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The Economic Benefits of Sodium Hydroxide Chemistry in the Production of Organic Chemicals in the United States and Canada

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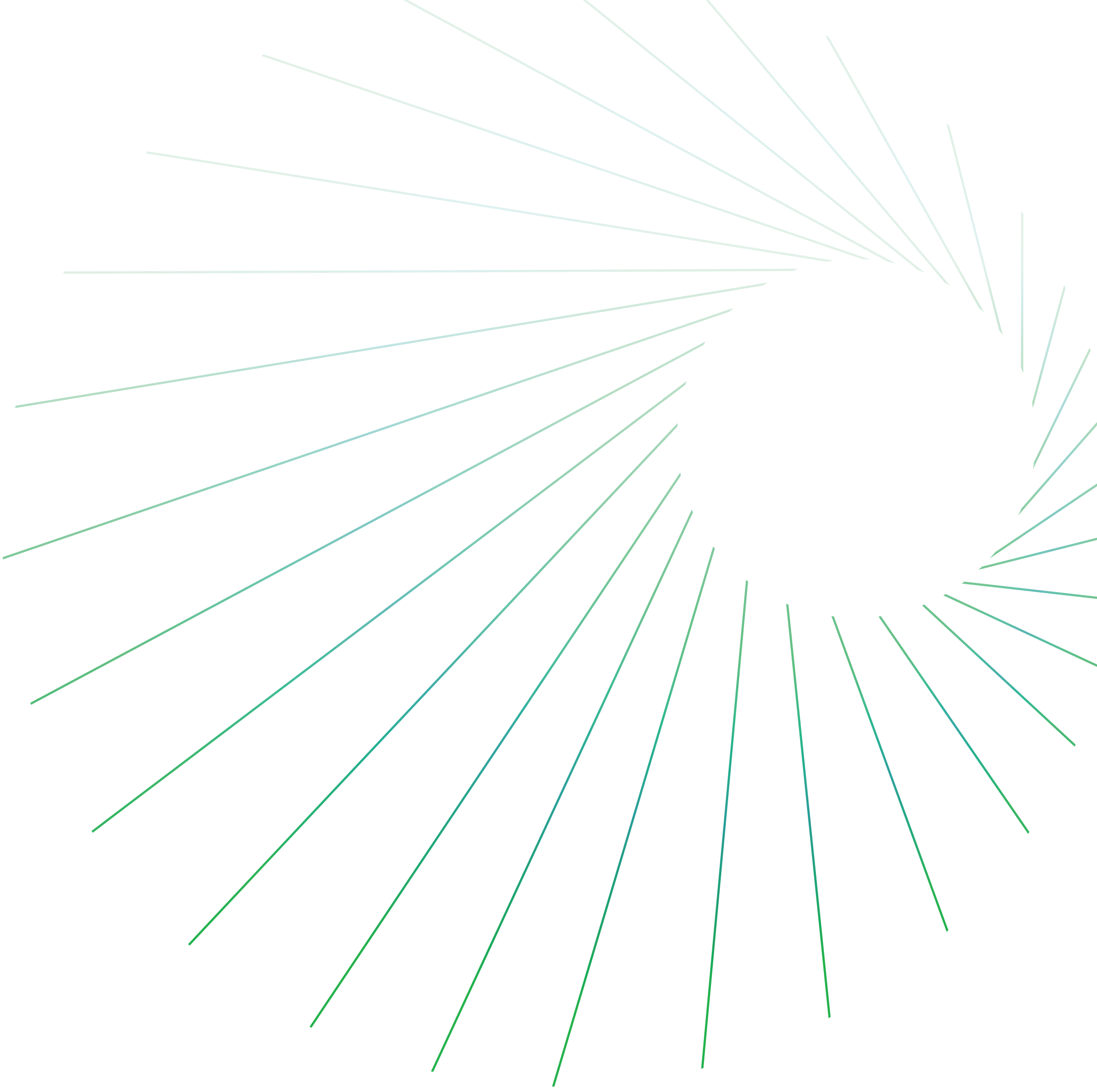

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Executive summary

The chlorine and sodium hydroxide industry (or simply the chlor-alkali industry) plays an extensive role in the economy. The two chemicals are co-products in the electrolysis process that produces about 1.1 pounds of sodium hydroxide per pound of chlorine. Items that rely on chlorine chemistry include such common consumer products as soft contact lenses, top-selling pharmaceuticals, smart phones, insulating wire, and non-stick cookware. The markets for sodium hydroxide are more numerous but tend to be smaller than those for chlorine. Among other characteristics, it is highly valued as a neutralizing agent, for pH control, as a dehydrochlorinating agent, and as an absorbent in off-gas scrubbing.

Due to the significant volume and diversity of uses of sodium hydroxide, IHS Markit prepared four research reports, each focusing on one of the following categories: organic chemicals, inorganic chemicals, pulp and paper, and specialty applications. In this report, IHS Markit researched the use of sodium hydroxide in organic chemical manufacture in which the sodium hydroxide is produced the traditional way by electrolysis as a co-product with chlorine. We refer to it as “electrolytic sodium hydroxide” to distinguish it from other methods to produce sodium hydroxide. We quantify the significant costs that would be incurred if consumers were deprived of access to electrolytic sodium hydroxide. For these consumers, the economic benefits can be measured as the opportunity cost of the next best alternative. We monetize these benefits by answering the question: what would it cost consumers to purchase a substitute product or substitute a non-electrolytic sodium hydroxide manufacturing process that provides the same level of performance or consumer satisfaction? To phrase it differently, what do consumers of these products gain by electrolytic sodium hydroxide?

In the absence of electrolytic sodium hydroxide, consumers would have limited choices of technically and economically acceptable substitutes. The most likely substitutes would be either soda ash or sodium hydroxide produced by treating soda ash solutions with slaked lime. In some applications, consumers may have sufficient incentives to use slaked lime directly as a substitute for electrolytic sodium hydroxide.

IHS Markit estimates that the economic benefit to consumers of electrolytic sodium hydroxide for organic chemical manufacture in the United States and Canada is approximately $714 million per year. The majority of these benefits, or $698 million per year, would accrue to consumers in the United States. The benefit for consumers in Canada would amount to $17 million per year. Substitution of alternative materials for non-electrolytic sodium hydroxide would require approximately $2.9 billion dollars in new investments, of which $2.8 billion of avoided capital expenditures would accrue to US consumers and $0.1 billion to Canadian consumers. The avoidance of these costs is part of the economic benefit of electrolytic sodium hydroxide.

Definitions

Chemical	Chemical formula	Chemical name
Trona	$Na_3(CO_3)(HCO_3)\cdot 2H_2O$	Hydrated sodium carbonate compound
Soda ash	Na_2CO_3	Sodium carbonate
Lime	CaO	Calcium oxide
Slaked lime	$Ca(OH)_2$	Calcium hydroxide formed when lime is mixed with water
Caustic soda	$NaOH$	Sodium hydroxide, caustic or lye

Source: IHS Markit

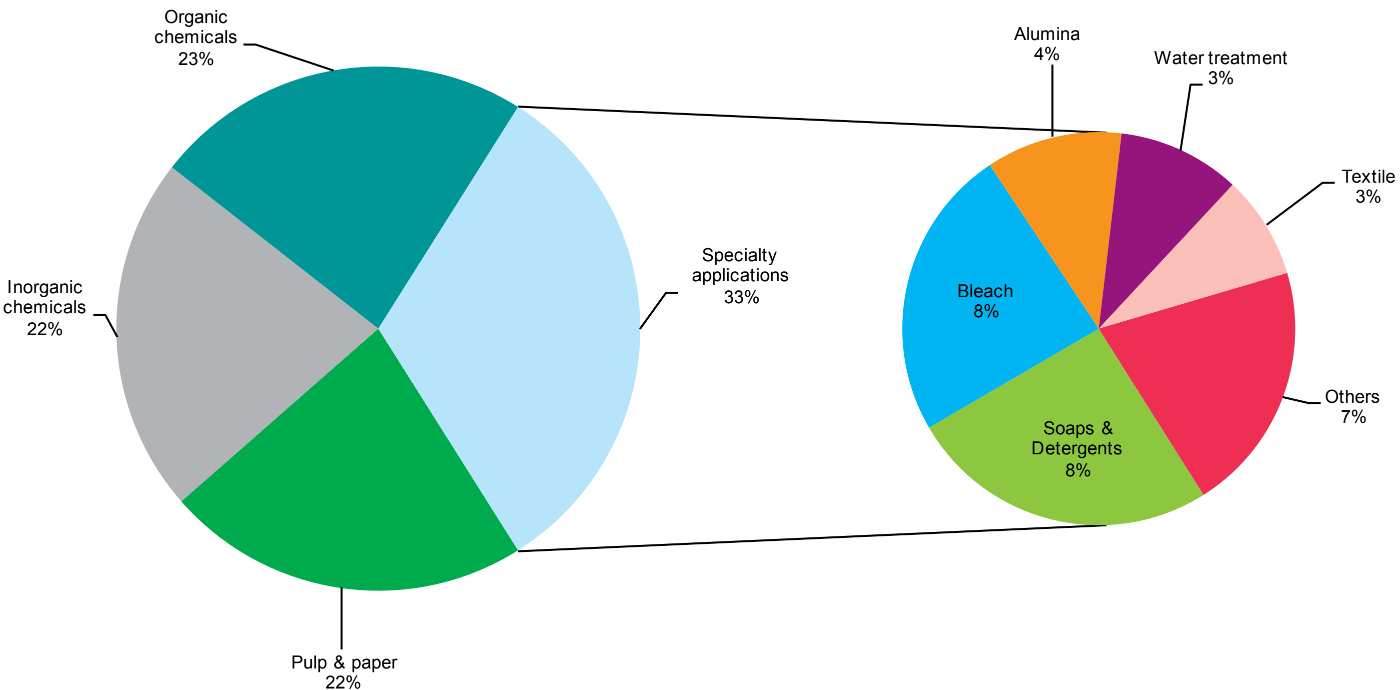
Introduction

Sodium hydroxide (also known as caustic soda, NaOH, or simply caustic) is a strong base used in a variety of end uses, especially within the manufacturing industry. Direct applications of sodium hydroxide include use in the pulp and paper, soaps and detergents, alumina, and textiles industries. Sodium hydroxide can be used as a neutralizing agent, for pH control, as a dehydrochlorinating agent, an absorbent in off-gas scrubbing, a catalyst, and as a source of sodium.

For purposes of this analysis, we have grouped the diverse uses of sodium hydroxide into four major categories: organic chemicals, inorganic chemicals, pulp and paper, and specialty applications.[1] Some of the major organic chemicals made from sodium hydroxide include propylene oxide, polycarbonates, ethyleneamines and epichlorohydrin; additionally, the manufacture of many organic chemicals uses sodium hydroxide in neutralization and gas scrubbing. Key inorganic chemicals made using sodium hydroxide include titanium dioxide, sodium silicates, sodium cyanide, and sulfur-containing compounds such as sodium hydrosulfide. This report evaluates the use of sodium hydroxide in the production of organic chemicals. The reader is referred to separate reports that evaluate its use in each of the other categories: inorganic chemicals, pulp and paper, and specialty applications.

Total US and Canadian demand for sodium hydroxide in 2015 totaled 12.4 million metric tons.[2] This was led by consumption for the production of inorganic chemicals and for pulp and paper, together making up 44% of total demand. In this report, unless otherwise noted, all volumes and costs refer to values in 2015.

United States & Canada: Sodium hydroxide demand by end use, 2015



Source: IHS Markit

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Sodium hydroxide—especially when used for pH control, neutralization of waste acids, and similar applications— competes with other alkalies, particularly sodium carbonate (more commonly known as soda ash) and lime. Sodium hydroxide is typically preferred as it is a stronger base, does not produce undesirable by-

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[1] The “specialty applications” category includes soaps & detergents, water treatment, alumina production, textiles processing, sodium hypochlorite, and miscellaneous uses.

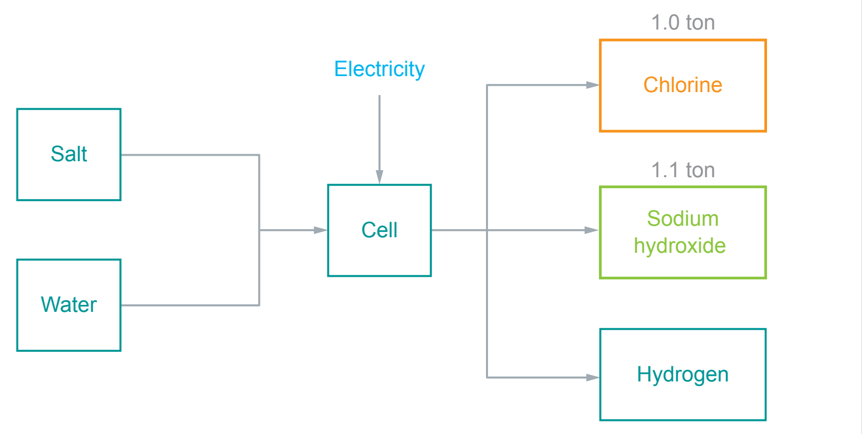
[2] IHS World Analysis Chlor Alkali, 2017.

products as is the case with lime, reacts faster than soda ash, is more soluble in water, and is easily handled as an aqueous solution.

Current technology for electrolytic sodium hydroxide

Current commercial technology produces sodium hydroxide and chlorine as co-products and together these two chemicals are regularly referred to as chlor-alkali.[3] By passing an electric current through a salt solution (commonly sodium chloride), the salt is decomposed into sodium ions at the cathode and chlorine ions at the anode. The ions lose their molecular charges at these electrodes, and neutral molecules are released. There is a defined ratio of products from this reaction; 1 unit of chlorine to 1.1 dry units of sodium hydroxide. This combined volume is called an electro chemical unit, or ECU. The figure illustrates the electrolytic process for making the co-products sodium hydroxide and chlorine.

Electrolytic production of sodium hydroxide and chlorine



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From the technology perspective, there are several variations of the electrolysis process. Globally, the most dominant process is the membrane cell process followed by diaphragm cell and mercury cell technology.[4] A relatively new modification of membrane technology is "brine-to-bleach" technology. It recombines the sodium hydroxide and chlorine streams in the integrated manufacture of sodium hypochlorite, or bleach.

Most producers set their production around chlorine demand, and as this demand can exhibit seasonality there can be frequent imbalances between supply and demand for sodium hydroxide causing price volatility. Additionally, the price for sodium hydroxide can vary significantly from end use to end use primarily due to significant disparities in purchase volumes. Unlike prices for many commodity chemicals, pricing for sodium hydroxide is opaque.

Most sodium hydroxide is produced and sold as a liquid solution, typically concentrated to 50% for commercial usage. Sodium hydroxide is also available as a solid or anhydrous material, which can be made in either flakes, beads (also called pearls or prills) or fused solid.

Sodium hydroxide in the production of organic chemicals

The largest single use for sodium hydroxide for organic chemical manufacture in North America is to manufacture propylene oxide via the chlorohydrin route. In this process, sodium hydroxide is consumed in the dehydrochlorination of propylene chlorohydrin to release propylene oxide. An alternative to using sodium hydroxide is using the less expensive slaked lime (calcium hydroxide), but the use of this substitute requires disposal of large volumes of calcium chloride by-product waste.

Another significant use is the production of epoxy resins, which are used in coatings, adhesives, and many other applications. Epoxy resins are mostly made from bisphenol A (BPA) and epichlorohydrin. Sodium

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[3] If potassium chloride (KCl) is used as the feedstock instead of salt (NaCl), the co-products will be chlorine and potassium hydroxide (KOH). Potassium hydroxide (also referred to as caustic potash) is also part of chlor-alkali.

[4] Mercury cell technology has largely been replaced. Diaphragm cell technology commands the majority share of installed capacity in the US and Canada.

hydroxide is typically used in the manufacture of epichlorohydrin (to convert the intermediate) and in the dehydrochlorination stage in epoxy resin manufacturing. Lime can also be used for the latter, but like propylene oxide production, it requires disposal of the by-product calcium chloride.

Ethyleneamines are another class of organic chemicals which utilize sodium hydroxide in their production. Via the ethylene dichloride (EDC) route, EDC is reacted with ammonia and the resulting amine hydrochloride solution is neutralized with sodium hydroxide to form ethylene amines. Sodium chloride is formed as a by-product.

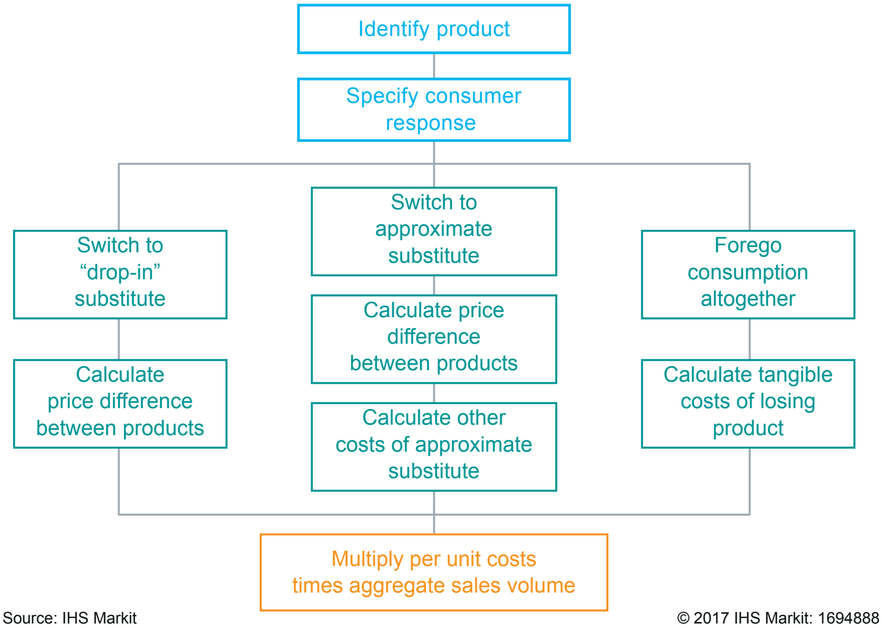
Polycarbonate production routes based on phosgene utilize sodium hydroxide. Sodium hydroxide is used to dissolve BPA, effectively making sodium BPA, which is phosgenated to form polycarbonate. Polycarbonate routes that are not based on phosgene have been developed and do not use sodium hydroxide.

Other examples of organic chemicals that consume sodium hydroxide in their production include: chelating agents such as ethylenediaminetetraacetic acid (EDTA), sodium citrate used as a builder in liquid laundry detergents, cellulose ethers used to modify flow properties in oil drilling muds, and pentaerythritol used in industrial coatings.

The total consumption of sodium hydroxide in the organic chemicals sector in 2015 is about 3.0 million tons per year, with about 42% used to produce propylene oxide, 6% used to produce epichlorohydrin, and 52% used for all other organic chemicals in this sector.

Economic benefits methodology

Range of potential consumer responses: Consumer benefits methodology



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The magnitude of the direct economic benefits that accrue to consumers in the United States and Canada by virtue of their access to electrolytic sodium hydroxide can be determined by estimating the differences in the total costs between the electrolytic sodium hydroxide they now use and the products that would be substituted if electrolytic sodium hydroxide was not available. A general methodology for estimating these benefits is illustrated in the figure.

Consumers normally make product or raw material selection decisions based on many considerations, not just the initial purchase price. At the manufacturing level, these factors may include ease of fabrication, compatibility with other components of a system, performance advantages, and the ability to reduce total costs through ease of installation, parts consolidation, or weight reduction. At the user level, reduced maintenance requirements, longer life, improved aesthetics, or increased convenience of use may be important considerations. If an alternative to electrolytic sodium hydroxide met all of these criteria, it would be considered a perfect or "drop-in" substitute, and the benefit to consumers of access to the sodium hydroxide product would be simply the difference in the initial prices of the products. Differences in product prices could result from differences in the costs of the raw materials used, in the costs of converting them into the finished products, and in the costs of putting them into service or installing them.

In practice, however, perfect substitution is quite difficult to achieve because different materials have different properties and attributes. This is certainly the case for finding a substitute for sodium hydroxide in many of its diverse end uses. If the products were perfectly substitutable and if the costs of the materials were not too dissimilar, the products should have comparable market shares in that application since consumers would have little reason to prefer one over the other. When a specific product has a commanding market share in a particular application, it usually indicates that products made from substitute materials are less desirable because of higher costs or lack of some other important performance attribute.

To the extent that an alternative material produces products that are deficient in one or more important attributes, substituting it for one containing electrolytic sodium hydroxide would constitute imperfect substitution. Imperfections could result from higher costs to put the product into service, differences in product life, higher maintenance requirements during use, differences in mechanical properties that would require changing component dimensions or altering other system components to accommodate them, or simply differences in the aesthetics due to changes in surface appearance or color. In these cases, the differences in costs to consumers would include not only the differences in initial costs, but differences due to the loss of utility experienced when using the imperfect substitute. In some cases, the loss of utility can be measured directly, as would be the case if a shorter life required that the consumer repurchase a substitute more frequently, or if the substitute material required more frequent or costlier maintenance. In other cases, utility loss is more difficult to measure, particularly when aesthetics are important in decision-making.

In extreme cases, if no good substitutes are available, consumers might be forced into making not-in-kind substitution choices or be forced to forgo consumption altogether. These conditions generally do not apply in the case of sodium hydroxide because substitutes are available, although most of them are imperfect in some respects. In some applications, however, insufficient capacity may exist to produce the amount of substitute materials required to displace the large volumes of electrolytic sodium hydroxide currently used. Additional capacity may need to be added, often with high capital requirements; and, the increased costs to bring non-electrolytic sodium hydroxide to market would be passed on to the consumers. In this case, the substitutes' prices would have to increase by amounts sufficient to justify the returns required on the capital invested. Avoidance of such price increases throughout the rest of the economy, and not just to the consumers of sodium hydroxide, represents an additional, indirect or derivative benefit that consumers enjoy through their access to electrolytic sodium hydroxide.

Alternative technologies for sodium hydroxide

Background

Sodium hydroxide, in either solid form or solution, is used in applications 1) where the sodium ion is required, but must be unaccompanied by such anions as chloride, nitrate, or carbonate; 2) where it is incorporated into a product, such as sodium-based soaps; or 3) where a strong base is required and the formation of solid by-products must be avoided. It may also be used in applications where less expensive options are available because of the convenience of storing, handling, and metering it, particularly in solution form.

Other bases might substitute for sodium hydroxide in certain applications, but are not considered generally acceptable substitutes for a variety of reasons. For example, potassium hydroxide could be substituted in applications where the sodium ion is not required and soluble reaction products are desired, but its cost in 2015 was over three times that of sodium hydroxide per mole and it is normally not an economically practical substitute. If the handling of solids or slurries and the potential formation of insoluble by-products can be tolerated, a low-cost base such as calcium hydroxide, or slaked lime, might be considered. Lime, calcium oxide, is used widely for neutralization of acidic streams, but can be inconvenient and expensive to store, handle, and meter in relatively small amounts; and, it cannot provide the sodium ion where it is required.

Although it is a weaker base than sodium hydroxide, sodium carbonate, or soda ash, can be a suitable substitute under circumstances where it is technically feasible and its cost at the point of application is lower than that of sodium hydroxide. For example, some pulp mills have installed storage, transfer and metering equipment for both sodium hydroxide solutions and solid soda ash, and can switch from one to the other depending on the delivered prices of the materials. This could be done in other applications where the presence of the carbonate anion is not technically objectionable, provided that the users are prepared to bear the expense of installing the equipment necessary to handle the solid soda ash and the economics favor the substitution.

In the absence of sodium hydroxide produced by electrolysis of brine solutions, consumers would have limited choices of technically and economically acceptable substitutes. The most likely substitutes would be either soda ash or sodium hydroxide produced by treating soda ash solutions with slaked lime [$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$]. In some applications, consumers may have sufficient incentives to use slaked lime directly as a substitute for electrolytic sodium hydroxide. Extensive substitution of soda ash for electrolytic sodium hydroxide would require substantial investment and development time.

Non-electrolytic sodium hydroxide

The United States is a major producer and exporter of low-cost soda ash, the great majority of which is obtained from trona ores mined in Wyoming. The dominant extractive technology is the monohydrate process in which the ores are crushed, calcined, and discharged into recycled aqueous solutions to dissolve their sodium carbonate content. Insoluble materials are removed from the solution and it is treated to remove organic impurities before being concentrated by evaporation and crystallization to produce a relatively pure monohydrate form. Soluble impurities are purged from the system and the recovered liquid is recycled to the dissolution step while the monohydrate crystals are washed and calcined to produce dense soda ash. The solids are cooled, screened to obtain the particle size distribution desired, and are transferred to storage and packaging. In 2015 soda ash production in the United States amounted to approximately 11.5 million metric tons per year of which about 5.2 million metric tons was consumed domestically, about a quarter of a million metric tons were exported to Canada, and about 6.1 million metric tons were exported to the rest of the world.[5] The large export share results from the favorable economics of the trona-based operations compared with the Solvay and similar processes used elsewhere in the world to produce sodium carbonate.

Sodium hydroxide can be produced from trona ores by treating the purified solution obtained from the calcined ore with a slurry of slaked lime in a multistage reaction system. The sodium carbonate and calcium hydroxide reactants are converted into a diluted solution of sodium hydroxide in a slurry of calcium carbonate in the reactor system, with the extent of conversion of sodium carbonate to the hydroxide depending on the solution concentration and reactor design. The calcium carbonate is separated from the slurry and calcined to produce calcium oxide, which is then slaked to produce a slurry of calcium hydroxide that is recycled back to the reaction system. The dilute sodium hydroxide solution is concentrated by evaporation to produce product for commercial use, typically at a concentration of 50% sodium hydroxide.

This process has not been used in the United States for many years because it cannot compete with production of electrolytic sodium hydroxide. In the absence of electrolytic sodium hydroxide, consumers would have to substitute either material produced chemically from trona ores, soda ash, or possibly lime where its use could be tolerated. Current consumption of electrolytic sodium hydroxide in the United States and Canada is about 12 million metric tons per year,[6] and substitution of this amount of material by a mix of soda ash and sodium hydroxide produced chemically from trona ores would require a major expansion of production in Wyoming. This would require very large investments in new mining and processing capacity and recovery of the capital invested would result both in an increase in the cost of the additional soda ash produced and the production of more expensive sodium hydroxide. While the necessary cost increase in soda ash might result in the repatriation of some material currently exported, the amount would not be nearly sufficient to meet the

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[5] IHS Soda Ash Industry Report, 2015.

[6] IHS World Analysis Chlor Alkali, 2017

increased demand. Additionally, on the order of three new world-scale plants for the production of soda ash and five for the production of sodium hydroxide from trona ores would be required.

Estimated costs of alternatives

IHS Markit estimated the capital requirements and costs required for new trona-based capacity and compared them to the average market prices for soda ash and electrolytic sodium hydroxide in 2015. The estimates were based on mines delivering about 4.2 million metric tons per year of ore to process plants producing either 2.3 million metric tons of dense soda ash or 1.6 million metric tons of sodium hydroxide as 50% solutions.

Estimated cost of new trona-based capacity, 2015 (‘000 MT)

Product	Cost component	Average market price, 2015	Estimated cost
Soda ash	Total investment ($/t)	N/A	528
	FOB price ($/t)	198	226
Sodium hydroxide	Total investment ($/t)	N/A	994
	FOB price ($/t)	380	408

Source: IHS Markit estimates

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The cost estimates for new capacity are for greenfield plants in Wyoming using natural gas for fuel. Use of coal would increase capital requirements, but decrease cash operating costs. The FOB[7] price includes the total of estimated plant cash operating costs, royalties and SG&A[8] expenses, plus an allowance for the returns on capital that would be required to justify the investment. Delivered to the markets, the average prices in 2015 of soda ash and sodium hydroxide differed by less than 10% on a contained sodium basis, so there is little incentive to substitute one for the other. However, the cost of producing non-electrolytic sodium hydroxide is much higher than producing electrolytic material, and would be around 25% higher than new soda ash material on a delivered, contained sodium basis.

Most sodium hydroxide solution is shipped to consumers by rail or barge, with smaller amounts shipped over shorter distances by truck. Almost 50% of chemical shipments in the United States and Canada, which includes shipments of sodium hydroxide, occur within the Southwest and Southeast regions of the United States, while less than 10% occur within the Mountain Pacific region, which includes the trona producing area of Wyoming. The shift of the geographic center of sodium hydroxide production from its current location on the US Gulf Coast to Wyoming would result in an increase in freight costs for most consumers as well as an increase in the FOB price of the material.[9]

This delivered price differential would provide sufficient incentive to not only install new solids storage and transfer and metering equipment for soda ash, but also to incur additional costs for their operation, provided that a sufficient return could be obtained on the new investment to justify the costs based on the savings in materials consumption. While the equipment is quite conventional in nature and easy to install and operate, provided that sufficient space is available, capital requirements are sensitive to the size of the operation. There are significant diseconomies of scale in small operations, and it is unlikely that the necessary investments and other costs can be justified if the amount of sodium hydroxide to be substituted for is less than about one thousand metric tons per year. The same consideration applies to the substitution of lime for trona-based sodium hydroxide.[10]

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[7] FOB is defined as free-on-board.

[8] SG&A is defined as the sum of selling, general, and administrative expenses.

[9] The freight costs estimated here are based on national averages in 2015. Individual costs are site specific and could be higher or lower that the national average.

[10] The costs of retrofitting soda ash or slaked lime equipment for those designed to use electrolytic sodium hydroxide are both site and process-specific as well as size dependent; small installations are economically disadvantaged in all cases.

Economic benefits in the production of organic chemicals

Almost half of sodium hydroxide consumed in the organic chemicals sector is used to produce propylene oxide and epichlorohydrin. Alternate processes exist for the manufacture of propylene oxide that do not require sodium hydroxide, but alternate processes for the manufacture of epichlorohydrin do require a base, as do the other half of organic chemicals manufacturing processes included in this sector.

The sodium hydroxide consumed in the manufacture of propylene oxide and epichlorohydrin is used to dehydrochlorinate the intermediate chemicals that are produced as precursors to the final products. The products of the dehydrochlorination reactions include a by-product stream of aqueous sodium chloride. The by-product stream is treated to remove dissolved organic compounds and is either disposed or recycled to an integrated chlor-alkali plant to regenerate the chlorine and sodium hydroxide used in the manufacturing process. It is technically feasible to use a slurry of slaked lime ($Ca(OH)_2$) derived from lime (CaO) as the base in the dehydrochlorination reactions, but the volumes of aqueous streams handled are almost five times those produced when sodium hydroxide is the base, and these larger volumes must be disposed of in an environmentally acceptable manner and significant capital investment would be required.

The balance of the sodium hydroxide consumed in this sector, which is highly fragmented in terms of the number and types of compounds produced, may also be used for dehydrochlorination, neutralization of acidic by-products, or have other uses specific to the chemistry of the compound being produced. In these uses, it is preferred on economic and operability grounds to use technically acceptable alternatives such as soda ash or lime.

The 2015 price of electrolytic sodium hydroxide was about $380 per ton, and we estimate that the average price of lime delivered to the producers of propylene oxide and epichlorohydrin would be about $131 per ton.[11, 12] Less lime than sodium hydroxide is required to dehydrochlorinate compounds (less than 0.8 t CaO/t NaOH). As a result, the producers would likely be willing to pay at least $130 per ton for the NaOH base – more than would be required for the equivalent amount of CaO base. The reason for this is that switching to CaO would require large investments to handle, transfer, slake and meter the lime, replace the dehydrochlorination reactor with a larger, more complex one, and treat a much larger volume of effluent. Since the difference between the delivered FOB price of non-electrolytic and electrolytic sodium hydroxide would be less than this, the producers would have no incentive to substitute lime for sodium hydroxide in this application.

This would apply to dehydrochlorination processes in the manufacture of other organic chemicals as well, where avoided costs would likely be even higher because of the diseconomies of scale of smaller production volumes. The choice of substitute for electrolytic sodium hydroxide in other applications would depend on both the specific chemistry involved and the scale of the operation.

Economic benefits of electrolytic sodium hydroxide in organic chemicals manufacture, 2015

	Units	United States	Canada	Total
Annual benefits	$MM/yr	697.5	16.7	714.2
Avoided capital expense	$B	2.8	0.1	2.9

Source: IHS Markit

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The benefits to consumers of the availability of electrolytic sodium hydroxide can be estimated as the costs that would be avoided by having to substitute the more expensive materials described above. IHS Markit estimates that the economic benefit to consumers of electrolytic sodium hydroxide for organic chemical manufacture in the United States and Canada is approximately $714 million per year. The majority of these benefits, or $698 million per year, would accrue to consumers in the United States. The benefit for consumers in Canada would amount to $17 million per year. Substitution of alternative materials

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[11] IHS Markit estimated an average market price including discount for 2015. This is an average contract price; prices are found to be sector/volume dependent therefore large quantity consumers will take discounts from this price point and only the smallest consumers pay the average price.

[12] IHS Markit estimates based on USGC average FOB price.

for non-electrolytic sodium hydroxide would require approximately $2.9 billion dollars in new investments, of which $2.8 billion of avoided capital expenditures would accrue to US consumers and $0.1 billion to Canadian consumers. The avoidance of these costs is part of the economic benefit of electrolytic sodium hydroxide.

Almost 97% of the annual benefits and the avoided capital expenditures would accrue to consumers in the United States because no electrolytic sodium hydroxide-consuming propylene oxide or epichlorohydrin are manufactured in Canada, and these compounds use significant amounts of electrolytic sodium hydroxide.

The economic benefits of sodium hydroxide in all uses

Sodium hydroxide is an exceptionally important chemical in our lives because it has so many diverse uses. The total consumption of electrolytic sodium hydroxide in 2015 amounted to approximately 11 million metric tons in the United States and 1 million metric tons in Canada, or 12 million metric tons overall. It is used in the manufacture of organic and inorganic chemicals, in pulp and paper manufacturing, and in a myriad of other uses. It is a versatile chemical that serves many functions, such as a catalyst, as a neutralization agent, as a source of sodium, and as an agent for removing hydrogen, chlorine or hydrogen chloride from various intermediate compounds. Consumption patterns are often difficult to establish since it is routinely used in many applications for acid neutralization and off-gas scrubbing.

The benefits to consumers of the availability of electrolytic sodium hydroxide can be estimated as the costs that would be avoided by having to substitute alternative materials or process technologies. In the absence of sodium hydroxide produced by electrolysis of brine solutions, consumers would have limited choices of technically and economically acceptable substitutes. The most likely substitutes would be either soda ash or trona-based non-electrolytic sodium hydroxide. Since the United States is a major producer of low-cost soda ash from trona mines in Wyoming, this would be the next best alternative in the vast majority of situations. In some applications, consumers may have sufficient incentives to use slaked lime directly as a substitute for electrolytic sodium hydroxide.

We estimate that the total benefits to consumers in the United States and Canada of the access to electrolytic sodium hydroxide used in the manufacture of inorganic and organic chemicals, pulp and paper production, and in specialty applications is almost $2.5 billion per year, or about $205 per metric ton of sodium hydroxide. The economic benefit for consumers in the United States amounts to $2.3 billion and the benefits for consumers in Canada amount to $0.2 billion.

Economic benefits to consumers of electrolytic sodium hydroxide, 2015
(million dollars per year)

	United States	Canada	Total
Organic chemicals	698	17	714
Inorganic chemicals	490	16	505
Pulp and paper	427	73	500
Specialty applications	691	109	801
Total	**2,306**	**215**	**2,521**

Source: IHS Markit © 2017 IHS Markit

In addition to these annual economic benefits, access to these alternative materials allows consumers to avoid capital expenditures of approximately $12.2 billion, primarily due to the avoided capital expenditures to open new trona mines in Wyoming and produce non-electrolytic sodium hydroxide. The avoided capital spending in the United States amounts to $11.1 billion and in Canada to $1.1 billion, or about $980 per metric ton of sodium hydroxide capacity.

Avoided capital expenditure due to electrolytic sodium hydroxide, 2015
(billions of dollars)

	United States	Canada	Total
Organic chemicals	2.8	0.1	2.9
Inorganic chemicals	2.7	0.1	2.8
Pulp and paper	2.3	0.4	2.7
Specialty applications	3.4	0.5	3.9
Total	**11.1**	**1.1**	**12.2**

Source: IHS Markit © 2017 IHS Markit