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Economic Evaluation of Solvay Processes for Sodium Bicarbonate Production with Brine and Carbon Tax considerations

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ABSTRACT

Reject brine discharge and high CO_2 emissions from desalination plants are major contributors to environmental pollution. Managing reject brine involves significant costs, mainly due to the energy-intensive processes required for brine dilution and disposal. In this context, Solvay process represents a mitigation scheme that can effectively reduce reject brine salinity and sequestering CO_2 while producing sodium bicarbonates simultaneously. The Solvay process represents a combined approach that can effectively manage reject brine and CO_2 in a single reaction while producing an economically feasible product. Therefore, this study reports a systematic techno-economics assessment of conventional and modified Solvay processes, while incorporating brine and carbon tax. The model evaluates the significance of implementing a brine and CO_2 tax on the economics of conventional and $Ca(OH)_2$ modified Solvay compared to industries expenditures on brine dilution and treatment before discharge to the sea. The results show that the conventional Solvay process becomes profitable after applying a brine tax of 1 dollar per meter cube of brine and a CO_2 tax of 42 dollars per tonne CO_2 —both figures lower than the current costs associated with brine treatment and existing carbon taxes. Moreover, the profitability of the $Ca(OH)_2$-modified Solvay process increases even further with minimal brine and CO_2 taxes. The findings highlight the significance of adopting modified Solvay process as an integrated solution for sustainable brine management and carbon capture.

Keywords: Solvay Process, Brine Management, Carbon Dioxide Capture, Carbone Tax.

INTORODUCTION

Carbon dioxide (CO_2) is a major contributor to climate change that is responsible for the considerable temperature rise. Considering the current fossil fuels consumptions, it is expected that by 2050, the CO_2 emission would reach 50 gigiatons per years that would cause the global temperature to increase by 2.5 °C [1]. However, implementing carbon pricing policies and technologies would limit the temperature increase to 1.5 and the CO_2 emission to 20 gigatons per year [2]. In addition, desalination plants produce tremendous amounts of reject brine of a concentration of 70 g/L, which is 20 times higher than the natural seawater concentration. This would cause direct harm to the aquatic species leading to serious consequences for the marine environment. In this context, Solvay process is a combined approach that can effectively mitigate CO_2 and reject brine in a single reaction. The traditional method involves the reaction of CO_2 and reject brine in the presence of Ammonia (NH_3) as a reagent to produce sodium bicarbonates ($NaHCO_3$). Then, NH_3 is recovered from the reactor effluents through the effluent reaction with calcium hydroxide $Ca(OH)_2$. The traditional Solvay process can effectively reduce the water salinity and CO_2 content by more than 30% and 80%, respectively [3]. The traditional Solvay process reactions are shown by equations 1 and 2.

$$NaCl + NH_3 + CO_2 + H_2O \leftrightarrow NaHCO_3 + NH_4Cl \quad (1)$$

$$2NH_4Cl + Ca(OH)_2 \rightarrow CaCl_2 + 2NH_3 + 2H_2O \quad (2)$$

Despite that, the traditional Solvay process utilizes NH_3 as a reagent, which is an environmentally hazardous chemical besides it is high recovery cost. To mitigate this problem, El-Naas et al [4] proposed the use of $Ca(OH)_2$ as a reagent instead of NH3 to minimize the environmental footprint and the process cost (equation 3). The proposed $Ca(OH)_2$ modified Solvay process showed a CO_2 and reject brine salinity reduction percentages of 99% and 35%, respectively.

$$2NaCl + 2CO_2 + Ca(OH)_2 \leftrightarrow 2NaHCO_3 + CaCl_2 \quad (3)$$

In this work, the economic feasibility of the conventional and $Ca(OH)_2$ modified Solvay are evaluated. The model evaluates the influence of different brine salinity on the process performance in terms of CO_2 and salinity reduction, product production, and process profitability. Furthermore, the process profitability with implementing carbon and brine taxes is investigated.

METHODOLOGY

Reject brine is mixed with an alkaline reagent in a mixer. The mixer is introduced into a bubble column (BR) in the case of conventional Solvay; Whereas in case of $Ca(OH)_2$ modified Solvay, the mixture is fed into a novel inert particle spouted bed reactor (iPSBR) developed by Muftah et al.[5]. Inside the reactor, the CO_2 is reacted with the mixture to produce $NaHCO_3$ and byproducts. The effluent from the reactor is introduced into filter to separate $NaHCO_3$ from low salinity water. However, in case of conventional Solvay, the effluent is introduced into a recovery reactor to recover NH_3 through the reaction of the effluent with $Ca(OH)_2$, which is an energy intensive process. The block flow diagram of the two processes is shown in Figure 1. The mathematical model of the conventional and $Ca(OH)_2$ modified Solvay processes including mass balance, energy consumption, and costing are shown in our previous study[3].

Constraints and assumptions

The process is considered to be steady stead without any side reactions taking [4]. Also, flue gas is assumed to be ideal gas, and the main constituent of the brine is sodium (Na). Moreover, the plant lifetime is set to 20 years. Table 1 shows the parameter used in the model obtained from experimental data [4, 6]. The current market chemical price for NH_3, $Ca(OH)_2$ and $NaHCO_3$ are around 9.81$/kg, 0.11 $/kg and 0.28 $/kg, respectively [7].

Table 1. List of experimental parameters used in the model.

Parameters	Conventional Solvay	$Ca(OH)_2$ modified Solvay
Brine mass flow rate (kg/min)	1000	
Reagent wt%	25	2
Flue gas wt%	17	17
BR/iPSBR conversion	0.86	0.6
Reactor temperature (°C)	20	
NH_3 recovery unit conversion	1	-
Reactor resistance time (minutes)	20	
Reagent to sodium ratio	0.03 NH_3: NaCl (Mass ratio)	0.3 $Ca(OH)_2$: NaCl (Molar ratio)
Recovery molar ratio	2 $Ca(OH)_2$: NH_4Cl	-

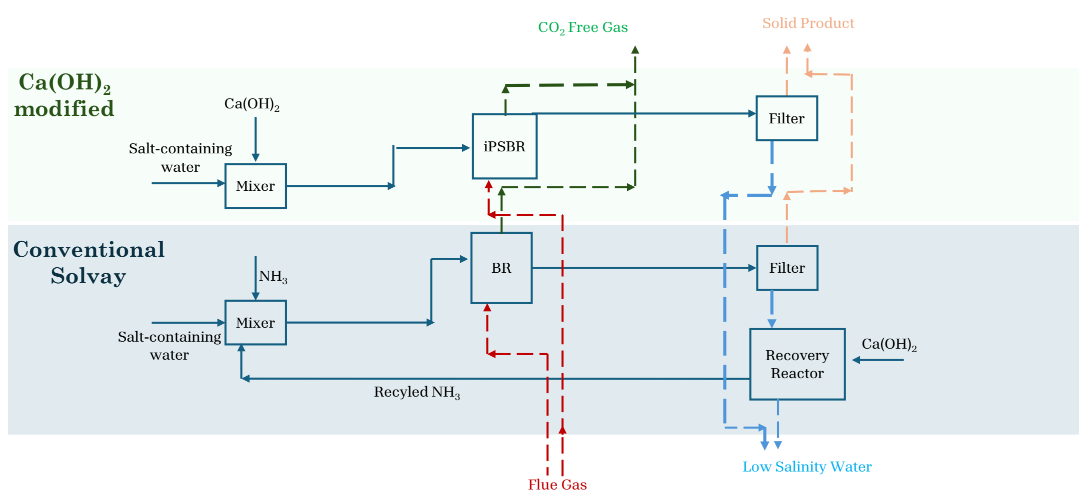

Figure 1. Block flow diagram of Conventional and $Ca(OH)_2$ modified Solvay processes.

RESULTS AND DISCUSSION

The CO_2 and sodium reduction percentages as well as the associated profit at different brine water salinities for conventional and $Ca(OH)_2$ modified Solvay processes are shown in Figure 2. It can be observed from Figure 2a that the CO2 removal percentage at brine salinity of 30 g/L, which is sea water quality, attain a CO2 and sodium removal of around 33% and 30%, respectively. The associated expenses is around 10 $\$/m^3_{of\ brine}$ which is mainly due to the low amount of $NaHCO_3$ produced at the indicated water salinity. At water salinity 70 g/L and 90 g/L, the CO_2 removal percentage is constant at around 80%, while the sodium removal percentage decreases from around 33% to 22%. In addition, the associated profit is negative and constant at -6 $\$/m^3_{of\ brine}$, which indicates that the conventional Solvay requires expenses to be operated. The constant profit value is mainly due to the constant production rate of $NaHCO_3$ that is also confirmed by the constant consumption of CO_2.

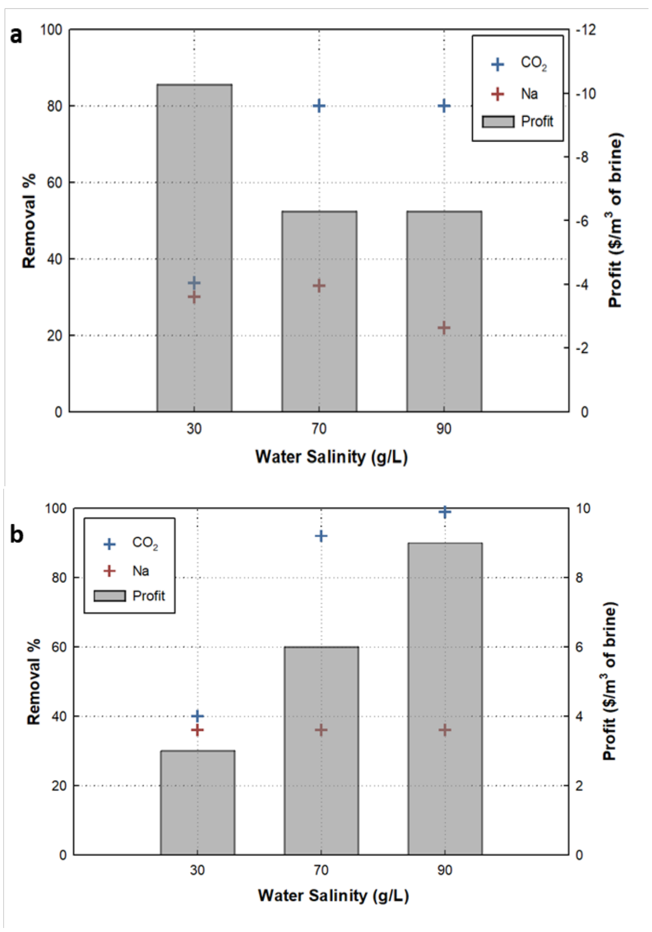

Figure 2. The Sodium, CO_2 reduction and process profitability of (a) conventional (b) $Ca(OH)_2$ modified Solvay.

On the other hand, it can be seen from Figure 2b that the $Ca(OH)_2$ modified Solvay that CO_2 removal increases from 40% to around 99% as the water salinity increases from 30 g/L to 90 g/L; yet the sodium removal is constant at 36%. This is due to the fact that the experimental data utilized the optimized $Ca(OH)_2$:NaCl molar ratio for the maximum sodium removal as indicated in Table 1. Yet, the associated profit is positive and increases from 3 $\$/m^3_{of\ brine}$ to around 9 $\$/m^3_{of\ brine}$. This is mainly due to the rise in $NaHCO_3$ production rate as the brine salinity increases and this is confirmed by the increase in CO_2 removal%. These results underscore the economic viability of the $Ca(OH)_2$ modified Solvay besides its high sodium and CO_2 reduction percentages for different water quality that varies from sea level salinity up to reject brine salinity level.

The results demonstrated above confirmed the economic feasibility of $Ca(OH)_2$ modified Solvay besides it superb CO_2 and sodium reduction percentage. Therefore, implementing CO_2 and/or brine tax will further increase the process profitability. Thus, herein, the influence of CO_2 and brine tax on the conventional Solvay profitability is investigated. The study considered brine tax values that ranges from 0 $\$/m^3_{of\ brine}$ to 6 $\$/m^3_{of\ brine}$ and CO_2 tax values that ranges from 0 \$/tonne CO_2 to 120 \$/tonne CO_2. Those values covers the range of the implemented tax in countries including Europe, Canada, and Mexico [8]. In fact, the economy of carbon tax is huge; It estimated that in 2023 that the world revenues from carbon tax and Emission Trading Systems (ETSs) are around 29.3 and 75 billion US dollars, respectively, as shown in Figure 3.

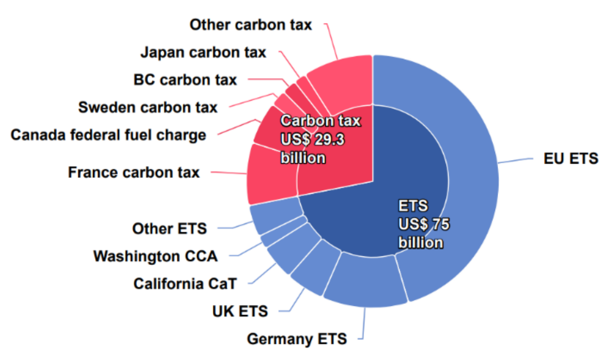

Figure 3. Countries contribution to carbon tax and ETSs [8].

Figure 4 shows the 3D plot of the combined effect of brine and CO_2 tax on the conventional Solvay process profitability. It is obvious that brine tax has a negligible influence on the Conventional Solvay profitability, whereas carbon tax influences the process profitability significantly. The figure clearly shows that the conventional Solvay requires a considerable amount of expense. However, implementing carbon and brine tax reduces the expenses required and eventually the process reaches the breakeven point. Table 2 demonstrates that considering a zero-brine tax, the conventional solvay reaches the breakeven point after implementing carbon tax of 42.5 $/tonne CO_2. While the optimum profit is obtained at the maximum implemnted carbon and brine tax.

Table 2. Conventional Solvay profitability.

Parameter	Brine tax	Carbon tax	Profit
Optimum Profit	7.03	116.56	$6.21x10^6$
Conventional Solvay breakeven	0	42.5	0

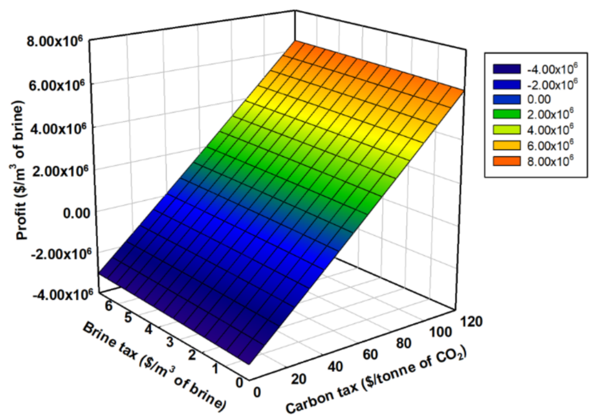

Figure 4 3D plots of the combined effect of carbon and brine tax on the Conventional Solvay profitability.

Table 3 shows a summary of the conventional and $Ca(OH)_2$ modified Solvay process performance from experimental and the model used in this study. It is evident that the CO_2 and sodium reduction percentages obtained from the model are close to the experimental data, which confirms the validity of the model. In addition, it can be seen that without the implementation of carbon tax, the $Ca(OH)_2$ modified Solvay generates profit of around 3.68 million dollars per year, while conventional Solvay requires expenses of 3.32 million dollars per year. Nevertheless, after implementing a carbon tax of 50 $/tonee CO_2, Conventional Solvay generates a profit of 0.6 million dollars per year, while $Ca(OH)_2$ modified Solvay becomes more profitable. This carbon tax value is much lower than the current value implemented in Europe countries and Canada, while is similar to the current value implemented in countries including Hungary, and Iceland. Figure 4 shows the carbon tax implemented in different countries in 2024. It is evident that, adopting conventional Solvay in those countries could contribute to carbon tax reduction if implemented the tax is implemented on industries as it in returns produces a considerable profit. More importantly, implementing the $Ca(OH)_2$ modified Solvay process could significantly reduce the carbon tax burden on both industries and individuals, as the process generating substantial profits from $NaHCO_3$ production, all without necessitating the imposition of a carbon tax. As a result, reducing carbon taxes for industries potentially leads to increased profit margins and enhanced competitiveness in both domestic and international markets. However, this could also result in poor investment in clean energy; therefore, it is substantial to implement a reasonable carbon tax value to ensure long term economic and environmental benefits.

Table 3. Summary of the experimental and model results.

Parameter	Experimental		Model	
	Conventional	$Ca(OH)_2$ modified	Conventional	$Ca(OH)_2$ modified
Brine concentration (mg/L)	71,700		70,000	
Inlet CO_2 wt%	17%			
Reagent wt%	25%	2%	25%	2%
CO_2 removal %	83	99	82	92
Na removal %	29	35	33	36
Profit ($/m³ of brine) (without tax)	-	-	$-3.32x10^{-6}$	$3.68x10^6$
Profit with carbon tax ($/m³ of brine)(50 $/tonne CO_2)	-	-	$6.20x10^5$	$7.62x10^6$

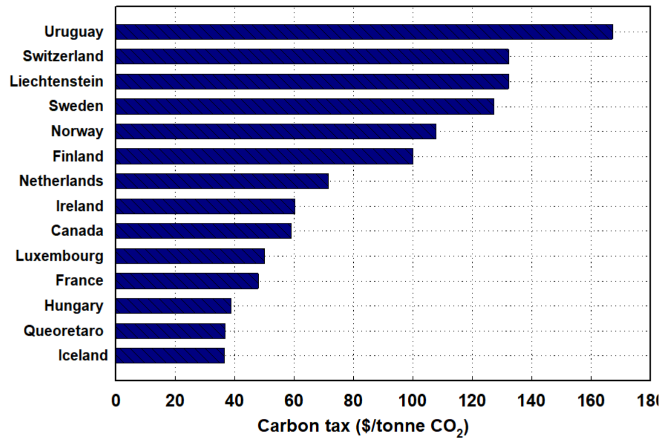

Figure 4. The implemented carbon tax in different countries in 2024 [8].

CONCLUSION

This work demonstrated a systematic techno-economic assessment of Conventional and $Ca(OH)_2$ modified Solvay process considering different brine salinities and brine and carbon tax. The results indicated that $Ca(OH)_2$ modified Solvay sodium and CO_2 reduction capability outperform conventional Solvay for all studied brine salinity values that varies from seawater to reject brine salinity level. In addition, conventional Solvay requires considerable expenses, but it becomes profitable after implementing a carbon tax of 50 $/tonne CO_2, while $Ca(OH)_2$ modified Solvay is profitable without any carbon tax implementation. These results underscore the economic viability of $Ca(OH)_2$ modified Solvay process besides being an environmentally friendly process compared to conventional Solvay.

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