matrix is presented in Table 2. The lactate market and the lithium (carbonate) market show the largest potential with regards to the application of the MIT technology. Both compounds demonstrate a significantly higher price point, a wider market and larger range of potential applications / customers. Specific pharmaceuticals were also discussed but will be left out of the thesis as the way to investigate those is significantly different.

<table>
<thead>
<tr>
<th>Potential target market</th>
<th>Selling Price</th>
<th>Size of the total Market</th>
<th>Number of Potential Applications /Customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyruvate</td>
<td>+++</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Acetate</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Formate</td>
<td>-</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Lactate</td>
<td>++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Benzoate</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Perchlorate</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Hexafluorophosphate</td>
<td>+++</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heavy metals (i.e. Lithium)</td>
<td>+++</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>
Identified market characteristics

The lactic acid market

Lactic acid is one of the most widely occurring hydroxy-carboxylic acids. It is a natural organic acid with a long history of application in food, pharmaceutical, textile and chemical applications (Kometsu et al. (2017), Datta et Henry (2006)). Based on the Ground View market research on lactic acid and polylactic acid (PLA), the lactic acid market will be worth $9.8 billion by 2025. The market was worth $1.65 billion in 2015 and is growing at a CAGR of 16.2%. The main market driver for the production of lactic acid is the market of the biodegradable bioplastic PLA, a “green” alternative to more traditional petrochemical products. A breakdown of its current application is presented in Figure 5.

Food industry
- acidulants
- preservatives
- flavours
- pH regulators
- improving microbial quality
- mineral fortification

Cosmetic industry
- moisturizers
- skin-lightening agents
- skin-rejuvenating agents
- pH regulators
- anti-acne agents
- humectants
- anti-tartar agents

Chemical industry
- descaling agents
- pH regulators
- neutralizers
- chiral intermediates
- green solvents
- cleaning agents
- slow acid release agents
- metal complexing agents

Chemical feedstock
- propylene oxide
- acetaldehyde
- acrylic acid
- propanoic acid
- 2,3-pentanedione
- ethyl lactate
- dilactide
- poly(lactic acid)

Pharmaceutical industry
- parenteral/IV solution
- dialysis solution
- mineral preparations
- tablettings
- prosthesis
- surgical sutures
- controlled drug delivery systems

Figure 5: Breakdown of the use and application of lactic acid per industry (Wee et al., 2006)

The distribution of the usage of lactic acid per application is presented in Figure 6. Polymers accounted for the largest share of lactic acid usage (39%), followed by food and beverages applications (35%). The two other large applications (both 13% of the market applications) are solvents and personal care products.
1,220,000 metric tons of lactic acid were produced in 2016, with demand still increasing at a CAGR of 15%. Food grade lactic acid price varied between $1,380 per metric ton and $2,000 per metric ton as a function of the purity of the product for a production cost between $550 and $800 per metric ton.

The 3 main producers of lactic acid are:

- Corbion (the Netherlands)
- Galactic (Belgium)
- Cargill /Dow (USA)

The lactic acid market is very likely to be a good candidate for the MIT technology. As it is a growing market, current suppliers are likely to look for opportunities to improve their production and streamline their processes. Furthermore, as there are several serious players in place, companies are very likely to be interested in differentiating technologies and processes that can give them an edge towards their main competitors. As developed a bit later, it is likely that the MIT technology can offer significant advantages compared to conventional treatment trains.

The lithium carbonate market

Lithium is sold in a number of forms. Lithium carbonate is the largest product based on volumes sold. The current lithium carbonate market is estimated around $1.5 Billion in 2017 growing at an average CAGR of 15% (from 8% CAGR for consumer electronics up to a CAGR above 30% for energy storage). Albermarle (2016) put together a very complete study on the state of the lithium market, and especially lithium carbonate (the one we are interested in with regards to the MIT
technology. The production needs forecast for lithium carbonate (in metric ton) from 2012 to 2020 are presented in Figure 7. It can be seen than most of the applications present steady growth (glass & ceramics, greases, portable batteries) with a cumulative need close to 200,000 metric tons of lithium carbonate. The uncertainty lies in the automotive market needs, varying between 50,000 to 150,000 metric tons by 2020. Overall, the need for lithium carbonate is expected to range between 200,000 and 325,000 metric tons by 2020.

![Figure 7: Lithium carbonate production need forecast between 2012 and 2020 (BCG-Albemarle, 2016)](image)

The main applications for lithium are presented in Figure 8. In transportation, lithium is used in batteries in product ranging from golf carts to buses and this sector is considered to be one of the fastest growing markets for lithium. Lithium is also used in consumer electronics and devices in products ranging from smartphones and tablets to power tools, toys and personal care devices.
There are currently two major sources of lithium, brine based and hard rock mineral based. Hard rock mineral operations have higher operating costs but lower capital costs and can respond more quickly to market conditions. Brine based operation extract lithium brine from a salar deposit via a series of pumping wells. The brine is stored for 9 to 12 months in large ponds where lime is added to precipitate impurities. The main concentration mechanism is solar evaporation. The processing scheme for hard rock lithium follows a more conventional mining approach. Ore is mined via conventional drills and blast methods. It is then excavated and undergoes multiple stages of crushing in a processing facility. Lithium bearing minerals (like spodumene) can then be separated and downprocessed to spodumene concentrate before further processing (Hocking et al. (2016)).

The main figures for both sources are summarized in Figure 9. The brine production represents 98,000 metric tons in 2016 with the main producers being Albermale, FMC and SQM. With regards to hard rock production, the yearly production for 2016 was 62,000 metric tons with the main producers being Talison and the Chinese national companies.

As with any commodity, the price of lithium fluctuates with time as function of the needs and traction of the market. The price evolution between 2002 and 2018 is presented in Figure 10. It can be seen that the price of lithium has steadily increased over time and that a sharp increase in
price from $6,000 to $16,000 can be observed between 2015 and 2018. This sharp increase seems to suggest a real need for this commodity that also matches the rapid growth of markets like transportation and energy storage.

Figure 9: Main lithium producer as a function of the lithium source (Albermale, 2016)

Figure 10: Evolution of lithium carbonate price commodity between 2002 and 2018 (metalary.com, 2018)
Two main markets were identified for the MIT technology. The selection of the market was based on the price of the end-product, the size and growth of the market and the numbers of applications and potential customers. The lactic acid and the lithium carbonate markets were selected. Both are growing markets sustaining a real demand over the years to come with very promising and diversified applications. We do think both have potential as each producer is likely to be interested in implementing an innovative technology to gain a competitive advantage and consequently increase its margin and/or its market share.
Technology development strategy and Positioning in the value chain

The aim of this section is to finally combine our understanding of the MIT technology and its benefits with their potential applications in the 2 identified markets, namely the lactic acid market and the lithium carbonate market. In order to be able to so, we conducted a series of interviews with different stakeholders of the lactic acid market and the lithium market and tried to figure out how to position the MIT technology to match their unmet needs.

The lactic acid market

- Current technologies and process train

Lactic acid is generally produced using a multi-step process. In order to produce lactic acid, the conventional process uses as a feedstock a corn-based or a sugar-based product. The feedstock is combined with water and lime (and nutrients) in a fermenter where bacteria digests it under regulated operating conditions (defined pH, residence time and temperature mostly). Calcium lactate is the main product resulting from the fermentation step. The calcium lactate then needs to be acidified to be transformed into lactic acid before purification and concentrated to the desired specifications. The main treatment steps used during the purification and concentration stage are ion exchange, membranes and electro-dialysis. An illustration of a traditional production scheme for lactic acid is presented in Figure 11 and Figure 12.

![Figure 11: illustration of the lactic acid production treatment train (Corbion website)](image-url)
Despite its wide range of applications, lactic acid is still considered limited by the final production costs associated with the downstream processes. The downstream processes are usually responsible for 30 to 40% of the total production cost of lactic acid (Komestu et al. (2017), Lopez-Garzon et al. (2014)). Kometsu et al. (2017) reported that while efficient lactic acid yields and purities can be obtained by combining different purification technologies, many drawbacks remain to be overcome. The high cost of the reagent during the precipitation steps, the need for filtration (significantly energy intensive) for high purity product and the large amount of wastewater generated are considered major concerns. Furthermore, the use of calcium sulfate is also an additional concern with regards to waste management. Solvent extraction requires
expensive equipment while electrodialysis is difficult to implement at scale due to potential fouling issues.

- **Customer interviews and needs identification**

Several stakeholders were contacted using social media (mostly the MIT infinite connection and LinkedIn) in order to check the interest of professionals and understand the current needs of this specific market. The two targeted companies for the lactic acid market were Corbion and NatureWorks. Corbion was contacted due to the fact they are the world leader in lactic acid production with a worldwide footprint. NatureWorks was also identified due to its North American base and therefore the potential to meet in person and/or to visit existing facilities. After e-mail exchanges at different levels within each organization, we were guided towards an individual in each company. Peter Beats (for Corbion) is a principal engineer in charge of the evaluation of novel and innovative technology for the lactic acid market. Manuel Natal (for NatureWorks) is a business development director in charge of their bio-innovation segment.

The main needs and point of discussion for Peter Beats and Manuel Natal are summarized in Table 3.

<table>
<thead>
<tr>
<th>Identified Needs</th>
<th>P. Beats (Corbion)</th>
<th>M. Natal (NatureWorks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low energy consumption</td>
<td></td>
<td>Low Price</td>
</tr>
<tr>
<td>High Capacity</td>
<td></td>
<td>High yields</td>
</tr>
<tr>
<td>Yields</td>
<td></td>
<td>No reagent</td>
</tr>
<tr>
<td>Purity of the final product</td>
<td></td>
<td>Decrease of chemical costs</td>
</tr>
<tr>
<td>Decrease of chemical costs</td>
<td></td>
<td>Simplification of the treatment train</td>
</tr>
<tr>
<td>Scaled production</td>
<td></td>
<td>Fermentation broth reuse</td>
</tr>
</tbody>
</table>

P. Beats was extremely interested in the potential of an Electro-chemical based technology. As the price of electricity is currently low in Europe, Corbion is actively looking for technology allowing them to capitalize on it. P. Beats expressed needs with regards to potential savings that could be achieved through energy savings and potential fermentation broth reuse. He was also interested in understanding what kind of yield can be achieved on a theoretical basis with the MIT technology. P. Beats was very curious about the fundamental principle of the technology during our discussion and focused strongly on the technological aspect of the matter. However, a
tangible need and interest could be perceived, with the main driver being the current price of electricity (very competitive compared to some other energy source) and the potential reduction in chemical consumption during the downstream processing.

M. Natal was very cost-driven during our discussion. He was mostly interested in potential gain and how the MIT technology would compare to technologies currently on the market. The reuse of the fermentation broth, potential simplification of the treatment line and cost reduction notably by cutting down reagent consumption were the primarily concerns formulated.

While the discussion were very preliminary a sure interest could be acknowledged in both cases (we passed the Sniff test). The main key points, question with regards to potential performances, and constraints are summarized below:

- Which energy consumption/savings can you achieve?
- What electrosorption capacity can you achieve?
- At which scale can you operate?
- How flexible is your technology with regards to the broth concentration?
- What kind of purity/selectivity can you achieve?
- Could you please define clearly your operating cycle?

- Positioning of the technology in the value chain

Projecting the MIT technology into the lactic acid process train, we could imagine a solution where the lactate is selectively extracted directly after the fermentation steps, allowing the direct reuse of the fermentation broth and therefore the valorization of the excess nutrient present in the solution. Furthermore, depending on the purity of the lactate collected, simplification of the downstream processing could also be considered. A summary of the identified needs and how the performance of the MIT technology aligns with them is presented in Table 4.
Table 4: Matching of the performances of the MIT technology with the needs expressed by the lactic acid producers

<table>
<thead>
<tr>
<th>Identified Needs</th>
<th>MIT Technology performance</th>
<th>Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low energy consumption</td>
<td>0.5-0.8 V</td>
<td>++</td>
</tr>
<tr>
<td>High Capacity</td>
<td>420mg/g of polymer</td>
<td>++ (compared to CDI)</td>
</tr>
<tr>
<td>Yields</td>
<td>8.5 kg lactic acid /h kg of polymer</td>
<td>?</td>
</tr>
<tr>
<td>Purity of the final product</td>
<td>TBD by lab testing</td>
<td>-</td>
</tr>
<tr>
<td>Decrease of chemical costs</td>
<td>?</td>
<td>-</td>
</tr>
<tr>
<td>Scaled production</td>
<td>?</td>
<td>-</td>
</tr>
<tr>
<td>Low Price</td>
<td>?</td>
<td>-</td>
</tr>
<tr>
<td>No reagent</td>
<td>Purely electricity driven</td>
<td>+++</td>
</tr>
<tr>
<td>Decrease of chemical costs</td>
<td>Purely electricity driven</td>
<td>+?</td>
</tr>
<tr>
<td>Simplication of the treatment train</td>
<td>?</td>
<td>-</td>
</tr>
<tr>
<td>Fermentation broth reuse</td>
<td>Direct reuse of the broth</td>
<td>+++</td>
</tr>
</tbody>
</table>

Low energy consumption, potential high capacity, no reagent use and the direct reuse of the fermentation broth are needs directly met by the technology developed at MIT. Yield is difficult to assess as we were not able to find relevant figures in literature. The purity of the lactate calcium product would be needed to be determined by lab testing as the purity will depend significantly of the broth and the feedstock used. Decrease of the overall chemical cost, simplification of the treatment train and lower price are likely, however it is difficult to make a statement without performing further pilot testing under real conditions.

A potential flow diagram of the lactic acid production including the MIT technology is presented in Figure 13. The MIT technology could fit between the fermentation step and the purification step. Depending on the purity that can be attain using the electrosorption technology developed at MIT, it is likely that the treatment train further downstream can be simplified, especially with regards to the concentration of the lactic acid. The purity obtained will depend on the selectivity of the electrodes towards lactate in the fermentation broth. It will be essential to run some pilot trial in order to assess the possible benefits of the technology.
Based on the needs collected during the interview session, we can see that the technology developed at MIT is able to answer 4 out of 11 of them (Table 4). While it can seem low, we are still very early in the development of the technology and we would consider this result very
promising. Four other needs are likely to be met or partially met as we test the technology under real condition putting the score to 8 out of 11.

As developed in this section, we observe that the technology developed at MIT can answer current needs expressed by lactic acid production professionals. The technology fits within the process train in between the fermentation steps and the purification step. While not answering all the issues in the downstream processing of lactic acid, we can still identify some real benefits of implementing the MIT technology. Some further real matrix testing is obviously necessary, but from a theoretical standpoint a positive alignment has been found.

The lithium carbonate market

- Current technologies and process train

A simplified process flow diagram for the production of lithium carbonate from (salar) brine is presented in Figure 14. The process train can be considered complex and involves many different steps. Salar brine is firstly concentrated using solar evaporation up to 6%. The concentrate then goes through multiple stages of precipitation and solid-liquid separation in order to remove boron and part of the impurities. The obtained product is then carbonated and re-concentrated and purified to the desired degree of purity.

A simplified process flow diagram for the production of lithium carbonate from hard rock (especially spodumene) is presented in Figure 15. Spodumene concentrate is roasted and then leached. A solid-liquid separation then take place where impurities are removed. The solid-liquid separation is followed by multiple steps of purification –concentration (ion exchange and evaporation steps) where the goal once more is to remove impurities and increase the concentration of the solution. The solution is then carbonate and purified a last time to separate the final product (lithium carbonate) from other by-products (mine dependent).

Both process trains can be considered very complex, requiring multiple stages of treatment and purification cycles, involving the use of a fair amount of chemicals, additives and regeneration agents. Furthermore, it is important to notice that the production of lithium carbonate issued from (salar brine) is currently not best suited to respond to the fast increase in demand from the market, notably due to the capital intensive nature of the business and the significant lead time (9 to 12 months) induced by the use of solar evaporation. In order to overcome this limitation, mining companies are currently investing and developing new brine processing technologies.
(Hocking et al., 2016). The technology focus is on developing direct extraction methods allowing the by-passing of solar evaporation and decreasing drastically the production lead time.

It is also currently admitted that the major economic constraint for brine is the cost of removing impurities (magnesium, calcium, iron and potassium) and mining companies are actively looking for novel solutions to tackle this issue.
Figure 14: Simplified process flow diagram of the production of lithium carbonate from a brine source (Hocking et al. (2016), Lithium Process Chemistry (2015))
Figure 15: Simplified process flow diagram of the production of lithium carbonate from a spodumene source (Hocking et al. (2016), Lithium Process Chemistry (2015))
Customer interviews and needs identification

We leveraged personal professional connections to collect first customer feedbacks and needs in the lithium market. I am currently working for Veolia Water Technologies, the world leader in environmental service. One of our business units specializes in evaporation and crystallization technologies (Veolia-HPD) and is currently actively involved in the lithium carbonate market as an equipment supplier to several mining companies. As I was explaining the MIT technology I was working on in the context of the SDM program, a lot of interest emerged quickly. Therefore interviewed 2 seniors experts of the company, both actively involved in providing solutions to the lithium mining producers. Sebastien Bessenet is Senior Process Advisor at Veolia-HPD and is in charge of validating process trains for large projects, especially in the lithium carbonate market. Bernie Mack is Principal Engineer in the technical direction of Veolia Water Technologies and is a prominent expert with regards to separation and physical-chemical processes. A summary of the needs identified during our interviews can be founded in Table 5.

Table 5: Identified needs of lithium market expert during interview process

<table>
<thead>
<tr>
<th>Identified Needs</th>
<th>S. Bessenet (Veolia-HPD)</th>
<th>B. Mack (Veolia Water Technologies)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease chemical use</td>
<td>Complexity of the process (operation)</td>
<td></td>
</tr>
<tr>
<td>Waste management</td>
<td>Boron management</td>
<td></td>
</tr>
<tr>
<td>Regeneration management</td>
<td>Membrane pretreatment</td>
<td></td>
</tr>
<tr>
<td>Impurity removal</td>
<td>Decrease Reagent use</td>
<td></td>
</tr>
<tr>
<td>Purity of the final product</td>
<td>Purity of the final product</td>
<td></td>
</tr>
</tbody>
</table>

Both S. Bessenet and B. Mack stressed during our discussion the complexity of the treatment notably due to the multiple steps needed to remove impurities and the amount of reagents and additives needed (especially with regards to the different ion exchange process steps involved). The use of reagent was generated two major issues. The first one is a very significant operating cost as a significant volume of each reagent is needed to purify the lithium carbonate. The second issue is related to waste and wastewater management. A significant amount of liquid and solid waste is produced in the current production train and it needs to be treated and/or disposed of, resulting in an increase of complexity and of the operational costs of the production site.

Both experts were very enthusiastic with the idea to substitute ion exchange processes or even to completely remove several treatment steps in the production lines. The idea to work with a
technology electricity driven not requiring the use of reagents or complex solutions for regeneration was considered a significant breakthrough compared to conventional technologies.

The main key points, questions with regards to potential performance, and constraints are summarized below:

- How selective can you be in a very complex matrix?
- What kind of yield can we expect?
- At which scale do you think you can operate?
- What kind of pretreatment would be needed?
- Can we run some preliminary tests?

- Positioning of the technology in the value chain

Projecting the MIT technology into the lithium carbonate process train, a range of possibilities can be formulated. The MIT technology is likely to be well positioned as a replacement of ion exchange technology at first. However, thinking the process stream through a bit more, we can think of a significantly more ambitious positioning. Depending on the selectivity of technology and the purity that can be achieved with the technology developed at MIT (further experiments required), we anticipate that the electrosorption step can be implemented early in the treatment train to capture the lithium compound and/or to get rid of most of the impurities. Depending on the concentration factor that can be achieved in the technology, light purification and concentration followed by carbonation could finalize the treatment needs. Potential positioning in the treatment train of lithium carbonate production from brine is presented in Figure 16. The potential positioning in the treatment train from hard rock is presented in Figure 17.

A summary of the identified needs and how the performance of the MIT technology aligns with them is presented in Table 6. Six of the expressed needs out of 9 are met or partially met by the technology developed at MIT. The decrease in chemical use, the decrease in waste handling and the regeneration management are issues addressed by the fact that the MIT technology can replace most the ion exchange steps in the treatment line. The management of the impurities is one of the strong advantages of the MIT technology if the technology proves to be selective enough with real effluent. The questions with regards to potential pretreatment and final purity of the product can only be answer after further real effluent testing.
Table 6: Matching of the performances of the MIT technology with the needs expressed by the lithium market experts

<table>
<thead>
<tr>
<th>Identified Needs</th>
<th>MIT Technology performance</th>
<th>Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease chemical use</td>
<td>Purely electricity driven</td>
<td>++</td>
</tr>
<tr>
<td>Waste management</td>
<td>Potential IX replacement</td>
<td>+++</td>
</tr>
<tr>
<td>Regeneration management</td>
<td>No regeneration</td>
<td>+</td>
</tr>
<tr>
<td>Impurity removal</td>
<td>Selective technology</td>
<td>++</td>
</tr>
<tr>
<td>Purity of the final product</td>
<td>TBD</td>
<td>-</td>
</tr>
<tr>
<td>Complexity of the process (operation)</td>
<td>&quot;1 step process&quot;</td>
<td>+</td>
</tr>
<tr>
<td>Boron management</td>
<td>Selective technology</td>
<td>+?</td>
</tr>
<tr>
<td>Membrane pretreatment</td>
<td>Technology can be used pre -concentri</td>
<td>?</td>
</tr>
<tr>
<td>Decrease Reagent use</td>
<td>Potential IX replacement</td>
<td>++</td>
</tr>
</tbody>
</table>

As developed in this section, we observe that the technology developed at MIT can answer current needs expressed by lithium production professionals. The technology fits well within the process train and has the potential to replace existing brick or even simplify significantly the current process. While not answering all the issues the lithium mining industry is facing, we can still identify some real benefits of implementing the MIT technology. Some further real matrix testing is obviously necessary, but from a theoretical standpoint a positive alignment has been found.

We investigated in this section the potential benefits of the technology developed at MIT within the production lines of lactic acid and lithium carbonate. We collected real-life feedback and worked on understanding the true pain point in the industry by conducting interviews with professionals in the field. Several unmet needs were identified thanks to this endeavor and we considered possible alignment with the benefits brought by selective electrosorption. New potential production lines were proposed including the technology developed at MIT. The new innovative treatment line allows for the simplification of the process train, a reduction of the chemicals and reagents needed and a likely decrease in solid waste and wastewater volume.
Figure 16: Potential positioning for the MIT technology as an alternative to the conventional treatment train (Brine source)
Figure 17: Potential positioning for the MIT technology as an alternative to the conventional treatment train (spodumene source)
Discussion, lesson learnt and moving forwards

The group of Prof. Hatton of the Chemical Engineering Department at MIT has developed a selective electrosorption technology. Based on their work, they are confident they can extract specific compounds such as carboxylates, sulfonates, phosphonates and specific heavy metals such as lithium. The goal of this research project was to identify potential markets sufficiently attractive to allow the deployment of the technology at scale. After a first period of time where we worked with Dr. Su to understand the specificity of the technology and the potential use-case, we started digging into potential market fit. The metrics we used to do so were price, size and growth of the market and number of applications and potential customers. These 3 main criteria allowed us to narrow down our potential (beach-head) market to two, namely the lactic acid market and the lithium carbonate market.

We interviewed professionals in both markets in order to identify the current pain points and unmet needs in their respective production process. Thanks to this exercise, we were then able to position and to align the technology developed at MIT accordingly. While doing bibliography work was useful to get a global picture of the market and evaluate in the first pass their potentials as possible beach-head, the real breakthrough and critical data collected came from speaking and interviewing professionals in their respective fields. The insights gained were invaluable and would have been very difficult to replicate otherwise. Talking with the professionals from Corbion and NatureWorks really gave us a sense of what currently matters to them, their strong interests in electricity driven technology and their main current drivers. It also allows us to assess the pace of innovation that they are willing to sustain and the risk and investment they are willing to make.

As we progress in our discussion with Corbion, it became rapidly clear that we were too early in our development process for them to be sufficiently interested in the technology that we have to offer. No matter the theoretical advantages we were bringing in and the needs we were meeting, Corbion was not willing to commit to such low TRL technology. This conversation was very useful to understand that targeting a conservative market with a product close to commodity has different expectations. We need to be able to move the technology to a relevant scale and to test it on complex matrices to be able to get a positive response.

The other interesting part of the discussion with Corbion was about positioning the discussion at the right level in the company. I am almost sure we failed to achieve that. After contacting different executives on social media, we were quickly directed towards P. Beats. Reflecting on
this, it felt like P. Beats acted as the gatekeeper for innovation within Corbion. He therefore focused a lot of the discussion on the technological aspects of the solution we were bringing when it would have been for us more fruitful to be able to have a more holistic and high level discussion with senior executives. Grounding the discussion into technology did not let us investigate much of Corbion strategy and get a global picture of their technology strategy as a whole. We are currently working on organizing a second round of interviews and will commit not to repeat the same kind of mistakes and insist on having the discussion at the right level with regards to the status of the technology development.

The positioning of the technology within the different production process trains would also have been difficult without extended discussions with colleagues and professionals in the field. Having access to Veolia know-how and understanding of the current limitations of the existing process was key in the lithium market. I still do think we need to make contact and discuss directly with mining companies, as their timeline and overall willingness to commit to technology development is likely to be greater as they are closer to the problem at stake. We are currently working the lithium carbonate market under two axes. Firstly, we want to organize a second round of interviews with people from the mining industry. Secondly, we are currently working on getting brine samples in order to make some testing under real matrix conditions. Doing so, we will be able to obtain some real figures to feed the discussion with lithium carbonate professionals.

As a professional, I am used to taking technology from the lab (low TRL) and bringing them to maturity or at least to a decent scale (TRL 6-8). It was extremely fascinating to work on a different aspect of the scaling of a technology during this SDM thesis. I truly appreciated working on the market research aspect of things and reflecting on what are the conditions / metrics that define a potential good market for a defined technology. I also really enjoy the much better insight you gain by going outside and meeting with people in order to get “real life” information. Finally, combining the market research work with what I am used to doing in the technology positioning felt like a great way to end this work. A lot of questions still need to be answered, from the selectivity of the technology with a real matrix to the purity that can be achieved, the questioning about the pretreatment that needs to be implemented and definition of the operating cycle, but I think we definitely were able to build a foundation and identify the right market that will let us grow the technology and answer those questions in time. I am very glad to have the chance to
work with the great team of Prof. Hatton and hope we will be able to bring this technology to market in a near future.
Conclusion

Electro-chemical technologies have been gaining tractions in the past few years due to their low energy consumption compared to other separative techniques, their reversibility and their reagent free nature. The Group of Prof. Hatton at the department of Chemical Engineering of MIT has been developing an innovative electroosorption technology allowing for the selective removal of specific compounds. They are now looking at potential deployments outside of their lab.

The goal of this research project was to identify potential markets for the technology developed at MIT and figure out how the technology could be positioned to answer critical unmet needs.

Based on the selection of key metrics, 2 markets of interest were identified: the lactic acid market and the lithium carbonate market. Interviews with professionals of both markets were conducted in order to better understand their current pain points and needs. We then worked on the positioning of the technology within their production lines to figure out how the technology developed at MIT could address some of their identified issues. The MIT technology is likely to be relevant in both markets if the results obtained at lab-scale are reproducible at larger scale on a real effluent. The selective electroosorption technology aligns fairly well with the need for a technology using less reagent and minimizing the different waste streams. Furthermore, the selectivity of the technology is likely to be beneficial to simplify the different treatment trains.

While it is still very early and some further testing is required, the technology developed looks promising and was able to generate a significant interest especially with the professionals from the lithium carbonate market. The next steps will be to organize a second round of interviews in order to validate the first round of feedback and to try to get access to different real source effluents in order to run some practical tests allowing to put figures on matters like selectivity and purity ratio achievement.
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