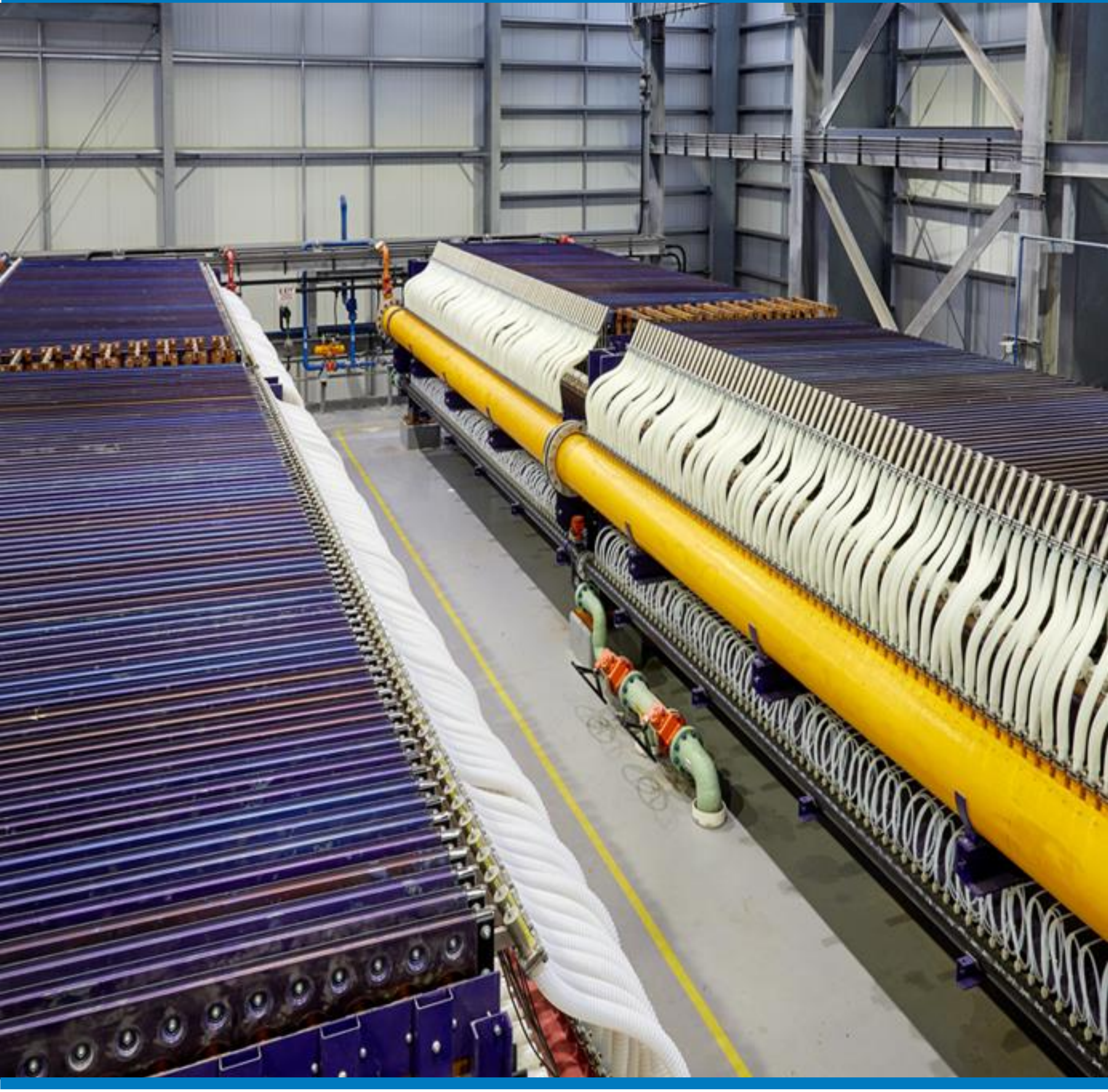
Energy Efficiency and Cost-Saving Opportunities for the Chlor-Alkali Industry

An ENERGY STAR® Guide for Energy and Plant Managers

January 2025

ENERGY STAR for Industrial Plants



United States Environmental Protection Agency

Document Number 430-R-24008
Office of Air and Radiation

Energy Efficiency and Cost-Saving Opportunities for the Chlor-Alkali Industry

An ENERGY STAR® Guide for Energy and Plant Managers

Katerina Kermeli, Utrecht University
Ernst Worrell, Utrecht University

Disclaimer

This guide was prepared for the United States Government and is believed to contain correct information. Neither the United States Government nor any agency thereof, nor any persons or organizations involved in its development, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe on privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or any persons or organizations involved in its development. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Development of this guide was funded by the U.S. Environmental Protection Agency. The research embodied in this report was supported through U.S. GSA Contract Number GS-00F-010CA, BPA 47QFDA21A0006BPA (ICF).

The cover photo is of the INEOS KOH plant cell room, courtesy of INEOS.

Table of Contents

Overview

This *Energy Guide* provides energy and plant managers with information to identify cost-effective practices and technologies for increasing energy efficiency and reducing energy-related greenhouse gas (GHG) emissions from plants dedicated to alkaline and chlorine manufacturing (NAICS 325181). The alkaline and chlorine industry, also known as the "chlor-alkali industry," includes plants primarily engaged in producing chlorine, sodium hydroxide (i.e., caustic soda), and other electrolysis co-products. Other important products include potassium hydroxide (i.e., caustic potash) or hydrochloric acid and sodium hypochlorite (bleach).

The energy efficiency and decarbonization opportunities addressed in this guide focus on the main processes involved in chlor-alkali production (i.e., brine preparation, brine electrolysis, and product processing) and common plant utility systems. Further, the guide addresses the systems, processes, and practices that account for the bulk of energy consumption. Detailed background information on the U.S. chlor-alkali market, manufacturing processes, energy consumption, and GHG emissions is provided in Appendix A and Appendix B of this guide.

Improving energy efficiency can produce savings that go directly to the bottom line of a plant or company. Further, implementing the energy-saving measures outlined in this guide can reduce energy consumption and potentially improve a plant's environmental performance and public image. This guide is organized as follows:

- **Chapters 1 and 2** explain the value of energy management and provide an overview of energy efficiency opportunities in chlor-alkali manufacturing.
- **Chapters 3 through 11** cover step-by-step best practices to save energy and reduce costs in common plant utility systems: motors, compressors, fans, pumps, coolers, hot water and steam generation, lighting, and building heating ventilation and air conditioning (HVAC).
- **Chapters 12 through 14** identify opportunities for optimizing and improving energy efficiency in the main chlor-alkali manufacturing processes.
- **Chapter 15** identifies opportunities for decarbonizing energy use.
- **Appendices** explain how energy is used in the chlor-alkali industry and in various processes and plant types, along with a variety of assessment approaches, standards, and guidelines for additional reference.

The estimated energy savings provided in this guide are intended as a source of information that must be evaluated by manufacturers for applicability to their unique circumstances. For any measure in this guide, users are cautioned to assess the project's economics, energy savings, and emission reductions for specific conditions at their plant.

The U.S. Environmental Protection Agency (EPA) offers tools and resources to help companies build strategic energy management programs that span all operations. Get started with ENERGY STAR at https://www.energystar.gov/industrial_plants/get-started-energy-star. Helpful resources can be found throughout the website to support development of an organization-wide energy program at no charge. If you have questions or need assistance with your energy program, contact energystrategy@energystar.gov.

Chapter 1: Why Energy Management Is Good for Your Business

Energy is of key importance for the future of your company, especially in times of strongly fluctuating energy prices and an energy sector that is transitioning to a sustainable energy system. This makes managing your energy use of strategic importance, not only for day-to-day operations but also for the long-term future of your company. Energy management is a set of practices that continuously drives down energy consumption and related costs in operations. It is a holistic approach to reduce energy use and costs in manufacturing plants and enable the transition to an environmentally and economically sustainable energy system. Energy projects, an important part of energy management, contribute savings to an energy management program. But energy management is more than just implementing energy projects. Organizations that experience the greatest financial returns from energy management establish effective and empowered energy programs that focus continuously on improving energy performance. The ENERGY STAR Guidelines for Energy Management provide a basic and adaptable framework for organizing energy management activities. See Appendix D: Energy Management Program Assessment Matrix for more details.

Did You Know?

Energy savings from improving energy efficiency go directly to a company's bottom line! Many companies can save 3% to 10% of energy costs annually.

Reducing the energy per unit of product is equal to growing your market share!

Energy management programs help companies control long-term energy risks and build business stability. Effective programs can reduce energy costs by 3% to 10% annually, depending on the business, and reduce GHG emissions associated with energy use (EPA 2006).

Beyond these direct benefits, well-run energy programs provide additional value. These energy programs support corporate sustainability efforts, help companies attract new talent, improve corporate reputation with stakeholders and communities, create value for corporate brands, and position companies to face risks from financial and climate-related impacts.

Corporate energy management programs focus on energy efficiency within manufacturing operations. Energy efficiency is a significant opportunity available to industry for decarbonizing operations, with the potential to reduce industrial emissions of carbon dioxide by up to 34% by 2050, according to the study by Worrell and Boyd (2022). Reducing the energy cost per unit of product (energy intensity) through energy efficiency is a practical method for growing market share. Energy efficiency is also the most cost-effective and foundational strategy for reducing direct and indirect GHG emissions from energy use.

Chapter 2: Where To Look for Energy Savings

By looking strategically at how energy is used throughout chlor-alkali manufacturing facilities, energy managers can better assess where energy efficiency efforts will have the greatest impacts. Start by identifying significant energy-using equipment and processes and quantifying the energy consumption of these systems. Reviewing energy use patterns and trends can help focus management efforts on areas and processes where improvements can save on operational costs. This chapter looks at where energy is consumed, as well as trends in energy consumption.

In the United States, the chlor-alkali industry is an important component of the U.S. chemical industry, supplying both chlorine and caustic soda needed for the manufacture of organic and inorganic chemicals, polymers, bleaches, pharmaceuticals, disinfectants, agricultural pesticides, and other products. Chlorine is a highly effective disinfectant used extensively in water treatment. It is estimated that in 2020, the U.S. chlor-alkali industry consumed 94 TBtu (28 TWh) of electricity and 36 TBtu of fuels, mainly natural gas.

Consider This

If you do not manage energy, your business is giving money away to the utility.

Chlorine manufacturing is electricity intensive with electricity forming the largest energy cost. In addition to the electricity costs, fuel costs are also important, especially when cogeneration units are in place. In 2020, the carbon dioxide (CO_2) emissions from generating steam, used primarily for heating brine and concentrating caustic soda, are estimated at 2.1 million tons. As the industry relies heavily on electricity, used almost entirely in electrolytic cells, the indirect emissions are significant, estimated at 14 million tons. At a glance, energy inputs at a chlor-alkali plant include the following.

- The most energy-intensive process in chlor-alkali manufacturing is electrolysis. It accounts for approximately 90% of the plant's electricity consumption. The next most energy-intensive process is caustic soda concentration, especially when plants operate diaphragm cells.
- Almost all fuel is used in boilers to generate steam needed for heating the brine and brine equipment, and for concentrating the caustic soda. When the plant uses cogeneration, fuel is consumed for both steam and electricity generation.
- Electricity is not only used in the electrolytic cells but throughout the entire plant. The other primary electricity users are motor systems, pumps, and air compressors.

Appendix B: Energy Consumption provides more details on energy use, CO_2 emissions, costs, and industry technology trends.

Energy Consumption Within the Chlor-Alkali Industry

In practice, the amount of energy and the proportion of energy used in each process step will vary among chlor-alkali plants, depending on the scale, source of raw materials (i.e., type of salt), type of technology used for electrolysis, product specifications (e.g., level of caustic soda concentration, need for chlorine liquefaction), and the efficiency of operations. The main process steps used in all chlor-alkali production facilities are the same. Variations are largely dependent on the type of cell technology used (i.e., mercury cells, diaphragm cells, and membrane cells). The three key manufacturing processes are outlined below and shown in Figure 1 (for more detail see Appendix A: The Chlor-Alkali Industry).

- **Brine preparation:** The brine is prepared based on electrolytic cell requirements. Key steps include saturating and resaturating the salt with water or depleted brine in vessels, removing impurities via precipitation and filtration, and dechlorinating the brine if brine is recirculated. Finally, the brine needs to undergo acidification to protect the anode coatings of the electrolytic cell. The brine is heated prior to entering the electrolysis cell.
- **Electrolysis:** The brine is electrolyzed in the electrolytic cell.
- **Product processing:** The main products are prepared (i.e., chlorine, caustic soda, and hydrogen for storage or further use). The chlorine extracted from all types of cells undergoes cooling, drying, and cleaning to avoid corrosion in downstream equipment; compression; and, if not used on site, liquefaction. The caustic soda is cooled and concentrated. If the caustic soda is produced in mercury cells, concentration is not needed. The by-product hydrogen is typically cooled and cleaned.

Generally, most fuel used on-site is for generating steam. When plants use cogeneration, fuel is used to generate both steam and electricity. Steam is used mainly to heat the brine and concentrate the caustic soda. Electricity is used throughout the plant, but the most significant consumer is the electrolytic cell. Other equipment with significant electricity use includes pumps for transferring the brine and products in the different equipment, compressors and chillers for compressing and cooling the chlorine and caustic soda, and rectifiers for providing direct current (DC) to the electrolytic cell.

Electrolysis accounts for about 90% of the electricity use in a chlor-alkali plant. There are three different cell technologies used: mercury cells, diaphragm cells, and membrane cells. Membrane cells are the newest and most energy-efficient technology with an electricity use range between 2,000 and 2,400 kWh/ton chlorine (Cl_2). Diaphragm cells are generally more energy intensive than membrane cells, requiring 2,100-2,600 kWh/ton Cl_2. At low current densities, diaphragm cells have an electricity use comparable to membrane cell technology. Mercury cells are the most electricity intensive, with electricity consumption of 2,800-3,100 kWh/ton Cl_2. The thermal demand of mercury cells is the lowest since the caustic solution produced does need concentration. The type of cell technology used affects the brine preparation process, with membrane plants requiring more sophisticated brine treatment. Diaphragm cells produce a less concentrated, “weaker” caustic solution resulting in higher thermal needs for caustic soda concentration.

In the U.S., there is currently only one mercury plant. Mercury plants are being phased out since the Minamata Convention entered into force, with most mercury plants ceasing operation by 2025.

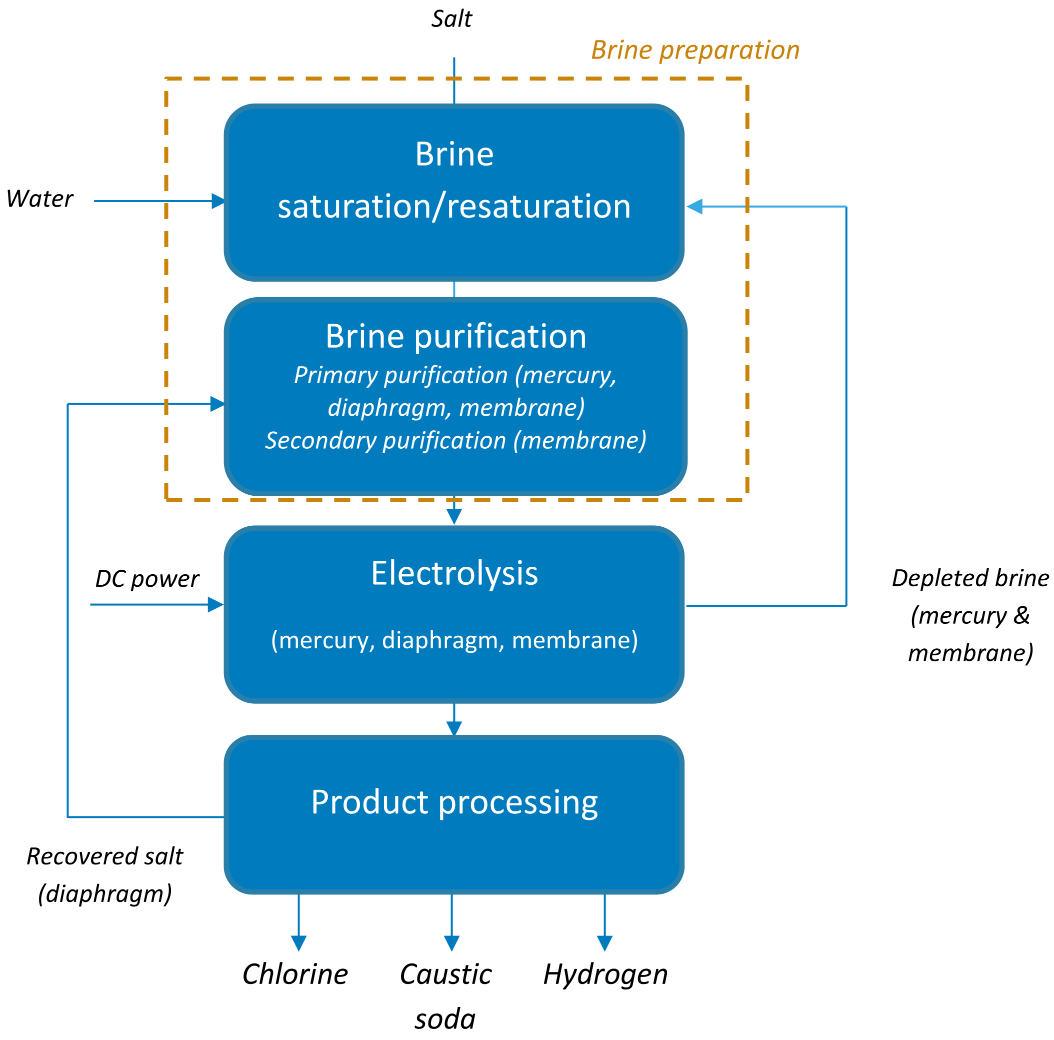


Figure 1: Major processes in chlor-alkali manufacturing

So where are the best opportunities to save energy and reduce costs given the trends in overall energy consumption in a chlor-alkali plant?

- Begin by improving operations and control of cross-cutting equipment that powers the production process of the plant, including motor systems, pumps, and compressors/chillers. These systems require regular maintenance, active oversight, and replacement of worn and obsolete equipment with more energy-efficient models when necessary.
- A second and equally important area is improving the efficiency of production processes (especially electrolysis and evaporation) and steam systems. Process optimization and the use of the most efficient technology are key to realizing energy savings in a plant's operations.

- Finally, look for opportunities to capture waste heat. Waste heat can be recovered from the electrolyzer and hot electrolysis products and used to raise the brine temperature and concentrate caustic soda.

While there may be opportunities to improve the chlor-alkali process, it may not always be feasible given product characteristics or other constraints. *However, energy use will almost always be associated with running equipment, pumping water, and heating and cooling activities. Opportunities to improve these systems can often be done without major changes to production processes.*

Energy Efficiency Opportunities

Use chapters 3 through 11 of this guide to identify energy efficiency measures found in common (or "cross-cutting") plant utility systems. These opportunities are also summarized in Table 1. Each of the systems is discussed in a separate chapter.

Chapters 12 through 14 explain energy efficiency opportunities that are unique to the processes found in chlor-alkali plants and are summarized in Table 2. Generally, each chapter begins with a description of the topic, a checklist for quick reference, and a description of best practices, starting with measures that are easier to implement. Figure 2 shows the key processes in a chlor-alkali plant and the common plant systems that are most applicable.

Figure 2: Core production processes and energy-consuming support equipment in chlor-alkali manufacturing

CORE PRODUCTION PROCESSES	Brine preparation	Electrolysis	Product processing
Core Process	Chapter 12: Brine preparation	Chapter 13: Electrolysis	Chapter 14: Product Processing
Key Supporting Equipment	Chapter 4: Motor Systems, Chapter 7: Pump Systems, & Chapter 9: Hot Water and Steam Systems	Transformers/rectifiers in Chapter 13: Electrolysis	Chapter 4: Motor Systems, Chapter 5: Compressed Air Systems, Chapter 7: Pump Systems, Chapter 8: Cooling Systems & Chapter 9: Hot Water and Steam Systems

Table 1: Summary of general energy efficiency measures

Chapter 3: Energy Management Programs and Systems	
Build an energy management program	Apply principles for developing energy management programs and systems
Use ENERGY STAR tools and resources	Install energy monitoring and advanced control systems
Chapter 4: Motor Systems	
Create a motor management plan	Purchase energy-efficient motors
Perform ongoing maintenance	Properly size and specify motors
Employ motor labeling	Automate motors
Use adjustable-speed drives (ASDs)	Correct power factor and vary motor speed according to demand
Minimize voltage unbalances	Use soft starters
Use advanced motor technologies	
Chapter 5: Compressed Air Systems	
Maintain systems	Monitor systems effectively
Reduce leaks	Turn off unnecessary compressed air
Modify the system instead of increasing pressure	Replace compressed air with other energy sources
Minimize pressure drops	Maximize allowable pressure dew point at the air intake
Improve load management	Reduce inlet air temperature
Optimize compressor controls and strategies	Properly size pipe diameters
Recover heat for water preheating or space heating	
Chapter 6: Fan Systems	
Maintain systems properly	Properly size fans
Use ASDs and improved controls	Install high-efficiency belts (cogged V-belts)
Repair duct leaks	Avoid system effect
Chapter 7: Pump Systems	
Maintain pump systems	Monitor the pump system
Minimize pump demand	Install/optimize controls

Install high-efficiency pumps	Properly size pumps
Use multiple pumps for variable loads	Install ASDs
Trim impellers	Avoid throttling and pressure-reducing valves
Replace belts when needed	Properly size piping
Clear the piping	Use precision casting, surface coatings, or polishing
Maintain proper seals	Reduce leakage through clearance reduction
Replace condensate return electric pumps with pressure powered pumps	
Chapter 8: Cooling Systems	
Chillers	
Check that system delta-T is equal to design delta-T	Optimize condenser and evaporator parameters
Keep heat transfer surfaces clean	Maintain adequate condenser water flow
Remove trapped air from the condenser	Install ASDs on centrifugal chillers
Change compressors to meet demand	Manage the load between chillers
Use free cooling	Choose the right cooling system
Use energy-efficient chillers	Use absorption chillers when waste heat is available
Use electric-drive centrifugal chillers	Use magnetic-drive chillers
Cooling Towers	
Use a cooling tower instead of a chiller	Use ASDs on cooling tower fans
Run pumps without fans when weather conditions permit	Schedule cleaning and maintenance
Monitor fill	Use water treatment systems for water makeup
Auxiliary Equipment	
Optimize the performance of auxiliary equipment	Use a trim cooler when dry bulb temperature is high
Use a chilled water tank/ice storage	Implement side-stream filtration systems
Install temperature control units (TCUs)	Use microchannel heat exchangers

Use pre-insulated acrylonitrile butadiene styrene (ABS) piping	Insulate the cooling line and jacket
Refrigerants	
Use low global warming potential (GWP) refrigerants	Monitor refrigerant charge
Monitor refrigerant contamination	
Cooling System Configurations	
Convert systems from constant to variable flow	Inspect frequently
Use infrared cameras to spot losses	Improve operations and maintenance (O&M)
Use glycol refrigerant for systems that must reach temperatures below -4°F (-20°C)	Replace glycol solution with water during warm months
Use refractometers to adjust the solution concentration	Recover waste heat
Monitor the overall system and individual equipment efficiency	Use controls to optimize the system
Integrate with the building management system (BMS)	Consider tri-generation
Chapter 9: Hot Water and Steam Systems	
Steam Supply—Boiler	
Match steam demand	Control boiler allocation
Install boiler flue shutoff dampers	Perform maintenance
Improve or repair mechanical insulation	Reduce fouling/clean boiler heat transfer surfaces
Optimize the boiler blowdown rate	Reduce excessive flue gas quantities
Reduce excess air	Monitor flue gas
Install turbulators on two- and three-pass fire-tube boilers	Use an economizer
Use a deaerator tank	Recover heat from boiler blowdown
Recover condensate	Install a modulating burner on the boiler
Consider electric boilers	Consider once-through boilers

Switch to more efficient and lower-carbon fuels	Consider solar-powered boilers
Steam Supply—Combined Heat and Power (CHP)	
Install gas turbines	Use reciprocating engines
Convert waste heat to power	
Steam Distribution	
Shut off excess distribution lines	Properly size piping
Insulate steam lines and vessels	Check and monitor steam traps
Use thermostatic steam traps	Shut off steam traps
Reduce distribution pipe leaks	Recover low-pressure waste steam through vapor recompression
Recover flash steam	Perform total site pinch analysis
Chapter 10: Lighting	
Turn off lights in unoccupied areas	Use occupancy sensors and other lighting controls
Upgrade exit signs to light-emitting diode (LED) signs	Use LED lighting
Update conventional lights	Replace magnetic ballasts with electronic ballasts
Reduce lighting system voltage	Use daylighting
Use brighter or more reflective finishes	Use photocell sensors for outdoor lighting
Chapter 11: Building HVAC	
Employ an energy-efficient system design	Consider recommissioning before replacing
Install energy monitoring and advanced control systems	Adjust non-production setback temperatures
Repair leaks	Consider variable air volume systems
Install ASDs	Consider heat recovery systems
Modify your fans	Use ventilation fans
Install efficient exhaust fans	Add building insulation
Employ solar air heating	Modify building reflection
Install low-emittance (Low-E) windows	

Table 2: Summary of energy efficiency measures specific to chlor-alkali plants

Chapter 12: Brine Preparation	
Use high-purity brine	Employ nanofiltration
Use iron (III) meso-tartrate for anticaking	Avoid salt pile dissolving
Use fluidized salt saturators	Minimize fouling
Recover waste heat from electrolysis products for brine heating	Recover waste heat from cell rooms for brine heating
Adjust the brine recirculation process to limit brine heating	Minimize clarifier and dissolver heat losses
Use online impurity control	Use a once-through brine system
Use multiple effect evaporation	Use mechanical vapor recompression
Use thermal vapor recompression	
Chapter 13: Electrolysis	
Electrolytic cell	
Switch to bipolar membrane electrolyzers	Operate bipolar electrolyzers in series
Convert from asbestos diaphragm to membrane technology	Use asbestos-free diaphragms
Use high-performance membranes (zero-gap electrolysis)	Replace aging membranes with new ones
Convert to oxygen depolarized cathodes (ODCs)	Recoat cathodes and anodes when needed
Consider adding cells to lower the current density	Improve cell control
Increase electrolyte temperature	Decrease electrolyte concentration
Accurately control brine flux	Maintain and control the structural and contact voltage drop
Avoid fluctuations	Use high-performance electrodes and coatings
Increase capacity for peak shaving	
Transformer-rectifier	
Use energy-efficient transformers	Place transformers closer to the load
Connect transformers in parallel	Operate transformer-rectifier systems close to the designed capacity
Use energy-efficient rectifiers	Install capacitors to improve the power factor
Install harmonic filters	

Chapter 14: Product Processing	
Chlorine	
Employ high-pressure liquefaction	Employ multistage liquefaction
Use electronic expansion valves	Clean the condenser and the evaporator when needed
Employ closed-circuit direct chlorine cooling	
Caustic Soda	
Reduce the needs for 50 wt.% NaOH	Use a four-stage caustic soda evaporation system in membrane cell plants
Increase the effects in caustic soda evaporation for diaphragm cells	Use mechanical vapor recompression for caustic soda evaporation
Properly heat and insulate caustic soda storage tanks	Properly heat and insulate piping
Hydrogen	
Combust hydrogen (H_2) for heat generation	Use H_2 in fuel cells to generate electricity and heat

Chapter 3: Energy Management Programs and Systems

In this chapter:	
Build an energy management program	Apply principles for developing energy management programs and systems
Use ENERGY STAR tools and resources	Install energy monitoring and advanced control systems

Building an energy management program is the first step to increasing energy efficiency and saving money. Energy management is a strategic approach consisting of a set of practices that continuously drive down energy consumption in operations. Energy management relies on a systematic and strategic approach and is more than just implementing individual energy projects. Industrial plants that appointed an energy manager responsible for the energy program experienced energy savings of about 6.4%, and those that undertook energy audits achieved energy savings of about 6.9% (Boyd et al. 2021). EPA, through ENERGY STAR, has seen companies that successfully manage energy achieve consistent savings over time. Furthermore, a corporate culture that encourages energy efficiency not only saves energy and money but also can enhance the reputation of the company through the emission-related reductions that are achieved through energy management.

Energy Savings Checklist: Energy Management

Energy Management Checklist	✓
Understand your energy use.	
Set goals.	
Assess plants for energy savings.	
Set an improvement plan.	
Develop good operations and maintenance (O&M) practices.	
Track and benchmark energy use.	
Encourage behavior changes and engage employees.	
Recognize and reward energy achievements.	

Best Practices for Energy Management Programs and Systems

- **Build an energy management program.** By constructing an energy management program, you can assess your energy consumption, motivate energy teams to manage energy across all facilities, and continuously benchmark and improve your company's energy performance.

- **Apply the principles for developing energy management programs and systems.** ENERGY STAR Guidelines for Energy Management can inform the development of your program through key actions for success.
- **Use the ENERGY STAR tools and resources.** ENERGY STAR offers a variety of assessment tools, guides, communication materials, and other resources to support your energy program.
- **Install energy monitoring and advanced controls.** Energy efficiency, product quality, and productivity can be improved with the use of submetering, monitoring and advanced controlling of processes.

Build an energy management program

Successful energy management goes beyond installing energy-efficient equipment. ENERGY STAR's Guidelines for Energy Management are designed to help companies develop an energy management program for continuous energy performance improvement. The guidelines describe in seven steps how to set up an energy program, and include suggested best practices from successful ENERGY STAR partner companies (e.g., how to establish an energy team and how to track plant data and set goals).

The Guidelines' seven steps form a solid basis for an energy program across a plant or company's operations. A few, key highlights include: (1) energy assessments; (2) energy teams; and (3) energy tracking, measurement, and benchmarking.

1. Assess the energy efficiency of your plant(s).

   Assessing how, where, and how much energy is used in a plant helps determine the steps needed to improve the facility's energy efficiency and to save money. Assessments may be focused on the whole site or specific systems and processes.

   Assessments may be conducted by company staff, the local electric utility, contractors, or government programs.

   - **Staff teams.** If company employees perform the plant assessment, include staff from various departments across the facility. This brings together a spectrum of experience and knowledge of the plant and its processes. Facilities of any size can successfully use this method. ENERGY STAR provides guidance for a type of assessment that uses employee teams, the Energy Treasure Hunt.
   - **Electric utility program.** Local utility companies work with their industrial clients to achieve energy savings in existing facilities and in the design of new facilities. Check with your local electric or gas utility to see what assistance it provides. Utilities sometimes offer specific programs for improving plant systems, such as lighting or motors.
   - **Federal government programs.** The U.S. Department of Energy (DOE) supports small and medium-sized industry through no-charge plant assessments conducted under the Industrial Training and Assessment Center (ITAC, formerly IAC) program. Universities that participate in the program offer assessments led by experienced engineering faculty and performed by both graduate and undergraduate students. ITACs are

Did You Know?

The cost of paying one employee to lead an energy management program should be more than recovered by potential energy savings!

designed to help small- and medium-sized enterprises save energy, improve productivity, and reduce waste by implementing recommendations identified during these assessments. After the site visit, the ITAC team provides a comprehensive report with specific details on all opportunities identified for improving competitiveness, including applicable rebates and incentives. In addition, as part of the recently passed Bi-partisan Infrastructure Law, qualifying small and medium-sized U.S. manufacturers that receive an ITAC, Onsite Energy/Combined Heat & Power Technical Assistance Partnerships, or qualified third-party equivalent assessment can now apply for grants for implementation of assessment recommendations at up to 50% of qualifying project costs with a maximum of **$300,000** ***per grant***.

2. Build an energy team.

   Establishing an energy team is an important part of making a commitment to energy management because a team can accomplish much more than a single person. The energy team is responsible for planning, implementing, benchmarking, monitoring, communicating, recognizing good performance and evaluating the organizational energy management program. The ENERGY STAR Teaming Up to Save Energy guide is designed to help organizations develop effective energy teams. The guide provides advice, checklists, and examples for starting an energy program, organizing an energy team, building capacity, sustaining the team, and maintaining momentum (see also Appendix E: Teaming Up to Save Energy Checklist).

3. Monitor your energy systems.

   Every company should compile, track, and benchmark energy data. Reliable energy data helps you manage energy and interpret energy efficiency trends over time so you can take corrective action when necessary.

   Monitoring energy is important because it:

   - Identifies increased energy use and costs that could be caused by operational inefficiencies.
   - Supports a plant's participation in emergency demand response programs where utility companies provide financial incentives to customers who reduce their energy loads during peak demand times.
   - Provides data useful for corporate GHG accounting initiatives.

   Data on energy use can be found in utility bills, in fuel purchase receipts, and from self-installed meters. Using an energy monitoring system is ideal. It requires little or no up-front capital and can result in immediate savings.

   Energy monitoring systems include submeters at key areas in a plant to strategically track and manage energy. Submetering of production departments can provide improved metrics and enable quick pinpointing of areas where energy problems may exist. The meters' data should be managed with a data management tool. A simple spreadsheet may be sufficient, or tailored software is also available.

   In its basic form, an energy monitoring system should be based on the following:

   - Monthly utility billing and energy-use data for the past 12 to 24 months.
   - Monthly production figures.

A simple spreadsheet may be used to plot graphs for visually understanding the relationship between energy use and production as well as to identify any trends. Graphs can be made for fuel and electricity separately, as well as for total energy use (showing both in the same units, such as megajoules [MJ] or British thermal units [Btu]) and costs. For example:

- Graphs of energy use and production over time.
- Graphs of energy costs and production over time.
- Graphs of energy use on the vertical axis against production on the horizontal axis.
- Graphs of energy use divided by production (showing specific energy consumption or energy intensity).

Often the analysis will show periods of good performance and poor performance. This information helps with setting targets for energy consumption based on expected production volumes. Tracking energy use by entering new data and re-evaluating it regularly will help identify problems and improve energy savings.

The ENERGY STAR Energy Tracking Tool is available at no cost to companies and sites for use in tracking energy. Another software tool is VERIFI, offered by the DOE. This dashboarding tool helps monitor, track, and improve the understanding of energy, water, waste, and GHG emission patterns.

Apply principles for developing energy management programs and systems

An organization-wide energy management program is the best way to save energy and money. It does not matter whether your company is big or small—any company can do it! Simply apply the following basic principles:

1. Make energy a priority.

   Everyone in the company*, especially senior management,* must recognize that reducing energy use is an important business objective that must be a part of decision-making.

2. Commit to saving energy.

   Every level of the organization must support the commitment to improve energy efficiency.

3. Assign responsibility.

   Someone must be assigned responsibility for managing energy across the company. Depending on the energy spend of your organization, the annual pay for a corporate energy manager often is more than covered by the costs of the energy you will save. An energy team with roles assigned to each member is a practical way to share the load across all facilities.

4. Look beyond your initial costs.

   You get what you pay for. Energy-efficient equipment and products may cost more initially but the long-term savings will surpass the initial costs.

5. Make energy management a continuous process – not a single project and done.

Use ENERGY STAR tools and resources

The EPA offers tools and resources to help companies build a strategic energy management program that spans all operations. Begin online at the ENERGY STAR for Industry website. Helpful resources can be found throughout the site, which is designed to walk you through the main steps of building an organization-wide energy program at no charge to your company.

To assess how well your company currently manages energy, use the ENERGY STAR Energy Program Assessment Matrix, located within the ENERGY STAR Guidelines for Energy Management. You may also locate the matrix in Appendix D: Energy Management Program Assessment Matrix of this guide. If your company has questions or needs assistance with building a corporate energy program, ask for assistance at energystrategy@energystar.gov.

Install energy monitoring and advanced control systems

The use of energy monitoring and process control systems can play an important role in energy management and in reducing energy use. These may include submetering, monitoring, and control systems. They can reduce the time required to perform complex tasks, often improve product and data quality and consistency, optimize process operations, and improve production budgeting. Although energy management systems are already widely disseminated in various industrial sectors, the performance of the systems can still be improved as automated controls and sensors become available. This reduces costs and increases energy savings further. Modern control systems are often not solely designed for energy efficiency but rather for improving productivity, product quality, and the efficiency of a production line. The systems can reduce the time required to perform complex tasks, often improve product and data quality and consistency, and optimize process operations. Monitoring and control systems can typically achieve energy savings of about 5%, while larger savings have been found in some cases. The savings and payback can vary greatly from plant to plant.

Artificial intelligence (AI) applied to industrial processes, also known as industrial artificial intelligence (IAI), can be used to improve productivity, resiliency, safety, and the sustainability of manufacturing operations and supply chains (Konrad 2024; NIST 2023). For example, IAI systems can be used to analyze historical data to identify patterns that are indicative of impending accidents and enable proactive intervention measures (Mao et al. 2019). With the use of AI-driven predictive modeling, AI systems can complement engineers' work. Plants can dynamically adjust process parameters, optimize energy and resource use, and reduce production costs (Shinkevich et al. 2021). Due to its reliance on large data sets, current IAI will primarily help optimization of operating plants (John et al. 2022).

The integration of AI in the industry is not novel, but its full potential is yet to be realized (Venkatasubramanian 2019). Some key IAI applications that could improve energy efficiencies in existing plants are (Yokogawa 2022):

- **Operation optimization.** AI can be used to monitor, control, and extract peak performance levels from assets and labor and thereby reduce energy use and manufacturing costs.
- **Trouble loss minimization.** AI can be used to detect and/or proactively predict damage to equipment or developing failure and thereby reduce production losses.
- **Supply chain efficiency.** AI can be used to monitor and manage the storage and supply of raw materials and intermediate and finished industrial products.

- **Quality stabilization.** AI can be used to monitor the quality of raw materials and to understand the impact of raw material quality on the finished product quality.
- **Advanced operations.** AI can be used to analyze the best practices of the best-performing plants and use the insights to improve operations in other plants across the company.

In the chlor-alkali industry, automatic process monitoring and fault diagnosis using well-known AI, such as artificial neural networks (ANNs) and support vector machines (SVMs), is not widespread. So far, SVMs and ANNs have been used to predict the cell voltage and the current efficiency of membrane cells. Generic algorithms (GA) have been used to find the best operating parameters (e.g., anolyte pH, flow rate and temperature, brine concentration), and Fuzzy fault tree analysis (FFTA) has been used to find the cause of chlorine releases (Batista et al. 2013).

Many AI process monitoring systems are currently in development. For example, Castlet is working on the development of an AI system for enhancing the monitoring of chlor-alkali cell process lines. The system will be able to monitor several critical parameters such as the individual cell voltage, total electrolyzer voltage, symmetry within each electrolyzer, and total electrolyzer current (CASTLET n.d.).

Chapter 4: Motor Systems

In this chapter:	
Create a motor management plan	Purchase energy-efficient motors
Perform ongoing maintenance	Properly size and specify motors
Employ motor labeling	Automate motors
Use adjustable-speed drives (ASDs)	Correct power factor and vary motor speed according to demand
Minimize voltage unbalances	Use soft starters
Use advanced motor technologies	

In chlor-alkali plants, motors are mainly used to drive pumps, compressors, mixers, belt systems and bucket elevators, and controls. The overall electricity consumption by electrical equipment, such as motors, pumps, and compressors, is about 170 kWh/ton Cl_2 (190 kWh/tonne Cl_2) (Brinkmann et al. 2014).

Using a "systems approach" to consider energy efficiency improvements for motors includes both the energy supply and energy demand sides of motor systems, as well as how these interact, to optimize total system performance. This includes not only energy use but also system uptime and productivity.

A systems approach involves the following steps.

1. Locate and identify all applications of motors in a facility.
2. Document the conditions and specifications of each motor in a current systems inventory.
3. Assess the needs and the actual use of the motor systems to determine if motors are properly sized and how well each meets the needs of its driven equipment.
4. Collect information on potential repairs and upgrades to the motor systems, including the economic costs and benefits of implementing repairs and upgrades to inform decisions.
5. Monitor the performance of the upgraded motor systems to determine the actual cost savings when upgrades are completed (SCE 2003).

Systems Approach

A systems approach strives to optimize the energy efficiency of an entire system. For motor systems this includes driven equipment such as pumps, fans, compressors, and controls, not just the energy efficiency of motors as single components.

The motor system energy efficiency measures below reflect important aspects of this systems approach, including matching motor speeds and loads, proper motor sizing, and upgrading system components.

Energy Savings Checklist: Motor Systems

To achieve energy efficiency improvements to motor systems, it is important to address the energy efficiency of the entire motor system. Use the checklist below to find new ways to save energy and money with motor system improvements.

Motor Checklist	✓
Are motors properly sized and specified?	
Are motors maintained properly?	
Can adjustable- or variable-speed drives be installed?	
Can existing technology be made more energy efficient?	
Do you have a motor management program?	

Best Practices for Energy-Efficient Motor Systems

- **Create a motor management plan.** A motor management plan can help companies realize energy savings and ensure that system failures are handled quickly and cost-effectively.
- **Purchase energy-efficient motors.** Considering life cycle costs and motor efficiency can reduce motor system life cycle costs.
- **Perform ongoing maintenance.** Motor maintenance prolongs motor life and helps foresee motor failure. Part of maintenance is also to assess whether replacing a motor is more energy- and cost-efficient.

Replacing a motor with a more efficient one can achieve an energy savings of 5% to 10%.

- **Properly size and specify motors.** Replacing oversized motors with properly sized motors saves U.S. industry, on average, 1.2% of total motor system electricity consumption.
- **Employ motor labeling.** Motors not in use should be identified and powered off.
- **Automate motors.** Running motors only when needed saves energy and does not significantly affect the lifetime of the motor.
- **Use ASDs.** ASDs better match speed to load requirements for motor operations and ensure that motor energy use is optimized to a given application.
- **Correct power factor.** Reducing the magnitude of reactive power in the system can reduce power consumption.
- **Minimize voltage unbalances.** Monitor voltages and minimize imbalances to increase motor efficiency.
- **Use soft starters.** Soft starters reduce power use during motor startup.
- **Use advanced motor technologies.** Install new motor designs and improve energy even further.

Create a motor management plan

A motor management plan is an essential part of a plant's energy management strategy. A motor management plan helps companies realize long-term motor system energy savings and ensures that motor failures are handled quickly and cost-effectively. The Motor Decisions Matter^{SM} campaign suggested the following key activities for a sound motor management plan (MDM 2012):

1. Create a motor survey and tracking program.
2. Develop guidelines for proactive repair/replace decisions.
3. Prepare for motor failure by creating a spare motor inventory.
4. Develop a purchasing specification.
5. Develop a repair specification.
6. Develop and implement a predictive and preventive maintenance program.

It is important to develop a motor purchasing policy and to stock a selection of preferred premium efficiency motors to replace existing motors at failure. Otherwise, it is likely and common that the motors will be replaced by less-efficient alternatives based on what is readily available after failure. Also, specific applications require the installation of specific types of motors. For example, if a plant has a motor that serves a baghouse fan, it needs to be a TEFC (totally enclosed, fan-cooled) motor. Otherwise, dust will enter the motor and the plant will experience unplanned downtime.

The Motor Decisions Matter^{SM} campaign's *Motor Planning Kit* contains further details on each of these elements (MDM 2012).

Purchase energy-efficient motors

Several factors are important when selecting a motor, including motor speed, horsepower, enclosure type, temperature rating, efficiency level, and quality of power supply. When selecting and purchasing a motor, it is also critical to consider the life cycle costs of that motor rather than just the price of its initial purchase and installation. Life cycle costing (LCC) is an accounting framework that enables calculation of the total costs of ownership for different investment options, leading to a sound evaluation of competing options in motor purchasing and repair or replacement decisions (Tolvanen 2008). A specific LCC guide has been developed for pump systems (DOE 2001), which also provides an introduction to LCC for motor systems.

Motor Selection

Up to 95% of a motor's costs can be attributed to the energy it consumes over its lifetime, while only around 5% of a motor's costs are typically attributed to its purchase, installation, and maintenance (MDM 2012).

The selection of energy-efficient motors is an important strategy for reducing motor system life cycle costs. Energy-efficient motors reduce energy losses through improved design, better materials, tighter tolerances, and improved manufacturing techniques. With proper installation, energy-efficient motors can also run cooler (which may help reduce facility heating loads) and have higher service factors, longer bearing life, longer insulation life, and less vibration.

To be considered energy efficient in the United States, a motor must meet performance criteria published by the National Electrical Manufacturers Association (NEMA). See Appendix C: Standards for NEMA Motors for more information. While some motors are exempt from the regulation, most new motors commercially available today need to meet the premium efficiency performance levels. Table 3 shows the average energy efficiency of motors currently installed in U.S. industry and the premium efficiency performance level. The premium efficiency performance is higher than the average installed at all horsepower ranges (Rao et al. 2022).

Table 3: Average energy efficiency of installed motors compared to premium efficiency level motors (Rao et al. 2022)

Motor size bin (hp)	Average efficiency of installed industrial motors (%)	Premium efficiency performance level (%)
1.0-6.0	83	86.4-90.1
6.0-21.0	89	89.2-93.1
21.0-51.0	92	92.0-94.7
51.0-101.0	93	94.1-95.9
101.0-201.0	93	94.5-96.2
201.0-501.0	93	94.5-96.2
501.0-1,001.0	93	-
1,001.0-2,001.0	92	-
2,001.0-5,001.0	86	-
5,001.0-inf.	91	-

The choice of installing a premium efficiency motor depends on motor operating conditions and the life cycle costs associated with the investment. In general, premium efficiency motors are most economically attractive when they replace motors with annual operations exceeding 2,000 hours/yr., when utility rates are high, when the costs for repairing the motors are an important fraction of the new replacement motor, and when conservation incentives are available (DOE 2012c). DOE's MEASUR tool has a motor inventory management module where users can input their motors and analyze energy efficiency options (e.g., rewinding vs. replacing with more energy-efficient motors). See Appendix F: Support Programs for Industrial Energy Efficiency Improvement for information on available support programs.

Sometimes, even replacing an operating motor with a premium efficiency model may have a short payback period. The early replacement of installed motors with premium efficiency motors can decrease motor system electricity consumption in U.S. industry by 2.8%. At current motor prices, about 16% of the energy savings is cost-effective (Rao et al. 2022). For electric motors driving a compressor, buying the most efficient motor is almost always the sensible choice due to the heavy duty and load operation in most compressors. The payback time in this case is less than a year (DOE and CAC 2016).

NEMA and other organizations have created the Motor Decisions Matter^{SM} campaign to help industrial and commercial customers evaluate their motor repair and replacement options, promote cost-effective applications of NEMA Premium™ motors and "best practice" repair, and support the development of motor management plans before motors fail.

In some cases, it may be cost-effective to rewind an existing energy-efficient motor, instead of purchasing a new motor. As a rule of thumb, when rewinding costs exceed 60% of the costs of a new motor, purchasing the new motor may be a better choice (MDM 2012). When rewinding a motor, it is important to choose a motor service center that follows best practice motor rewinding standards to minimize potential efficiency losses. An American National Standards Institute–approved recommended best practice standard has been offered by the Electrical Apparatus Service Association (EASA) for the repair and rewinding of motors (EASA 2015). When rewinding practices are implemented, efficiency changes can range from an increase of 0.3% to a reduction of about 0.5%. The average reduction in the rewound motors tested was 0.1% (EASA 2019). However, poor quality rewinds may result in larger efficiency losses. It is therefore important to inquire whether the motor service center follows EASA-recommended practice standards (EASA 2006; EASA 2015).

Using the most efficient type of motor can result in significant reduction in electricity use. The average payback time is currently 2.5 years (IAC 2024).

Perform ongoing maintenance

Motor maintenance prolongs motor life and helps anticipate motor failure. Motor maintenance measures can be categorized as either *preventative* or *predictive*. Preventative measures, which prevent unexpected downtime of motors, include electrical consideration; voltage imbalance minimization; load consideration; and motor ventilation, alignment, and lubrication. With predictive maintenance, measurements are made (e.g., temperature, vibration) to detect system degradation. Predictive maintenance bases the maintenance needs on the actual conditions of the motor system, while preventative maintenance is based on a preset schedule. Some effective predictive maintenance tools include vibration analysis, lubricant analysis, infrared (IR) scanning, and motor analyzers that can perform motor diagnostic tests. The savings associated with an ongoing motor maintenance program are significant and could range from 2% to 30% of total motor system energy use (Efficiency Partnership 2004).

Establishing a preventative maintenance program has a payback period of about 1.6 years, and establishing a predictive maintenance program has a payback of 1.3 years (IAC 2024).

Properly size and specify motors

Inappropriately sized motors cause unnecessary energy losses. When motor systems are operated at low load factors,[1] the energy efficiency is much lower than the efficiency when operating at design conditions. According to Rao et al. (2022), about 14% of industrial motor systems operate at a low constant load factor ranging between 45% and 75%. Replacing oversized motors with properly sized motors saves, on average for U.S. industry, 0.2% of total motor system electricity consumption (Rao et al. 2022). Higher savings can often be realized for smaller motors and individual motor systems.

---

[1] The load factor is the ratio of the operating output power to the full load power.

Properly sizing a motor depends on the following: load on the motor, operating efficiency of the motor at that load point, the full-load speed of the motor to be replaced, and the full-load speed of the replacement motor. DOE provides a range of technical assistance, tip sheets, and software tools for decision-making on motor systems. The payback time for sizing electric motors for peak operating performance is 2 years (IAC 2024).

Employ motor labeling

Motors not in use should be powered off. This can be done through automated systems (see below), or motors can be labeled to show the typical use (e.g., continuous operations [365/24/7], number of operation days [24/X], during production, or when an operator is present). In conjunction with motor labeling, maintaining an inventory of premium efficiency-ready spare motors, and tracking operation and maintenance, can ensure that the function and use of each motor is known; that motors are correctly operated and properly maintained; and that when a motor fails, a premium efficiency motor is installed (DOE 2014a). Toyota and Bodine Casting have successfully introduced (colored) labeling for motor systems in several plants.

Motor Automation

A 10% reduction in motor operating time can save more energy than replacing a conventional motor with a NEMA Premium™ efficiency motor (DOE 2012d). Therefore, automatic shutdown of motors that would otherwise be left idling can reduce energy costs without requiring high investment.

Automate motors

Motors should only run when needed. Though some people are concerned that frequent motor startups will negatively affect a motor's lifetime, if the frequency of motor startups is not excessive, the lifetime will not be significantly affected (DOE 2012d). NEMA (2017) gives the maximum number of allowable motor startups per hour and the duration of rest time between startups for various horsepower motors and synchronous speed ratings. With the use of automatic shutdown timers, motors are turned off when they would otherwise be running idle or unloaded for intervals longer than the rest intervals specified at NEMA (2017).

Use ASDs

Load control can be improved with the use of ASDs or with the adoption of advanced motor technologies, such as permanent magnet (PM) motors and reluctance motors (Rao et al. 2022). An ASD is a device that controls the rotational speed of motor-driven equipment. The most common type of ASD is the variable frequency drive (VFD). VFDs are solid-state electronic motor controllers that can efficiently meet the varying process requirements by adjusting the frequency and voltage of power supplied to an alternating current (AC) motor to enable it to operate over a wide speed range. The terms "ASD" or "variable speed drive" (VSD) are inclusive of all types of variable speed control drives (mechanical, magnetic, and electronic) while VFDs are a type of ASD (electronic).

ASDs can better match speed to load requirements for motor operations and therefore ensure that motor energy use is optimized to a given application. Motor systems operating at variable load factors can achieve significant energy savings with ASDs. Motor systems operating constantly at low load factors are good candidates for downsizing (Rao et al. 2022). ASD systems are offered by many suppliers and are available worldwide.

Only about 16% of industrial motor systems are currently equipped with VFDs. With the adoption of VFDs, industrial electricity use in motor systems can decrease by 8%. Most motors (> 5 hp) can realize cost-effective energy savings at current VFD costs (Rao et al. 2022). For applications with low horsepower (< 10 hp or less), electronically commutated motors are another type of advanced motor that is more efficient than other motors in those sizes.

In recent years, the cost of ASDs has fallen significantly, such that it almost equals the cost of the motor (Dols et al. 2014). The average payback time of adopting ASDs or multiple-speed motors on existing motor systems is 1.8 years (IAC 2024).

Correct power factor and vary motor speed according to demand

Inductive loads like transformers, electric motors, and HID lighting may cause a low power factor, which may result in increased power consumption and increased electricity costs. The power factor can be corrected by minimizing idling of electric motors (a motor that is turned off consumes no energy), replacing motors with premium efficiency motors (see above), and installing capacitors in the AC circuit to reduce the magnitude of reactive power in the system.

Minimize voltage unbalances

A voltage unbalance degrades the performance and shortens the life of three-phase motors. A voltage unbalance causes a current unbalance, which will result in torque pulsations, increased vibration and mechanical stress, increased losses, and motor overheating, all of which can reduce the life of a motor's winding insulation. Voltage unbalances may be caused by a faulty operation of power factor correction equipment, an unbalanced transformer bank, or an open circuit. A rule of thumb is that the voltage unbalance at the motor terminals should not exceed 1%. Even a 1% unbalance will reduce motor efficiency at part load operation while a 2.5% unbalance will reduce motor efficiency at full load operation (DOE 2012b).

For a 100 hp motor operating 8,000 hours per year, a correction of the voltage unbalance from 2.5% to 1% will result in electricity savings of 9,500 kWh or almost $760 at an electricity rate of $0.08/kWh (DOE 2012b).

By regularly monitoring the voltages at the motor terminal and through regular thermographic inspections of motors, voltage unbalances may be identified. It is also recommended to verify that single-phase loads are uniformly distributed and to install ground fault indicators as required. Another indicator that a voltage unbalance may be a problem is 120 Hz vibration, which should prompt an immediate check of voltage balance (DOE 2012b). The typical payback period for voltage controller installation on lightly loaded motors in the United States is about 2 years (IAC 2024).

Use soft starters

Soft starters are special devices that allow the gradual speed acceleration of the motor and can limit not only the wear and tear on the motor system but also decrease the power use for motor startup by up to 19% (de Oliveira et al. 2011). Installing soft starters has an average payback period of about 2 years (IAC 2024).

ASDs can also provide soft start and stop functionality. However, if only soft-starting capability is needed and no operation at variable speeds, then a soft starter is usually the better choice. The cost of a soft starter for a mid-size motor ranges between $35/hp for a 10-hp motor and $10/hp for a 100-hp motor. The cost of ASDs from the same manufacturer ranges between $45/hp for a 10-hp motor and $30/hp for a 100-hp motor. Although soft starters are less expensive, they do not allow for the efficient operation at variable loads that ASDs do (NEEA 2020).

Use advanced motor technologies

Recent motor technology advancements have led to the development of motors with energy efficiencies higher than the premium efficiency performance levels. Important advanced new motors are permanent magnet (PM), switched reluctance (SR), synchronous reluctance (SynRM), permanent magnet synchronous reluctance (PM SynRM), and copper rotor (CR). All these technologies have high efficiencies, especially at low load factors, while also offering (in all technologies except the CR) the benefits of VFDs (Rao et al. 2022). Table 4 shows their additional energy efficiency compared to the premium energy performance level. To operate, PM, SynRM, and PM SynRM motors need a controller, thereby making them variable speed capable, while SR motors have inherent load controller capabilities (see Table 4 for estimated savings due to variable speed capabilities).

Table 4: Energy efficiency of premium efficiency motors operating at full load and the additional energy efficiency improvement of advanced motors (Rao et al. 2022)

		Additional energy efficiency improvement (%)				
Size (hp)	**Premium energy efficiency**	**PM**	**SR**	**SynRM**	**PM SynRM**	**CR**
1-5	86.4-90.1	3.2	3	1.5	1.9	1.5
6-20	89.2-93.1	1.5	2.3	1.2	1.5	1.0
21-50	92.0-94.7	1.0	2.0	0.8	1.1	-
51-100	94.1-95.9	1.0	1.0	0.7	0.1	-
101-200	94.5-96.2	0.7	1.0	0.6	0.1	-
201-500	94.5-96.2	0.8	-	0.6	-	-

PM synchronous motors are currently the most energy-efficient commercially available technology. Due to the highest energy efficiency across the 1-5 hp range and its availability in large sizes (200-500 hp), the PM can offer the highest energy savings potential in both constant load and variable load motor systems used in the industry (Rao et al. 2022). This technology relies on the use of rare-earth metals integrated into a magnet. The permanent magnet typically used in PM motors is neodymium iron boron (NdFeB) (Newkirk et al. 2021).

Table 5 shows the industrial energy savings potentials from the application of the different advanced motor technologies in U.S. industry. The energy savings from replacing motors handling variable loads not yet fitted with VFDs with PM technology motors is slightly higher than the energy savings achieved from the replacement with premium efficiency motors with VFDs.

Table 5: Energy saving potentials in U.S. industry from the replacement of motors operating at constant loads and variable loads (with and without fitted VFDs) with advanced motor technologies (calculated from Rao et al. [2022])

	Premium Efficiency+ VFD	**PM**	**SR**	**SynRM**	**PM SynRM**	**CR**
Constant loads (> 75%)	-	4.2%	4.3%	3.8%	3.5%	1.7%
Constant loads (< 75%)	-	4.9%	4.0%	4.5%	3.2%	1.5%
Variable loads (> 75% – fitted with VFDs)[1]	-	2.6%	3.0%	2.4%	1.8%	-
Variable loads (> 75% – not fitted with VFDs)[1]	63.8%	64.4%	46.3%	64.4%	44.3%	-

[1] In this case the advanced motor technologies are also fitted with VFDs

Chapter 5: Compressed Air Systems

In this chapter:	
Maintain systems	Monitor systems effectively
Reduce leaks	Turn off unnecessary compressed air
Modify the system instead of increasing pressure	Replace compressed air with other energy sources
Minimize pressure drops	Maximize allowable pressure dew point at the air intake
Improve load management	Reduce inlet air temperature
Optimize compressor controls and strategies	Properly size pipe diameters
Recover heat for water preheating	

In chlor-alkali plants, reciprocating/rotary and centrifugal compressors are used in a variety of applications from supplying instrumentation air, to transferring chlorine by padding (using air expansion to move chlorine), and to compressing dry chlorine before liquefaction.

Compressed air systems consist of a supply side, which includes compressors and air treatment equipment such as mist eliminators and dryers, and a demand side, which includes distribution piping, condensate traps, storage systems, and end-use equipment.

Energy Savings Checklist: Compressed Air

Compressed air is often the ***most expensive form of energy*** available in a plant because of its poor efficiency. However, there are several possible steps to improve the energy efficiency of compressed air. Use the checklist below to find new ways to save energy and costs.

Compressed Air Checklist	Potential Gains	✓
Reduce the system supply pressure to determine if it is higher than optimal.	A 2 to 3 psi discharge pressure reduction results in a 1% energy decrease.	
Is a compressed air leak detection and repair program in place to minimize air leaks?	Typically, 15% to 25% of air usage is air leaks if no compressed air program is in place.	
Are the compressors sequenced with ASDs?	If there is no sequencing in place, there is the potential for a 15% to 25% energy reduction. For the operation of multiple compressors, sequencing is better accomplished with a control system.	
Is waste heat being captured?	Every 100 cubic feet per minute (CFM) of rejected heat equates to 50,000 Btu of available heat.	

Compressed Air Checklist	Potential Gains	✓
Are all air compressors on a master controller?	Use of a master system controller results in an energy savings of 10% to 20%.	
Can the temperature of air intake be reduced?	For every 5°C to 10°C of reduction, there is a resulting 1% energy savings.	
Does the system have a proper amount of dry and wet storage?	Adequate storage, 5 to 10 gallons/cfm (0.2-0.4 gallons/lpm) air storage with one-third being wet and two-thirds being dry storage, reduces compressor and dryer load and avoids frequent cycling.	
Have you sized your system properly?	Use of the greatest-size pipe diameter feasible and economically possible can reduce energy use by 3%.	

Best Practices for Energy-Efficient Compressed Air

- **Maintain systems.** Reduce leakage and pressure variability, and increase efficiency, by conducting proper maintenance.
- **Monitor systems effectively.** Use measures such as temperature and pressure gauges and flow meters to save energy and money.
- **Reduce leaks.** Conduct regular leak maintenance to reduce leak rates to less than 10%.
- **Turn off unnecessary compressed air.** Turn off unneeded compressors or use valves to stop compressed air from flowing to unused parts of the system.
- **Modify the system instead of increasing pressure.** Eliminate all open blowing applications and inappropriate compressed air uses instead of raising the pressure.
- **Replace compressed air with other energy sources.** Decrease energy use and costs by replacing compressed air with other sources of energy that can perform the same work and are usually more economical and more efficient than compressed air.
- **Minimize pressure drops.** Use a systems approach to minimize pressure drop, reduce energy consumption, and increase system performance. Note: As leaks and inappropriate uses are reduced, it is important to go back to the compressor room to check whether any compressors can be shut off. A general rule of thumb is that a typical compressor generates between 4 and 5 CFM per horsepower. If 400 CFM of leaks are repaired, it may be possible to take 100 hp of compressor capacity offline.
- **Maximize allowable pressure dew point at the air intake.** Use a dryer with a floating dew point to maximize efficiency.

Pressure Reductions

As a rule of thumb, every 2 to 3 pounds of reduction in header pressure yields 1% in energy savings.

- **Improve load management.** Use two-stage compressors or multiple smaller compressors to save energy. Large compressors consume more electricity when they are unloaded than do multiple smaller compressors with similar overall capacity.

- **Reduce inlet air temperature.** Reduce air temperature to reduce the energy used by the compressor and increase compressor capacity.

- **Optimize compressor controls and strategies.** Shut off unneeded compressors by installing programmable logic control (PLC)-based automation to manage compressors, which can save up to 12% in energy costs annually.

- **Size pipe diameters properly.** Increase pipe diameters to minimize pressure losses and leaks, reduce system operating pressures, and reduce energy consumption by 3%. As a rule of thumb, compressed air piping and vessels should be sized for maximum flow per cycle. If they are sized smaller than maximum flow per cycle, it will cause operators to increase pressure at points of use, which means they will demand higher discharge pressures from the compressors.

- **Recover heat for water preheating.** Use a heat recovery unit to recover thermal energy and save up to 20% of the energy used in compressed air systems annually for heating water or space heating in winter or cold seasons.

Maintain systems

Poor maintenance lowers compression efficiency and increases air leakage and pressure variability. This leads to increased operating temperatures, poor moisture control, and excessive contamination. Improved maintenance reduces these problems and saves energy. Proper maintenance includes the following (DOE and CAC 2016; Scales and McCulloch 2007):

- *Keep the compressor and intercooling surfaces clean and foul-free.* Blocked filters increase pressure drop and energy consumption. A 2-psig pressure drop will increase energy costs by 1% (CEATI 2007). Inspect and periodically clean filters to reduce pressure drop. Use filters with just a 1-psig pressure drop over 10 years. Fixing improperly operating filters also will prevent contaminants from entering tools and causing them to wear out prematurely. Generally, when a pressure drop exceeds 2 to 3 psig, replace the particulate and lubricant removal elements. Inspect all systems at least annually. Consider adding filters in parallel that decrease air velocity and, therefore, decrease air pressure drop. A 2% reduction of annual energy consumption in compressed air systems is projected when filters are replaced frequently (Radgen and Blaustein 2001). Based on experimental results, it was shown that by replacing a single particulate low-flow filter with two of the same filters placed in parallel, the pressure drop decreases by 50%. Adding a third filter in parallel decreases the pressure drop by another 30%. Using a medium filter results in a slightly higher pressure drop than the triple filter. In the case of coalescing filters, the results are similar: Using two filters in parallel decreases the pressure drop by 60% compared to one filter, while when three filters are placed in parallel, the pressure drop decreases by an additional 27% (Milenkovic et al. 2023).

- *Keep motors properly lubricated and cleaned.* Poor motor cooling can increase motor temperature and winding resistance, shorten motor life, and increase energy consumption. Compressor lubricant should be changed every 2 to 18 months and checked to make sure it is at the proper level. In addition to energy savings, this can help avoid corrosion and degradation of the system.

- *Inspect compressed air condensate drains and traps* periodically to ensure they are clean and are not stuck in the open or closed positions. Some users leave automatic condensate traps partially open at all times to allow for constant draining. This practice wastes substantial energy and has no role in a properly maintained system. Instead, install level-operated mechanical traps, electronically operated solenoid traps, or zero air loss traps with reservoirs. Malfunctioning traps should be cleaned and repaired, and not left open (DOE and CAC 2016).

- *Maintain the coolers* on the compressor so that the dryer gets the lowest possible inlet temperature. A higher inlet temperature will decrease the dryer's rated capacity. The dryer ratings are usually based on the standard dryer inlet conditions, commonly referred to as "the three 100s": 100 psig, 100°F (inlet compressed air temperature), and 100°F ambient temperature. Any deviations from these conditions will have an impact on the dryer capacity (DOE and CAC 2016).

- *Check belts for wear* and adjust them. A good practice is to adjust after every 400 hours of operation.

- *Replace air lubricant separators* according to specifications or sooner. Rotary screw compressors generally start with their air lubricant separators having a 2 to 3 psid pressure drop at full load. When this increases to 10 to 12 psid, change the separator (DOE and CAC 2016).

- *Check water cooling systems* for water quality (pH and total dissolved solids), flow, and temperature. Clean and replace filters and heat exchangers per manufacturer's specifications.

- *Check for excess pressure, duration, and volume* in applications that require compressed air. Applications not requiring maximum system pressure should be regulated, either by production line sectioning or by pressure regulators on the equipment itself. Using more pressure than required wastes energy and can shorten equipment life and add maintenance costs.

Monitor systems effectively

Effective monitoring systems save energy and money and typically include the following:

- Pressure gauges on each receiver or main branch line and differential gauges across dryers, filters, etc.

- Temperature gauges across the compressor and its cooling system to detect fouling and blockages.

- Flow meters to measure the quantity of air used.

- Dew point temperature gauges to monitor the effectiveness of air dryers.

- Kilowatt-hour meters and hours-run meters on the compressor drive.

- Checking of compressed air distribution systems after equipment has been reconfigured to be sure that no air is flowing to unused equipment or obsolete parts of the compressed air distribution system.

- Checking for flow restrictions of any type in a system, such as an obstruction or roughness, which can unnecessarily raise system operating pressures. As a rule of thumb, every 2 psig in pressure rise resulting from resistance to flow can increase compressor energy use by 1% (DOE and CAC 2016). The largest pressure drops are usually found at the points of use, including undersized or leaking hoses, tubes, disconnects, filters, regulators, valves, nozzles, and lubricators (demand side), as well as air/lubricant separators, after-coolers, moisture separators, dryers, and filters.

- Checking for compressed air use outside production hours. Energy Treasure Hunts can be a good way to understand how much compressed air is being used off production and whether there are opportunities to reduce unnecessary compressed air consumption during periods of no or low production.

Reduce leaks

A typical plant that has not been well maintained will likely have a leak rate equal to 20% of total compressed air production capacity (DOE and CAC 2016). Leak maintenance can reduce this number to less than 5% to 10%. Overall, a 20% reduction of annual energy consumption in compressed air systems is projected for fixing leaks (Radgen and Blaustein 2001). Complete leak prevention is not always practically achievable. Hence, lowering the leaks to 10% is recognized as an acceptable leak level (Kaya et al. 2021).

Leak Reduction

The payback period for leak reduction efforts is generally around half a year (IAC 2024).

The amount of compressed air leakage depends on the line pressure, the temperature of the leaking air, the air temperature at the compression suction, and the size of the hole in the pipes or equipment. Because the higher the line pressure, the higher the leak losses will be, determining the lowest pressure required and lowering the pressure with pressure regulators will also decrease the cost of leaks (Kaya et al. 2021). Figure 3 draws the power losses for different leak sizes.

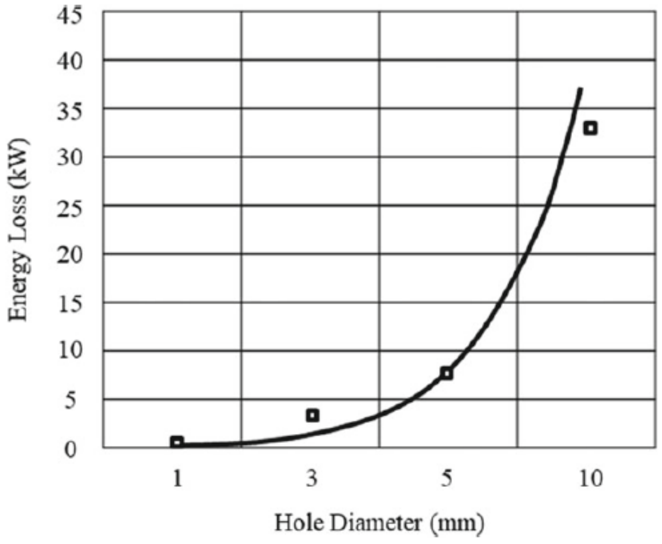


Figure 3: Power loss for different hole sizes (line pressure: 94 psi [650 kPa]; temperature of escaping air 68°F [20°C]; atmospheric pressure 15 psi [101 kPa]) (Kaya et al. 2021)

In addition to increased energy consumption, leaks can make air tools less efficient and adversely affect production, shorten the life of the equipment, lead to additional maintenance requirements, and increase unscheduled downtime. In the worst case, leaks can add unnecessary compressor capacity.

The most common areas for leaks are couplings, hoses, tubes, fittings, pressure regulators, open condensate traps and shutoff valves, pipe joints, disconnects, and thread sealants. A simple way to detect leaks is to apply soapy water to suspect areas and look for bubbling. Another simple way is a bleed down test (Bayne 2011). In a bleed down test, the plant air system is brought to full pressure and then shut down. By recording the system pressure while compressed air is not used anywhere in the plant, any pressure losses can be attributed to existing leaks. Two more modern and better ways to detect leaks are to use an ultrasonic acoustic detector, which can recognize the high-frequency hissing sounds associated with air leaks, or use an acoustic imager, which creates a sound map of an area to identify leaks in compressed air. After identification, leaks should be tracked, repaired, and verified. Leak detection and correction programs should be ongoing efforts.

Eliminating leaks in compressed air lines/valves has an average payback time of 0.6 years (IAC 2024).

Turn off unnecessary compressed air

Equipment that is no longer using compressed air should have the air turned off completely using a simple solenoid valve. Compressed air distribution systems should be checked when equipment has been reconfigured to ensure that no air is flowing to unused equipment or obsolete parts of the compressed air distribution system. Also, after compressed air system energy efficiency projects are implemented, for example reducing the pressure drop, facility personnel need to shut off unneeded compressors when automatic controls are not in place.

Modify the system instead of increasing pressure

For individual applications that require higher pressure, instead of raising the operating pressure of the whole system, special equipment modifications should be considered, such as employing a dedicated compressor with secondary storage, employing a booster, increasing a cylinder bore, changing gear ratios, or changing operations to off-peak hours. Removing or closing unnecessary compressed air lines has an average payback period of 0.8 years (IAC 2024).

Continue the Program

Leak detection and correction programs should be ongoing efforts.

Replace compressed air with other energy sources

Many operations can be accomplished more economically and efficiently using energy sources other than compressed air (DOE and CAC 2016). Various options exist to replace compressed air use, including:

- Cooling electrical cabinets with air conditioning fans instead of compressed air vortex tubes.
- Creating a vacuum with a vacuum pump instead of compressed air Venturi methods.
- Cooling, aspirating, agitating, mixing, or inflating packaging with blowers.
- Cleaning parts or removing debris with brushes, blowers, or vacuum pump systems.
- Moving parts with blowers, electric actuators, or hydraulics.

- Using special case tools or actuators: Pneumatic tools receive power from compressed air, and electric tools receive power from electricity. Electric tools that can perform the same work should be considered because they are more efficient than using compressed air. The power use of a 0.5 hp pneumatic tool operating for 400 hours/yr. is 1,320 kWh. Using an electric tool instead of the pneumatic would only consume 230 kWh. The actual energy savings of switching from pneumatic to electric should be carefully analyzed. Not all applications are suitable for this conversion (Zolkowski 2016). Replacing pneumatic equipment with electric equipment has a payback time of 2.3 years (IAC 2024).

Minimize pressure drops

Excessive system pressure drop results in poor system performance and excessive energy consumption. Flow restrictions of any type in a system, such as an obstruction or roughness, result in higher operating pressures than needed. Resistance to flow increases the drive energy on positive displacement compressors by 1% of connected power for each 2 psi of differential (DOE and CAC 2016). The largest pressure drops are usually found at the points of use, including undersized or leaking hoses, tubes, disconnects, filters, regulators, valves, nozzles, and lubricators (demand side), as well as air/lubricant separators on lubricated rotary compressors and after-coolers, moisture separators, dryers, and filters (supply side).

Minimizing the pressure drop requires a systems approach in design and maintenance. Air treatment components should be selected with the lowest possible pressure drop at specified maximum operating conditions and best performance. Manufacturers' recommendations for maintenance should be followed, particularly in air filtering and drying equipment, which can have damaging moisture effects like pipe corrosion. Finally, minimize the distance the air travels through the distribution as friction losses that increase pressure drop are proportional to the surface area of piping.

Maximize allowable pressure dew point at the air intake

Choose the dryer that has the maximum allowable pressure dew point (PDP) (temperature at which water condenses in a pressurized gas) and best efficiency. There are two dryer categories mainly used in industries: desiccant dryers and refrigerated dryers. Desiccant dryers use both electricity and compressed air. Depending on the controls used, they can use between 5% and 18% of the compressed air (Taylor 2021; Ursillo 2013). Heatless desiccant dryers are simpler to operate but use 18% of the compressed air from the dryer to purge back. Heated desiccant dryers use a lower flow of purged air, about 5% to 7%, and blower purge dryers use no compressed air, thus maintaining the compressed air supply, but use heat and a blower (Taylor 2021). Of the desiccant-type dryers, the blower purge dryer has the higher upfront cost but is the most energy efficient as it does not use compressed air (Ursillo 2013). Refrigerated dryers consume 1% to 2% as much energy as the compressor (Ingersoll Rand 2001). The power use is essentially used for the refrigeration compressor, controls, and condenser fans. There are two types of refrigerated dryers: cycling dryers and non-cycling dryers. Non-cycling dryers are less expensive but because cycling dryers are more energy efficient, they are the least costly to operate over the lifetime of the dryer (Ursillo 2013). Refrigerated dryers are more energy efficient than desiccant dryers but do not produce air that is as dry as the air from desiccant dryers, which is critical for certain operations. Consider using a dryer with a floating dew point control that can control the external temperature while keeping the humidity at the desired level.

Improve load management

Because of the large amount of energy consumed by compressors, whether in full operation or not, partial load operation should be avoided. For example, unloaded rotary screw compressors still consume 15% to 35% of full-load power while delivering no useful work (DOE and CAC 2016).

Air receivers, also called "secondary storage," can be employed near high-demand areas to provide a supply buffer to meet short-term demand spikes that can exceed the normal compressor capacity. In this way, the number of required online compressors may be reduced. Multistage compressors theoretically operate more efficiently than single-stage compressors. Multistage compressors save energy by cooling the air between stages, reducing the volume and work required to compress the air. The investment for a new two-stage rotary screw air compressor can be up to 30% higher than a single-stage compressor of the equivalent size. Power consumption will, however, be about 13% lower. The power savings alone will recover the premium initial price for the two-stage compressor in about 7 months (Folsom 2020). Replacing single-stage compressors with two-stage compressors typically provides a payback period of 2 years or less (Ingersoll Rand 2001). Using multiple smaller compressors instead of one large compressor can save energy as well. Large compressors consume more electricity when they are unloaded than do multiple smaller compressors with similar overall capacity. An analysis of U.S. case studies shows an average payback period of about 2.7 years for optimally sizing compressors (IAC 2024).

Reduce inlet air temperature

For the compressors to operate efficiently, the air absorbed must be cool, clean, and dry. As density is higher at lower temperatures, by reducing the inlet air temperature more air is compressed with less power use. Because compressors are usually operated indoors, the temperature of the air they draw is usually higher than the temperature of the air outside. With the use of an air duct, compressors can operate with outside air and decrease the power consumption. As a rule of thumb, each 5°F to 10°F (3°C) decrease will reduce compressor energy use 1% (Kaya et al. 2021). In addition to energy savings, compressor capacity is increased when cold air from outside is used. Industrial case studies have found an average payback period of less than 1.5 years for importing outside air (IAC 2024), but costs can vary significantly depending on facility layout. A chlor-alkali plant in Ohio had a payback time of 0.2 years (IAC 2024). Table 6 shows the energy savings from changing the incoming air temperature.

Table 6: The impact of inlet air temperature on compressor energy use (Kaya et al. 2021)

Temperature of incoming air (°F)	Air volume required for 264,200 gallons (1,000 m^3) flow at 70°F (21°C)	Energy savings or overlifting by 70°F (21°C) temperature
30	244,359	7.5% savings
41	249,114	5.7% savings
50	254,133	3.8% savings
61	259,153	1.9% savings
70	264,172	0% savings

Temperature of incoming air (°F)	Air volume required for 264,200 gallons (1,000 m^3) flow at 70°F (21°C)	Energy savings or overlifting by 70°F (21°C) temperature
81	269,455	1.9% excess consumption
90	274,739	3.8% excess consumption
99	280,022	5.7% excess consumption
109	285,306	7.5% excess consumption
120	290,589	9.5% excess consumption

Optimize compressor controls and strategies

The primary objectives of compressor control strategies are to shut off unneeded compressors and to delay bringing on additional compressors until truly needed. Energy savings for sophisticated compressor controls have been reported at around 12% annually (Radgen and Blaustein 2001). An excellent review of compressor controls can be found in Compressed Air Challenge® *Best Practices for Compressed Air Systems* (Second Edition) (Scales and McCulloch, 2007). Upgrading controls on compressors has an average payback time of 1.6 years (IAC 2024). Common control strategies for compressed air systems include:

- *Start/stop (on/off) controls*, in which the compressor motor is turned on or off in response to the discharge pressure of the machine. Start/stop controls can be used for applications with very low duty cycles and are applicable to reciprocating or rotary screw compressors.

- *Load/unload controls*, or constant speed controls, which allow the motor to run continuously but unloads the compressor when the discharge pressure is adequate. In most cases, unloaded rotary screw compressors still consume 15% to 35% of full-load power while delivering no useful work (DOE and CAC 2016). Hence, load/unload controls can be inefficient.

- *Modulating or throttling controls*, which allow the output of a compressor to be varied to meet flow requirements by closing down the inlet valve and restricting inlet air to the compressor. Throttling controls are applied to centrifugal and rotary screw compressors.

- *Single master sequencing system controls*, which take individual compressor capacities online and offline in response to monitored system pressure demand and shut down any compressors running unnecessarily. System controls for multiple compressors typically offer higher efficiency than individual compressor controls.

- *Multi-master controls*, which are the latest technology in compressed air system control, utilizing dedicated PLC-based automation. Multi-master controls are capable of handling multiple compressors and provide an efficient compression operation while maintaining a constant air pressure. The controllers share information, allowing the system to respond more quickly and accurately to demand changes. One controller acts as the lead, regulating the whole operation. This strategy allows each compressor to function at a level that produces the most efficient overall operation. The objective of this automated control system is to match the demand for compressed air with compressors operating at or near their maximum efficiency level (DOE and CAC 2016). According to Nadel et al. (2002), such advanced compressor controls are expected to deliver energy savings of about 3.5%, where applied.

- *ASDs,* which control the speed of the machinery. Although compressors are constant torque loads, energy savings can be achieved with the use of ASDs (also called VSDs). The energy savings depend on the control strategy they replace. Figure 4 compares the power consumption between the different strategies. In a rotary screw air compressor using modulating control, which operates at 50% of the rated capacity, switching to ASDs will decrease the power consumption by 30% (Ferreira 2009).

In addition to energy savings, the application of controls can sometimes eliminate the need for some existing compressors, allowing extra compressors to be sold or kept for backup. Alternatively, capacity can be expanded without the purchase of additional compressors. Reduced operating pressures will also help reduce system maintenance requirements (DOE and CAC 2016).

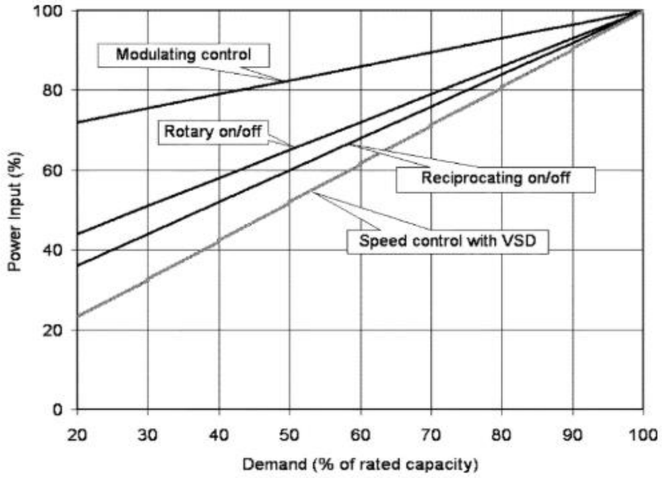


Figure 4: Energy saved by using a VSD on a screw compressor (Ferreira 2009)

Properly size pipe diameters

Increasing pipe diameters to the greatest size that is feasible and economical for a compressed air system can help to minimize pressure losses and leaks, which reduces system operating pressures and leads to energy savings. Increasing pipe diameters typically reduces compressed air system energy consumption by 3% (Radgen and Blaustein 2001). Further savings can be realized by ensuring other system components (e.g., filters, fittings, hoses) are properly sized. The DOE's MEASUR software platform has a pipe sizing tool that can determine the pipe diameter for a specific volumetric flow velocity, design velocity, and pressure.

Recover heat for water preheating

As much as 80% to 93% of the electrical energy used by an industrial air compressor is converted into heat. In many cases, a heat recovery unit can recover up to 90% of this available thermal energy for space heating, industrial process heating, water heating, makeup air heating, boiler makeup water preheating, industrial drying, industrial cleaning processes, heat pumps, laundries, or preheating aspirated air for oil burners (Kaya et al. 2021). It has been estimated that approximately 50,000 Btu/hour of energy is available for each 100 CFM of capacity (at full load) (DOE and CAC 2016). Paybacks are typically less than 1 year (Galitsky et al. 2005; Kaya et al. 2021).

Heat recovery for space heating is not as common with water-cooled compressors because an extra stage of heat exchange is required and the temperature of the available heat is lower. However, with large water-cooled compressors, recovery efficiencies of 50% to 60% are typical (DOE and CAC 2016). Implementing this measure saves up to 20% of the energy used in compressed air systems annually for space heating (Radgen and Blaustein 2001).

Chapter 6: Fan Systems

In this chapter:	
Maintain systems properly	Properly size fans
Use adjustable-speed drives (ASDs) and improved controls	Install high-efficiency belts (cogged V-belts)
Repair duct leaks	Avoid system effect

Chlor-alkali plants use fan systems to support the boiler and for ventilation purposes.

Considerable opportunities exist to upgrade the performance and improve the energy efficiency of fan systems. In particular, concerns about failure or underperformance have led to many fans being oversized for their particular application (DOE 2003b). Oversized fans do not operate at optimal efficiency and therefore waste energy. However, the efficiencies of fan systems vary considerably across impeller types.

Best Practices for Energy-Efficient Fan Systems

- **Maintain systems properly.** A proper maintenance program can improve system performance, reduce downtime, minimize repair costs, and increase system reliability.
- **Properly size fans.** Properly sized fans have lower capital, maintenance, and energy costs.
- **Use ASDs and improved controls.** Retrofitting fans with ASDs can save up to 49% in energy costs.
- **Install high-efficiency belts (cogged V-belts).** Replace standard V-belts with cogged belts to save energy and money.
- **Repair duct leaks.** Installing duct insulation and performing regular duct inspection and maintenance reduce system leaks and save significant amounts of energy.
- **Avoid system effect.** Improve fan system performance by improving the interaction of the various system components.

Maintain systems properly

As for most energy-using systems, a proper maintenance program for fans can improve system performance, reduce downtime, minimize repair costs, and increase system reliability. DOE recommends establishing a regular maintenance program for fan systems, with intervals based on manufacturer recommendations and experience with fans in similar applications (DOE 2003b). Additionally, DOE recommends the following important elements of an effective fan system maintenance program (DOE 2003b):

- *Inspect belts*. In belt-driven fans, belts are usually the most maintenance-intensive part of the fan assembly. Belts wear out over time and can lose tension, reducing their ability to transmit power efficiently. Regularly inspect and tighten belts, especially for large fans, given the potential size of the power loss.

- *Clean fans*. Many fans experience a significant loss in energy efficiency due to the buildup of contaminants on blade surfaces. Buildup can create imbalance problems that reduce performance and contribute to premature wear of system components. Fans that operate in particulate-laden or high-moisture airstreams are particularly vulnerable and should be cleaned regularly.

- *Inspect and repair leaks.* Leakage in a fan duct system decreases the amount of air that is delivered to the desired end use, which can significantly reduce the efficiency of the fan system. Inspect ductwork on a regular basis and repair leaks as soon as possible. In systems with inaccessible ductwork, use temporary pressurization equipment to determine whether the integrity of the system is adequate.

- *Lubricate bearings.* Worn bearings can lead to premature fan failure, as well as create unsatisfactory noise levels. Monitor and frequently lubricate fan bearings based on the manufacturer's recommendations.

- *Replace motors.* Eventually, all fan motors will wear out and will require repair or replacement. The decision to repair or replace a fan motor should be based on a life cycle cost analysis, as described in the motor systems section.

Properly size fans

About 28% of industrial fans are not appropriately sized (Rao et al. 2022). Conservative engineering practices often result in the installation of fans that exceed system requirements by sizing the fan so that it meets the highest expected load. When the demand is low, the air flow is reduced with the use of inlet guide vanes or discharge dampers, which is one of the least efficient methods (DOE 2014a). Such oversized fans lead to higher capital costs, maintenance costs, and energy costs than fans that are properly sized for the job (DOE 2003b). However, other options may be more cost-effective than replacing an oversized fan with a smaller fan (DOE 2002). Other options include the following (DOE 2003b):

- Decreasing fan speed using different motor and fan sheave sizes (may require downsizing the motor).
- Installing an ASD or multiple-speed motor (see below).
- Using an axial fan with controllable pitch blades.

Use ASDs and improved controls

Significant energy savings can be achieved by installing ASDs on fans. Savings may vary between 14% and 49% when retrofitting fans with ASDs (DOE 2002). About 19% of motors used in industrial fan and blower systems have the most commonly used type of ASDs, VFDs, while 75% do not use any form of control. Larger systems are more likely to be fitted with VFDs (Rao et al. 2021). Adopting VFDs in fan and blower systems currently not using them can decrease the total electricity used in fans and blowers in the industry by 12%, saving about 13,724 GWh/yr (Rao et al. 2022).

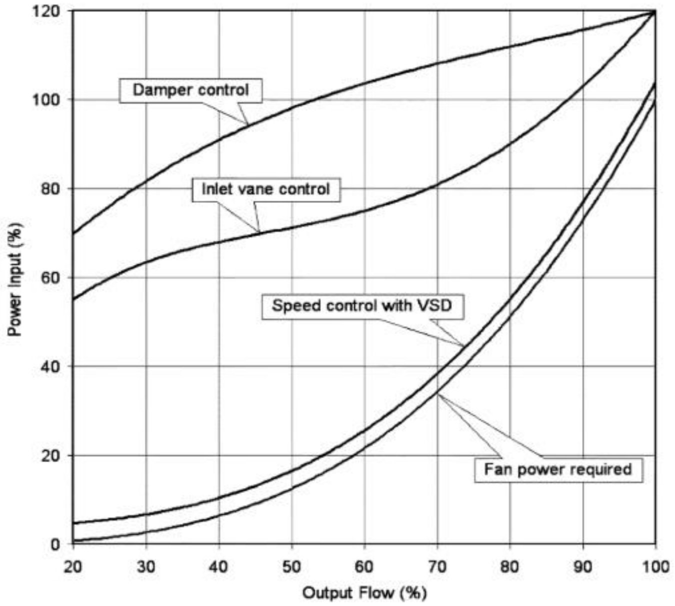


Figure 5: Power input for different flow control methods of centrifugal fan (Almeida et al. 2005)

CASE STUDY

A chlor-alkali plant in the Hallabat Industrial Park in Jordan (Middle East) installed adjustable frequency drives on the large cooling fans. Implementing ASDs was expected to decrease electricity consumption by 75,600 kWh/yr and reduce CO_2-eq emissions by approximately 40 tons.

Source: United States Agency for International Development (USAID) (2015). Sahab Factory Improves Production, Saves Resources, and Investigates Solar Initiative. https://pdf.usaid.gov/pdf_docs/PA00KK3F.pdf

Install high-efficiency belts (cogged V-belts)

Belts make up a variable, but significant, portion of the fan system in many plants. It is estimated that about half of the fan systems use standard V-belts. As shown in Figure 6, about 8% of industrial fan and blower systems use V-belts, and another 17% use belts of an unknown type but that are likely V-belts. This combined share of systems represents about half of the total share of known systems (i.e., excluding the systems for which information could not be collected) (Rao et al., 2021). Standard V-belts tend to stretch, slip, bend, and compress, which leads to a loss of efficiency. Replacing standard V-belts with cogged belts can save energy and money, even as a retrofit. Cogged belts run cooler, last longer, require less maintenance, and have an efficiency that is about 2% higher than standard V-belts (NREL 2018). Replacing the V-belts with cogged belts can reduce industrial energy consumption by 271 GWh (Rao et al. 2022). The average payback period (based on more than 1,000 recommendations across U.S. plants) is 0.8 years (IAC 2024).

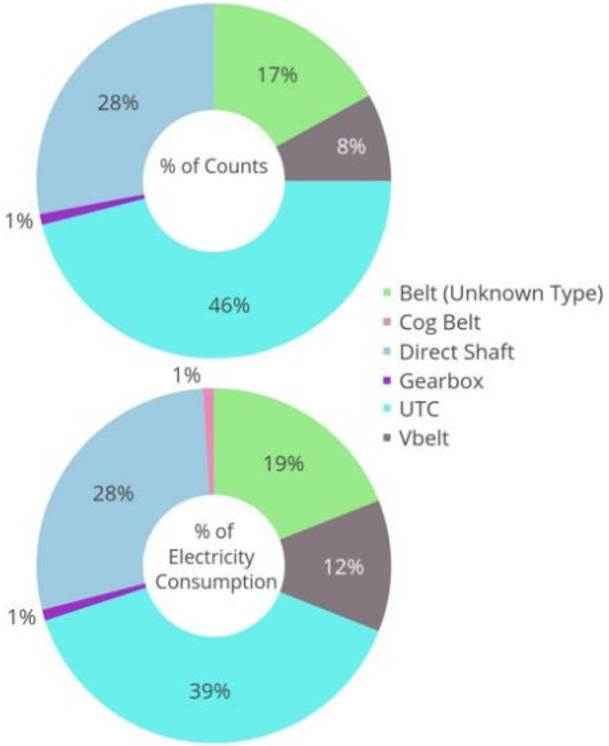


Figure 6: Transmission types used in the industrial fan and blower systems (Rao et al. 2021); UTC: unable to collect

Repair duct leaks

Duct leakage can waste significant amounts of energy in fan and ventilation systems. Measures for reducing duct leakage include installing duct insulation and performing regular duct inspection and maintenance, including ongoing leak detection and repair. For example, per studies by Lawrence Berkeley National Laboratory, repairing duct leaks in industrial and commercial spaces could reduce heating, ventilation, and air conditioning (HVAC) energy consumption by up to 30% (Galitsky et al. 2005).

Because system leakage can have a significant impact on fan system operating costs, as proactive leak prevention measures, DOE recommends considering as part of the fan system design process the type of duct, the tightness and quality of the fittings, joint assembly techniques, and the sealing requirements for duct installation (DOE 2003b).

Avoid system effect

In very compact fan assemblies, usually made to save floorspace, fan system performance can be affected. Using multiple elbows close to a fan inlet or outlet can create a system effect. The system effect is the change occurring in the system performance because of the interaction of the different system components (e.g., dampers, filters, ducts, elbows) (DOE 2003b). The small duct size and compact duct configuration increases operating costs. Having the first elbow or T-shaped section of ducting within 3 feet of the fan blades can form swirls in the air stream, which can increase the fan load.

Chapter 7: Pump Systems

In this chapter:	
Maintain pump systems	Monitor the pump system
Minimize pump demand	Install/optimize controls
Install high-efficiency pumps	Properly size pumps
Use multiple pumps for variable loads	Install adjustable-speed drives (ASDs)
Trim impellers	Avoid throttling and pressure-reducing valves
Replace belts when needed	Properly size piping
Clear the piping	Use precision casting, surface coatings, or polishing
Maintain proper seals	Reduce leakage through clearance reduction
Replace condensate return electric pumps with pressure powered pumps	

Pumps are widely used in chlor-alkali plants to circulate the brine from one purification stage to the other and for pumping cooling water and wastewater, circulating finished product to storage tanks, and loading transportation bulk packages.

Pumping systems consist of a pump, a driver, piping systems, and controls (such as ASDs or throttles). There are two main ways to increase pump system efficiency, aside from reducing use. These are reducing the friction in dynamic pump systems (not applicable to static or "lifting" systems) (such as with the use of coatings that reduce the frictional head in pumps) or upgrading/adjusting the system so that it draws closer to the best efficiency point on the pump curve (Hovstadius 2007). Correct sizing of pipes, surface coating or polishing, and ASDs, for example, may reduce friction loss, increasing energy efficiency. Correctly sizing the pump and choosing the most efficient pump for the applicable system will push the system closer to the best efficiency point on the pump performance curve, also simply known as "pump curve." Furthermore, pump systems are part of motor systems, and, thus, the general "systems approach" to energy efficiency for motors described in Chapter 4: Motor Systems applies to pump systems as well.[2]

---

[2] U.S. DOE's Industrial Efficiency and Decarbonization Office provides a variety of resources for improving the efficiency of industrial pumps, which can be consulted for more detailed information on many of the measures presented in this chapter. DOE's *Improving Pumping System Performance: A Sourcebook for Industry* is a particularly helpful resource (DOE 2006). For a collection of tips, tools, and industrial case studies on industrial pump efficiency, visit DOE's website at www.energy.gov/eere/iedo/pump-systems.

Energy Savings Checklist: Pump Systems

Energy is typically the most significant cost associated with the life cycle of a pump system, accounting for up to 95% of the lifetime costs of the pump. Use the checklist below to find new ways to save energy and money.

Pump Systems Checklist	✓
Can you minimize pump demand by better matching pump requirements to end-use loads?	
Is a control system in place to automatically shut off pumps when demand is reduced?	
Can existing technology be made more energy efficient?	
Are pumps properly sized, including the use of multiple pumps for variable loads?	
Are pump systems properly maintained?	
Are ASDs being used?	
Is the impeller properly sized or trimmed?	
Replace V-belt with energy-efficient belt (i.e., cogged V-belt).	

Opportunities for Energy Efficiency

Initial costs are only a fraction of the lifetime cost of a pump system. Energy expenditures, and sometimes operations and maintenance (O&M) expenditures, are much more important. In general, for a pump system with a lifetime of 20 years, energy expenses account for 50% to 60% of lifetime expenses (Dutta et al. 2023; DOE 2001; Hennecke 2006). Depending on the pump application, energy outlays may comprise about 98% of the lifetime expenses of the pump (MacHarg and Sessions 2013). Hence, the initial choice of a pump system should be highly dependent on energy cost considerations rather than on initial costs such as the price of the pump and related parts.

Optimization of the design of a new pumping system should focus on optimizing the life cycle expenditures. Hodgson and Walters (2002) discuss software developed for this purpose and several case studies in which they show large reductions in energy use and lifetime costs of a complete pumping system. Typically, such an approach will lead to energy savings of 10% to 17%. Using pump system optimization models can decrease the energy use by about 7% while extending the operational life (Torregrosa and Capitanescu 2019). Designing pump systems with energy conservation as the main consideration and installing the right size pumps for the activity can achieve energy savings in the excess of 50% (Schofield 2022).

Best Practices for Energy-Efficient Pump Systems

- **Maintain pump systems.** A maintenance program keeps pumps running optimally and can save up to 7% in energy.
- **Monitor the pump system.** Monitoring and maintenance can detect problems and determine solutions to increase the efficiency of the system.

- **Minimize pump demand.** Reducing demand through holding tanks and elimination of bypass loops can save up to 20% in energy.
- **Install/optimize controls.** Control systems increase the efficiency of pump systems and significantly reduce costs.
- **Install high-efficiency pumps.** New high-efficiency pumps can result in up to 10% in energy savings.
- **Properly size pumps.** Replacing oversized pumps with properly sized ones can reduce electricity by up to 25%.
- **Use multiple pumps for variable loads.** Using multiple pumps in parallel is a cost-effective and energy-efficient method for pump systems with variable loads.
- **Install ASDs.** Including modulation features like ASDs can save an estimated 20% to 50% of pump energy consumption.
- **Trim impellers.** Reducing an impeller's diameter reduces the energy added to the pump system.
- **Avoid throttling and pressure-reducing valves.** Pump demand reduction, controls, impeller trimming, and multiple pump strategies (all previously discussed in this section) are more energy-efficient flow management strategies than throttling valves.
- **Replace belts when needed.** Replacing belt drives with cogged belts saves energy and money.
- **Properly size piping.** Increasing the pipe diameters, as part of a system retrofit, reduces pumping energy.
- **Use precision casting, surface coatings, or polishing.** Using castings, coatings, or polishing reduces pump surface roughness and increases energy efficiency.
- **Maintain proper seals.** Use gas barrier seals, balanced seals, and no-contact labyrinth seals to decrease seal losses.
- **Reduce leakage through clearance reduction.** Use hard construction materials such as chromium steel to reduce the wear rate of the clearance between the impeller suction and pressure sides.
- **Replace condensate return electric pumps with pressure powered pumps.** It uses saturated steam or compressed air for energy savings and a longer life cycle.

Maintain pump systems

Inadequate maintenance can lower pump system efficiency, cause pumps to wear out more quickly, and increase pumping energy costs. Figure 7 shows the decrease in energy efficiency with and without proper maintenance. Energy efficiency losses can range between 10% and 25% (Cella 2021; Kaya et al. 2021). Some important signs of wear are cavitation, higher clearance between moving and fixed parts, and increased wear in rings and bearings. A pump system maintenance program will help keep pumps running optimally and reduce energy efficiency losses from increased wear. Improved pump system maintenance can lead to energy savings of 2% to 7% (Cella 2021).

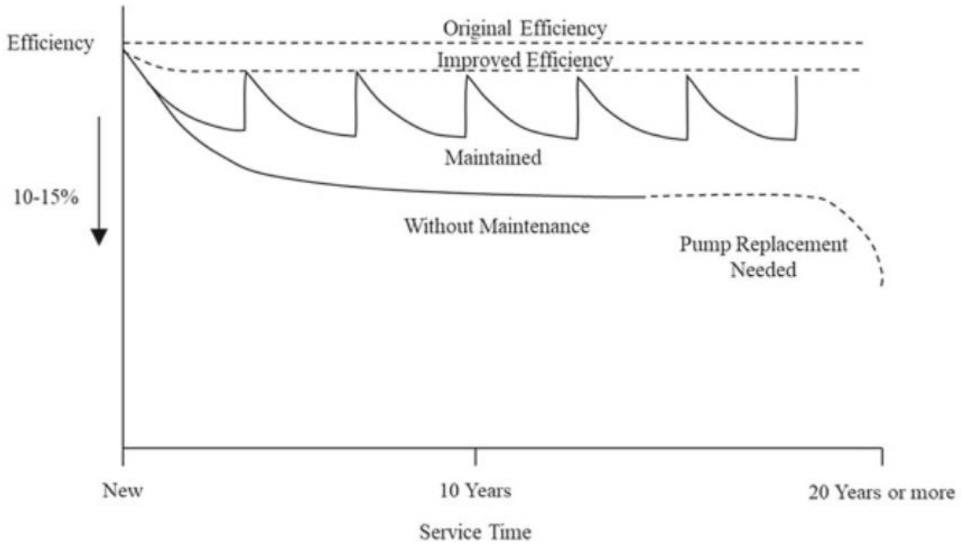


Figure 7: The effect of pump maintenance on pump energy efficiency (Kaya et al. 2021)

A pump system maintenance program will generally include the following tasks (DOE 2006; DOE 2002):

- Replacing worn impellers, especially in caustic or semi-solid applications.
- Inspecting and repairing bearings.
- Replacing bearing lubrication on an annual or semiannual basis.
- Inspecting and replacing packing seals. Allowable leakage is typically between 2 and 60 drops per minute.
- Inspecting and replacing mechanical seals. Allowable leakage is typically 1 to 4 drops per minute.
- Replacing wear ring and impeller. Pump efficiency degrades by 1% to 6% for impellers less than the maximum diameter and with increased wear ring clearances.
- Checking pump/motor alignment.
- Inspecting motor condition, including the motor winding insulation.

Monitor the pump system

Monitoring in conjunction with O&M can be used to detect problems and determine solutions to create a more efficient system. Monitoring can determine clearances that need adjustment and indicate a blockage, impeller damage, inadequate suction, operation outside of preferences, clogged or gas-filled pumps or pipes, or worn-out pumps. Monitoring should include the following:

- Specific energy consumption (i.e., electricity use/flow rate) (Hovstadius 2007).
- Wear monitoring.

- Vibration analyses.
- Pressure and flow monitoring.
- Current or power monitoring.
- Differential head and temperature rise across the pump (also known as thermodynamic monitoring).
- Distribution system inspection for scaling or contaminant buildup.

Minimize pump demand

An important component of the systems approach is to minimize pump demand by better matching pump requirements to end-use loads. Two effective strategies for reducing pump demand are using holding tanks and eliminating bypass loops. Holding tanks can be used to equalize pump flows over a production cycle, which can allow for a more efficient operation of pumps at reduced speeds and lead to energy savings of 10% to 20% (DOE 2002). Using holding tanks can also reduce the need to add pump capacity. Eliminating bypass loops and other unnecessary flows can result in energy savings of 10% to 20% (DOE 2002). Other effective strategies for reducing pump demand include lowering process static pressures, minimizing elevation rises in the piping system, and lowering spray nozzle velocities.

Install/optimize controls

Control systems can increase the energy efficiency of a pump system by shutting off pumps automatically when demand is reduced or, alternatively, by putting pumps on standby at reduced loads until demand increases.

Install high-efficiency pumps

Considering that a pump's efficiency may degrade by 10% to 25% over the course of its life, replacing aging pumps can lead to significant energy savings. Installing newer, higher-efficiency pumps typically results in energy savings of 2% to 10% (Hamer 2002). In addition, replacing the motors with high-efficiency motors will improve energy efficiency by another 2% to 5% (Kalaiselvan et al. 2016).

Several high-efficiency pumps are available for specific pressure-head and flow-rate capacity requirements. Choosing the right pump often saves both operating and capital costs. For a given duty, selecting a pump that runs at the highest speed suitable for the application will generally result in a more efficient selection, as well as the lowest initial cost (DOE 2001).

Properly size pumps

Pumps that are oversized for an application consume more energy than is necessary (see also "Avoid throttling and pressure-reducing valves" below). In general, industrial facilities select the correct size. Rao et al. (2021) explain that 84% of industrial pumps are appropriately sized for their application.

Replacing oversized pumps with pumps that are properly sized can often reduce the electricity use of a pumping system by 15% to 25% (DOE 2002). Where peak loads can be reduced through improvements to pump system design or operation (e.g., via the use of holding tanks), pump size can also be reduced. If a pump is dramatically oversized, often its speed can be reduced with gear or belt drives or a slower-speed motor. The typical payback period for the above strategies can be less than 1 year (Galitsky et al. 2005).

In general, an oversized pump is a pump that does not operate within 20% of its best efficiency point (BEP). Each centrifugal pump has its own BEP that is the point with maximum efficiency where the losses are the lowest. The BEP point is often indicated on the pump curve, which can be obtained from vendors. The pump curve specifies the allowable pressure and flow rate operating points of a pump and the energy efficiency at a certain pressure and flow rate level. It thereby gives important information on how well the pump operates with respect to its performance specifications. However, for only 26% of industrial pumping systems is the pump curve available to the facility (Rao et al. 2022).

It is, however, possible to operate at the BEP level with an oversized pump that is conveying extra fluid through a bypass tank. In this case, while the pump may be operating efficiently, it is using more energy than needed.

Use multiple pumps for variable loads

In 2020, 35% of pumping was from motors operating at variable loads while most pumps (57%) operated under constant load (Rao et al. 2021). In the case of variable loads, the use of multiple pumps installed in parallel can be a cost-effective and energy-efficient solution for pump systems (DOE 2002; Kaya et al. 2021). Parallel pumps offer redundancy and increased reliability and can often reduce pump system electricity use by 10% to 30% for highly variable loads (DOE 2002). Parallel pump arrangements often consist of a large pump, which operates during periods of peak demand, and a small pump (or “pony” pump), which operates under normal, more steady-state conditions. Because the pony pump is sized for normal system operation, this configuration operates more efficiently than a system that relies on a large pump to handle loads far below its optimum capacity.

Install ASDs

ASDs better match speed to load requirements for pumps, whereas, for motors, energy use is approximately proportional to the cube of the flow rate.[3] Hence, small reductions in flow rates that are proportional to pump speed may yield large energy savings for friction-dominated pump systems. However, in static head-dominated systems, the energy use might increase when using ASDs if the speed is turned down too much. New installations may result in short payback periods. In addition, the installation of ASDs improves overall productivity, control, and product quality, and reduces wear on equipment, thereby lowering future maintenance costs.

About 71% of the motors used to drive pumps in U.S. industry have no load modulation feature (or ASD). The penetration of VFDs, the most common type of ASDs, reaches approximately 21% of the motors while the penetration of other forms of control is negligible (Rao et al. 2021). When ASDs are adopted by rotodynamic pump installations, such as centrifugal systems, energy use can decrease 30% to 50% (Hydraulic Institute et al. 2004; DOE 2007).

ASDs are the preferred flow control option when the pumps operate for at least 2,000 hours per year and the process flow rate requirements vary over time by 30% or more (DOE 2007). For pumps operating without ASDs, select a premium energy efficiency motor with a full-load speed comparable to that of the standard efficiency motor to be replaced. Selecting a

---

[3] This equation applies to dynamic systems only. Systems that solely consist of lifting (static head systems) will accrue no benefits from ASDs (but often will become more inefficient) because pump efficiency usually drops when speed is reduced in such systems. A careful choice of operating points can, to some extent, overcome this problem. Similarly, systems with more static head will accrue fewer benefits than systems that are largely dynamic (friction) systems. More careful calculations must be performed to determine actual benefits, if any, for these systems.

premium energy efficiency motor that drives the pump at a higher speed will result in lower energy savings. When the motor is controlled by ASDs, buying a motor with a higher full-load speed will not change energy use (DOE 2014a).

Trim impellers

Impeller trimming refers to the process of reducing an impeller's diameter via machining, which will reduce the energy added by the pump to the system fluid. Per DOE (2006), one should consider trimming an impeller when any of the following conditions occur:

- Many system bypass valves are open, indicating that excess flow is available to system equipment.
- Excessive throttling is needed to control flow through the system or process.
- High levels of noise or vibration indicate excessive flow.
- A pump is operating far from its design point.

Trimming an impeller is slightly less effective than buying a smaller impeller from the pump manufacturer but can be useful when an impeller at the next smaller available size would be too small for the given pump load. The energy savings associated with impeller trimming depend on pump power, system flow, and system head, and are roughly proportional to the cube of the diameter reduction (DOE 2006). An additional benefit of impeller trimming is a decrease in pump operating and maintenance costs. Care must be taken when an impeller is trimmed or the speed is changed so that the new operating point does not end up in an area where the pump efficiency is low.

In the case of pumping systems that operate constantly underloaded, impeller trimming can deliver the same energy savings as installing VFDs without the losses across the VFD. Impeller trimming is not recommended for significantly underloaded systems and is irreversible as, once done, the pumping load cannot increase (Rao et al. 2022). Impeller trimming can decrease the total industrial pump system energy consumption by 1% (about 5,493 GWh) when adopted by industrial pumps with a load factor lower than 75% (Rao et al. 2022).

Avoid throttling and pressure-reducing valves

Throttling valves and bypass loops are indications of oversized pumps, as well as the inability of the pump system design to accommodate load variations efficiently, and should always be avoided (Iowa State University 2005). Figure 8 shows the power use of a pump under different output flows and flow control methods. Pump demand reduction, controls, impeller trimming, and multiple pump strategies (all previously discussed in this section) should always be more energy-efficient flow management strategies than throttling valves. Also, throttling valves create mechanical stresses (excessive pressure and temperature) on the pumping system which can cause seal or bearing failure.

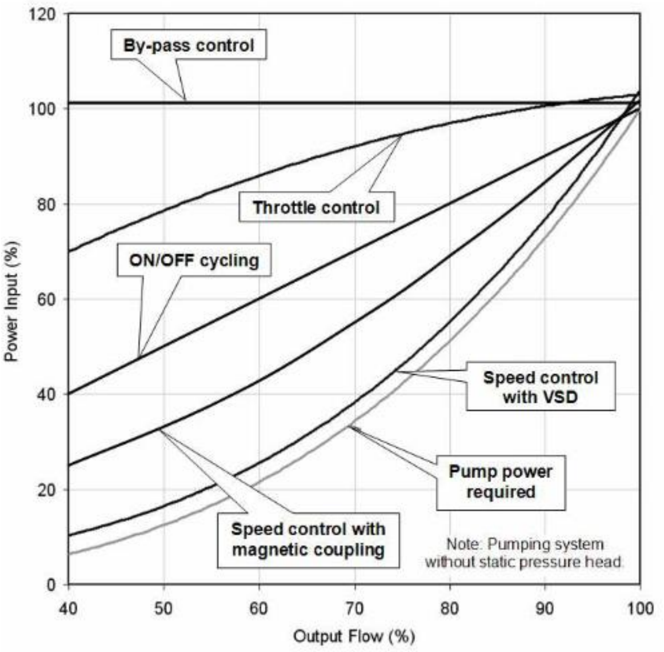


Figure 8: Power input for different flow controls of a centrifugal pump without static pressure head (Ferreira, 2009)

Figure 9 shows the energy losses in a pumping system where the flow is controlled with a throttling valve (top) and with an ASD (bottom). The system using an ASD does the same work while using 23% less energy (DOE 2014b).

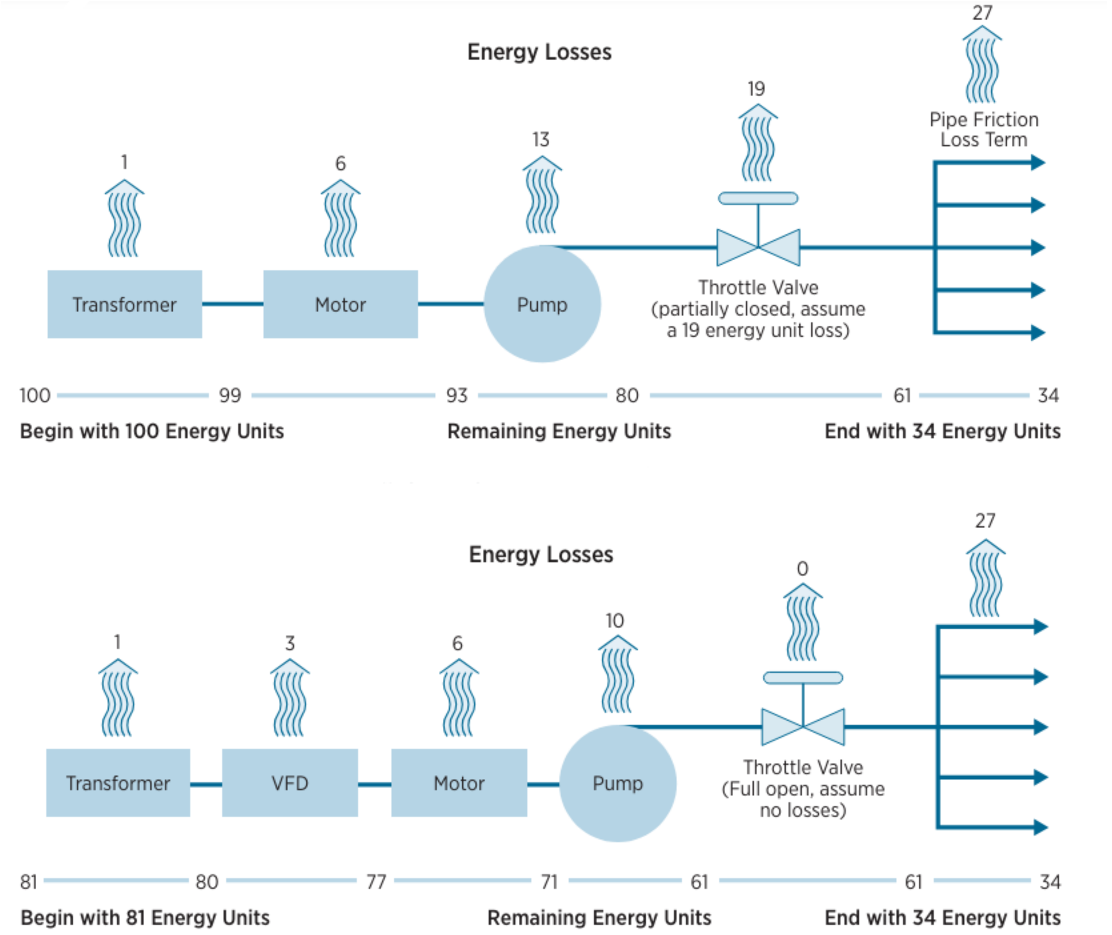


Figure 9: Energy losses in a pump system when the flow is controlled by a throttle valve (top) and a VFD (bottom) (DOE 2014b)

Replace belts when needed

Most pumps are directly driven. However, about 17% of pumps have belts, with 2% being V-belt drives (Rao et al. 2021). In chlorine plants they are not very common. Standard V-belts tend to stretch, slip, bend, and compress, which leads to a loss of efficiency. Replacing standard V-belts with cogged V-belts can save energy and money, even as a retrofit. It is better to replace the pump with a directly driven system, which can result in increased savings of up to 8% (Studebaker 2007).

For centrifugal pumps, characterized by a strong relationship between operating speed and power consumption, it is recommended to use synchronous belt sprockets that take into account the absence of belt slippage. This is because if slippage is reduced and the load is driven at slightly higher speed, the fluid flow, pressure, and operating costs could actually increase (DOE 2012r).

Properly size piping

Pipes that are too small for the required flow velocity can significantly increase the amount of energy required for pumping, in much the same way that drinking a beverage through a small straw requires a greater amount of suction.

Where possible, pipe diameters can be increased to reduce pumping energy requirements, but the energy savings due to increased pipe diameters must be balanced with increased costs for piping system components. That said, sizing a pipe too large can result in pressure reduction, which forces a pump to work even harder. To properly size a pipe, consider the amount of volume that needs to move per minute and the distance being travelled. In cases where a single pipe or hose feeds into a larger pipe, efficiency can be lost. A life cycle costing approach is recommended to ensure positive economic benefits when energy savings, increased material costs, and installation costs are considered. Increasing pipe diameters will likely only be cost-effective during greater pump system retrofit projects. U.S. DOE estimates typical industrial energy savings in the 5% to 20% range (DOE 2002; Augustyn 2012).

Clear the piping

Internal buildup due to deposits of dirt, lime, scale, and other minerals can increase the frictional head against which the pump has to work and decrease the flow. Industries with significant deposits, such as mining, often use a pig to clean the pipes. Pipeline pigging products are available in several designs and materials to conform to the shape of the pipes for maximum contact and buildup removal.

Use precision castings, surface coatings, or polishing

The use of castings, coatings, or polishing reduces pump surface roughness, which, in turn, increases energy efficiency. It may also help maintain efficiency over time.

There is a wide range of corrosion-resistant coating technologies available that can be used to protect the pump’s interior and enhance pump efficiency. Some coating materials include glass flake, thermosetting polyurethane, and nonsolvent-free epoxy coatings (Sanada and Oharriz 2020). Coatings have shown to increase the efficiency of new pumps by as much as 6% (Maillard 2008).

In some case it may be advantageous to apply coatings to the inside of the piping, particularly in applications where there is a lot of grit or residues that are in the fluid being pumped.

Maintain proper seals

Seal failure accounts for up to 70% of pump failures in many applications (Kaya et al. 2021). The sealing arrangements on pumps will contribute to the power absorbed. Often the use of gas barrier seals, balanced seals, and non-contacting labyrinth seals decreases seal losses. Choosing appropriate and reliable seals is very important for the lifetime of the pumps. For very high-temperature operations, mechanical unshielded seals can be used (Kaya et al. 2021).

In some case it may be advantageous to apply coatings to the inside of the piping, particularly in applications where there is a lot of grit or residue in the fluid being pumped.

Reduce leakage through clearance reduction

Internal leakage losses are a result of differential pressure across the clearance between the impeller suction and pressure sides. The larger the clearance, the greater the internal leakage causing inefficiencies. The normal clearance in new pumps ranges from 0.014 to 0.04 inch (0.35 to 1.0 mm) (DOE 2001). With wider clearances, the leakage increases almost linearly with the clearance. For example, clearance of 0.2 inch (5 mm) decreases the efficiency by 7% to 15% in closed impellers and by 10% to 22% in semi-open impellers. To prevent excessive backflow, clearance should be less than

(0.3 mm) while a clearance of 0.01 mm was found to provide a higher head and improved efficiency (Karlsen-Davies and Aggidis 2016). Abrasive liquids and slurries, even rainwater, can affect the pump efficiency. Using very hard construction materials (such as high chromium steel) can reduce the wear rate. Trimming also increases the clearance between the impeller and the casing; therefore, trimming should be limited to about 75% of the pump's maximum impeller diameter (DOE 2006).

Replace condensate return electric pumps with pressure powered pumps

The pressure powered pump is a non-electric pump that transfers high temperature condensate, or other liquids, from a low point, low pressure, or vacuum space to an area of higher pressure or elevation. It uses steam, compressed air, or any other suitable pressurized gas as the pumping force for energy savings and longer life cycle. It requires no electric motors or power switches and therefore no power use. The payback time is claimed to be less than 6 months (Spirax Sarco 2020).

If the plants have low-pressure steam that they are venting, it makes sense to reuse it in mechanical pumps that use steam or compressed air.

Chapter 8: Cooling Systems

In this chapter:	
Chillers	
Check that system delta-T is equal to design delta-T	Optimize condenser and evaporator parameters
Keep heat transfer surfaces clean	Maintain adequate condenser water flow
Remove trapped air from the condenser	Install adjustable-speed drives (ASDs) on centrifugal chillers
Change compressors to meet demand	Manage the load between chillers
Use free cooling	Choose the right cooling system
Use energy-efficient chillers	Use absorption chillers when waste heat is available
Use electric-drive centrifugal chillers	Use magnetic-drive chillers
Cooling Towers	
Use a cooling tower instead of a chiller	Use ASDs on cooling tower fans
Run pumps without fans when weather conditions permit	Schedule cleaning and maintenance
Monitor fill	Use water treatment systems for water makeup
Auxiliary Equipment	
Optimize the performance of auxiliary equipment	Use a trim cooler when dry bulb temperature is high
Use a chilled water tank/ice storage	Implement side-stream filtration systems
Install temperature control units (TCUs)	Use microchannel heat exchangers
Use pre-insulated acrylonitrile butadiene styrene (ABS) piping	Insulate the cooling line and jacket
Refrigerants	
Use low global warming potential (GWP) refrigerants	Monitor refrigerant charge
Monitor refrigerant contamination	
Cooling System Configurations	
Convert systems from constant to variable flow	Inspect frequently
Use infrared cameras to spot losses	Improve operations and maintenance (O&M)
Use glycol refrigerant for systems that must reach temperatures below -4°F (-20°C)	Replace glycol solution with water during warm months

In this chapter:	
Use refractometers to adjust the solution concentration	Recover waste heat
Monitor the overall system and individual equipment efficiency	Use controls to optimize the system
Integrate with the building management system (BMS)	Consider tri-generation

In a chlor-alkali plant, cooling is needed to lower the temperature of chlorine, caustic soda, and hydrogen and remove heat from equipment (e.g., transformers). The chlorine exiting the electrolytic cell is treated in the chlorine house where the chlorine is cooled, dried, filtered, and finally liquefied (liquefaction also requires cooling). Chlorine compression and cooling consume about 200 kWh/ton Cl_2 and refrigeration another 50-55 kWh/ton Cl_2.

In primary chlorine cooling, the chlorine leaving the cell is cooled to around 59°F (15°C). Further temperature reduction is avoided as chlorine hydrate is formed that can lead to equipment blockage at temperatures below 50°F (10°C). Primary chlorine cooling is achieved in one or several stages with water, brine, and other fluids. There are two methods used: indirect cooling through a titanium surface and direct cooling with water or other fluids where the water/fluid is sprayed from the top of the tower as the chlorine flows counter-currently (Brinkmann et al. 2014).

Liquefaction requires even lower chlorine temperatures. Chlorine liquefaction can be achieved at different pressures and temperatures, such as at ambient temperature and high pressure (e.g., 64°F and 102-174 psi) or low temperature and low pressure (-95°F and 15 psi) (Brinkmann et al. 2014). The choice of liquefaction conditions dictate the electricity consumption for cooling and compression. For high liquefaction pressures, the need for cooling is low and the indirect refrigerant can be water. For relatively low liquefaction pressures, the energy use for cooling is much higher while the refrigerants typically used are hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), ammonia, and others.

Cooling systems in manufacturing plants support both building and process cooling. Building, or comfort, cooling regulates the temperature and humidity in a room. It typically has a variable cooling load requirement due to the ambient temperature and humidity. Process cooling corresponds to the removal of unwanted heat from a process. It can be broken down into variable cooling loads (i.e., batch processes) and constant cooling loads (i.e., continuous processes). Cooling processes with a variable load are designed to meet the peak load requirements, which often only occur for 1% of the operating hours. These systems tend to be inefficient during low-load and medium-load periods.

A cooling system could have a cooling tower, which reduces the temperature of the water or coolant; a chiller that cools the water; and auxiliary systems that support its operation, including chilled water tanks, piping, and insulation. The temperature requirements are an important variable in choosing the equipment and type of cooling system required. Three types of cooling system configurations exist, depending on the temperature requirements (Table 7):

1. In a once-through cooling system, water is pumped from a nearby water source (e.g., river, lake, ocean, well) and passed through a heat exchanger to cool a refrigerant or medium directly. It is then discharged back to the source. The temperature of the water supply source and return water should be closely monitored. The temperature of the water supply changes with seasonal weather conditions and in summer could reach temperatures that are too high to be used as a cooling source. Care must be taken to ensure that the return temperature does not negatively impact the aquatic ecosystem. Some discharge permits limit the temperature rise.
2. Closed recirculating systems work in a closed-loop circuit where the heat is released into the atmosphere (i.e., air-cooled) or transferred to a second coolant (i.e., water-cooled). The heat transfer into the atmosphere could occur in two ways: dry or evaporative. Dry systems pass the coolant through rows of finned tubes cooled with ambient air blown using a fan. Evaporative systems use cooling towers to spray water across the distribution system.
3. The open recirculating cooling system cascades water directly through an upward airflow to evaporate it. The remaining water is cooled during evaporation, and the evaporated water is replaced with makeup water. The remaining and makeup water are collected in a basin and pumped to the load, and the cycle repeats. On average, this type of system requires 4 gallons/minute of makeup and blowdown water per 1 MBtu/hour of heat rejected (Williams 2013).

Table 7: Summary of cooling system configurations (Prajapati 2021; Williams 2013)

Type of Cooling System	Average Temperature Change	Water Use	Equipment Used	Examples
Once-through	5°F to 10°F (3°C to 6°C)	High	Pump, heat exchanger	Potable water systems, process water, and general service
Closed recirculating (dry and evaporative)	10°F to 15°F (6°C to 8°C)	Negligible	Pump, heat exchanger, fans, cooling tower	Automobile radiator and food temperature controllers
Open recirculating	10°F to 30°F (6°C to 17°C)	Moderate	Pump, heat exchanger, cooling tower	Cooling towers and spray ponds

Chilled water systems or chillers are used for both process and building cooling. They provide cooling capacity regardless of changes to the ambient temperature, heat load, and flow requirements. There are two types of chillers: vapor absorption and vapor compression. Vapor absorption chillers use a heat source to move the refrigerant between areas of different temperatures and pressure (Evans 2018). The chiller is the main part of a cooling system, consisting of a compressor, a condenser, an expansion valve, and an evaporator. It has three circuits—the refrigeration circuit, chilled water circuit, and condenser circuit. The refrigeration circuit consists of a refrigerant that passes through the main components. The compressor increases the pressure, and therefore the coolant's temperature, and provides the force to convey it through the chiller. The condenser cools the refrigerant from a separate water line that goes to a cooling tower and changes phase into a saturated liquid. The expansion valve converts the saturated refrigerant into a liquid/vapor mixture, lowering its pressure and temperature. Finally, in the evaporator, the excess heat from the building or process is transferred to the refrigerant, changing its phase to saturated vapor (Figure 10). The evaporator and condenser are both heat exchangers.

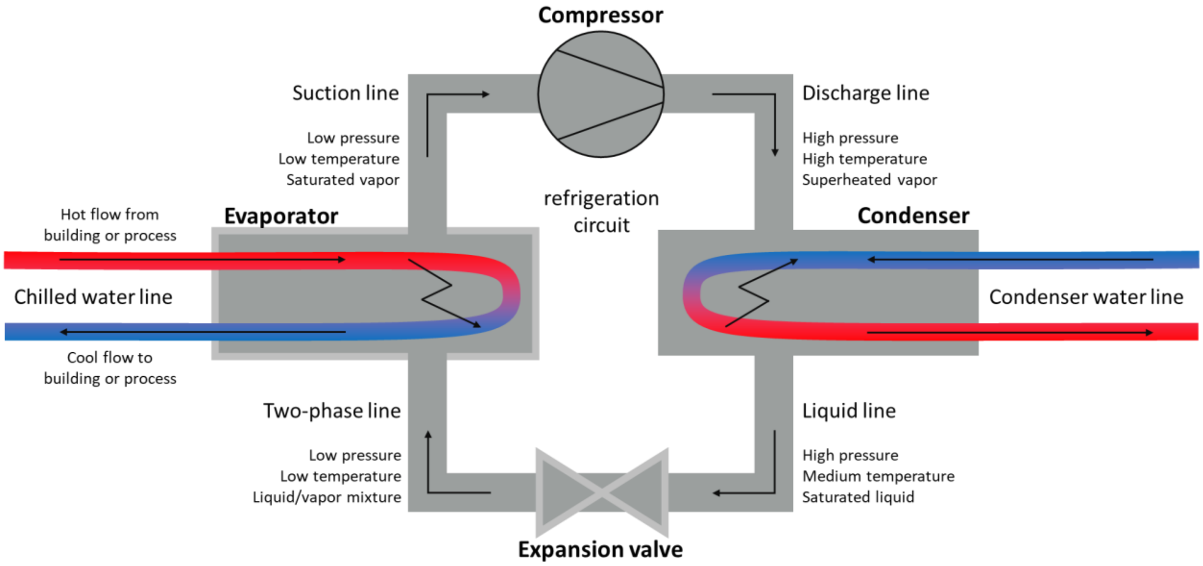


Figure 10: Schematic of a chiller (Zietlow 2016)

Energy-efficient chillers use larger heat exchange areas and more efficient compressors to achieve more efficient overall operation. The chiller coefficient of performance (COP) represents the chiller efficiency. It is a unitless number defined as the ratio between the cooling capacity of the chiller (cooling provided) and the power consumed to provide the cooling.

Depending on the type of compressor used, chillers are categorized as follows:

- **Centrifugal compressors** are aerodynamic or turbine compressors that move gas by converting kinetic energy to pressure energy. These are water-cooled and have a capacity range of 200 to 21,000 kW (60 to 6,000 refrigeration tons).
- **Reciprocating compressors** use cylinders with pistons acting as pumps to increase refrigerant pressure. They can be air-cooled or water-cooled. They have a capacity range of 10 to 1,800 kW (3 to 510 refrigeration tons).
- **Rotary-screw compressors** compress the refrigerant between rotating screws. They are air-cooled or water-cooled and have a capacity range of 10 to 7,000 kW (3 to 2,000 refrigeration tons).
- **Scroll compressors** use a stationary scroll within a rotating scroll to compress the refrigerant. They have a capacity range of 10 to 1,800 kW (3 to 510 refrigeration tons).

Energy Savings Checklist: Cooling Systems

Cooling Systems Checklist	✓
Can multiple chilled water circuits be interconnected to reduce chillers/pumps during low load months?	
Is a chilled water optimization control system in place?	
Are pumps in winter shut off to protect them from freezing? (chiller condenser water)	
Are appropriate controls and appropriate setpoints in place?	
Is there an opportunity to shut off the equipment in winter?	
Is there a water treatment system in place to prevent fouling or corrosion?	
Are the evaporator and condenser regularly cleaned?	
Is the water temperature in the cooling tower kept at a minimum (wet bulb dependent)?	
Review using VFDs on fans and pumps. Constant speed fans can be converted to variable speed and provide significant saving opportunities, especially for variable loads, up to 50%.	
Can the chilled water setpoint be adjusted based on the outside temperature? (Raising the chilled water temperature by 2°F to 3°F can increase efficiency by as much as 3% to 5%.)	
Can the condenser water setpoint be adjusted based on the outside temperature? (Decreasing the condenser water temperature by 2°F to 3°F can increase efficiency by as much as 2% to 3%.)	
Is the chilled water system properly insulated?	
Can free cooling with a heat exchanger to the cooling tower be used during cold outside temperatures?	
Can rainwater or cooling coil condensate be used for cooling tower makeup water?	
Can three-way valves be eliminated? Use pressure compensating two-way valves to reduce bypass and increase delta-T.	

Best Practices for Energy-Efficient Cooling Systems

Chillers

- **Check that system delta-T is equal to design delta-T.** A low delta-T increases the energy consumption of chilled water pumps.
- **Optimize condenser and evaporator parameters.** Minimize the differences between the condenser and the evaporator to reduce power input while increasing refrigeration output.
- **Keep heat transfer surfaces clean.** Scale and fouling buildup insulate the tubes in the heat exchanger, thus causing inefficiencies.
- **Remove trapped air from the condenser.** Air limits the amount of cold surface exposed to the refrigerant.
- **Maintain adequate condenser water flow.** Blockage of the filter in the condenser water line reduces water flow.
- **Install ASDs on centrifugal chillers.** ASDs provide accurate control to the speed of the chiller compressor in response to load and evaporator and condenser pressures.
- **Change out compressors to meet demand.** A compressor and motor drive that closely match the observed load can reduce energy use.
- **Manage the load between chillers.** Manage the load of two or more chillers to obtain a combined peak efficiency.
- **Use free cooling.** If the outside air temperature is low enough, the chiller should be shut off and outside air used.
- **Use the right cooling system.** Water-cooled chillers are more efficient and slightly less expensive than equivalent air-cooled chillers.
- **Use energy-efficient chillers.** These chillers typically have larger heat exchange areas and compressors.
- **Use absorption chillers when waste heat is available.** They are energy efficient when waste heat from a process can be captured and used to generate chilled water.
- **Use electric-drive centrifugal chillers.** 0.2 Btu of electric energy is required in modern electric-drive centrifugal chillers to remove 1 Btu of energy from thermal water.
- **Use magnetic-drive chillers.** They operate more efficiently than reciprocating and screw compressors. Power savings averaged 49% for three case studies in the United States.

Cooling Towers

- **Use a cooling tower instead of a chiller.** Cooling towers require a lower investment and are characterized by lower operational costs when compared with chillers.
- **Use ASDs on cooling tower fans.** It is more efficient to operate two or more cell fans at reduced speed than one at full speed during lower load conditions.

- **Run pumps without the fans when climate conditions permit.** During cold weather, the cooling tower pumps can be run without the fans and achieve the same cooling effect while reducing power consumption.

- **Schedule cleaning and maintenance.** Scale and foul are left behind when water is evaporated, which affects efficiency in the heat transfer.

- **Monitor fill.** Service or replace the fill in cooling towers to avoid fouling.

- **Use water treatment systems for water makeup.** Water treatment reduces tower blowdown frequency and limits tower fouling, keeping them more efficient.

Auxiliary Equipment

- **Optimize the performance of auxiliary equipment.** Opportunities to improve compressors, pumps, motors, and fans are found in previous sections of this guide.

- **Use a trim cooler when dry bulb temperature is high.** Trim coolers add a supplemental fluid cooler to a closed-loop system.

- **Use a chilled water tank/ice storage.** This expands the total system volume and increases thermal inertia.

- **Implement side-stream filtration systems.** These systems can reduce fouling, which has poor heat transfer.

- **Install TCUs.** These help to control process temperatures by circulating water or an oil-based fluid through the process application.

- **Use microchannel heat exchangers.** These heat exchangers are optimized to use low-density and low-GWP refrigerants.

- **Use pre-insulated ABS piping.** These systems are vapor tight, showing no thermal bridges, which minimizes energy loss along the lines.

- **Insulate the cooling line and jacket.** Insulation is a cost-effective way to reduce energy waste along cooling lines, expansion valves, and evaporators.

Refrigerants

- **Use low-GWP refrigerants.** Often, energy efficiency measures are implemented to lower GHGs. If that is the aim, also consider using lower GWP refrigerants.

- **Monitor refrigerant charge.** Significant amounts of energy can be wasted in a refrigeration system with an inappropriate level of charge.

- **Monitor refrigerant contamination.** Energy savings due to the implementation of this measure are estimated at 2%.

Cooling System Configurations

- **Inspect frequently.** Reduce inefficiencies due to improperly working equipment.

- **Use infrared cameras to spot losses.** A temperature change would show that there is a leak or an uninsulated spot.
- **Improve O&M.** A low-cost energy savings practice is to increase O&M.
- **Convert systems from constant to variable flow.** VFDs on pumps are used to match the cooling water supply to the cooling water demand to save energy.
- **Use glycol refrigerant for systems that must reach temperatures below -4°F (-20°C).** Glycol is commonly used as the heat transfer fluid in chillers.
- **Replace the glycol solution with water during warm months.** Glycol solution has a slightly lower heat transfer coefficient than water and requires more energy to cool.
- **Use refractometers to adjust refrigerant concentration.** These provide a simple way of checking concentration.
- **Recover waste heat.** Extract heat from the chilled liquid that can be used along with the energy of compression to warm the circuit water for reheating and cooling.
- **Monitor the overall system and individual equipment efficiency.** Track energy consumption, diagnose poor performance, optimize system performance, and identify problem areas before major repairs are needed.
- **Use controls to optimize the system.** Control and optimization help to regulate and efficiently equilibrate energy consumption.
- **Integrate with the BMS.** Improperly configured BMS systems are believed to account for 20% of building energy usage.
- **Consider tri-generation.** Combined heat and power (CHP) offers the option to provide cooling by using absorption in combination with generation of heat and power.

Chillers

Check that system delta-T is equal to design delta-T

Delta-T is the difference between the temperature of supply and return chilled water. Low delta-T syndrome is a common problem in many chilled water systems that increases the energy consumption of chilled water pumps, decreasing the system's overall operating efficiency and undermining occupant comfort (Dai et al. 2021). Several causes of low delta-T syndrome exist; some of the most common are the following:

- Limited heat exchange capacity of terminals due to coil fouling, clogged filters, undersized coils, improper valves, and poor valve authority.
- Poor system design and construction with unbalanced water loops and oversized pumps.
- Inappropriate adjustment of control parameters leading to local control failure.

Optimize condenser and evaporator parameters

An optimized refrigeration system works with minimal differences between condenser and evaporator conditions (i.e., temperature and pressure). Energy use increases as the pressure or temperature difference between the evaporator and the condenser increases because the compressor must work harder to achieve the lift. Lift is the difference in pressure or temperature of the refrigerant in the condenser and the evaporator.

For the condenser, the goal is to obtain the lowest possible condensing temperature and pressure of the refrigerant. When using a cooling tower, allow the condenser temperature to get as cold as the cooling tower supply water will permit; check with your chiller manufacturer to determine the minimum condenser temperature lower setpoint. It reduces power input while increasing refrigeration output. For the evaporator, an increase in temperature and pressure increases the power input of the compressor and can dramatically increase the refrigeration output of the system. Increasing evaporator temperature by 1° can reduce the electricity consumption of the compressor by 2% to 4% (Hart 2018; Sonnenrein et al. 2015).

One way to increase the evaporation temperature is by raising the temperature of the cooled fluid. The evaporation temperature can also increase by improving the performance of the evaporator. This can be achieved by ensuring that the expansion valve is set so that it avoids superheating, by having a larger evaporator, and by avoiding fouling that affects heat transfer (Hart 2018). Heat transfer could also be improved with the use of ventilators. However, it should be noted that ventilators will also consume power (Sonnenrein et al. 2015).

Keep heat transfer surfaces clean

The heat transfer surfaces in chillers tend to collect mineral and sludge deposits from the circulating water. Scale and fouling buildup insulate the tubes in the heat exchanger, causing inefficiencies in the exchange of heat. To compensate for this effect, a larger temperature difference is required between the water and the refrigerant. By keeping heat transfer surfaces clean, the chiller can more efficiently transfer heat.

Maintain adequate condenser water flow

Blockage of the filter in the condenser water line will increase condenser refrigerant temperature due to a reduced water flow. The regular maintenance of filters and condensers lines can mitigate or prevent these losses.

Remove trapped air from the condenser

Air trapped in the condenser causes increased pressure at the compressor discharge, resulting in increased compressor horsepower, which increases energy consumption. It also limits the cold surface exposed to the refrigerant, generating a similar effect of dirt buildup.

This is very common in low pressure chillers where air can enter the system during maintenance or faulty valves and build up eventually on the higher side of the system. Purge units will be installed typically in low pressure chillers to purge the air.

Install ASDs on centrifugal chillers

ASDs, which can include electronic VFDs, or variable-voltage/variable-frequency drives and variable-speed drives, are used to control motor speed and torque by varying motor input frequency and voltage. An ASD adjusts the compressor speed to match the cooling water supply with the cooling water demand.

Change compressors to meet demand

Generally, existing chillers are oversized, forcing the chiller to operate at reduced loads even during peak demand, causing surging and poor efficiency. Replacing the compressor and motor drive to match the observed load more closely can reduce energy use.

Manage the load between chillers

In general, the COP of chillers drops when they operate at a part load ratio of below 0.8. However, chillers operate frequently in underloaded conditions with low COPs. When chillers of different capacities are available, the cooling demand can be met by operating different combinations of chillers and of associated components in a way to obtain a combined peak efficiency. Studies have shown that load-sharing strategies' electricity consumption can decrease by 16% to 33% (Abou-Ziyan and Alajmi 2014; Yu and Ho 2019).

Running two chillers at full load and one at partial load might consume more energy than running three equally sized VFD chillers. It will depend on whether VFD or constant speed chillers are installed.

Use free cooling

In some cases, cooling is also required when outside temperatures drop below the minimum condenser water temperature. If the outside air temperature is low enough, the chiller should be shut off and outside air used. If cooling cannot be done with outside air, a chiller bypass can be used to produce chilled water without using a chiller.

Choose the right cooling system

When deciding on a new cooling system, a decision needs to be made between an air-cooled and a water-cooled system. Water-cooled chillers are more efficient and slightly less expensive than an equivalent air-cooled chiller. However, air-cooled systems eliminate the use of a cooling tower, which leads to lower installation and maintenance costs. To compare the two options, a detailed life cost analysis needs to be performed. In any case, the highest-efficiency chiller estimated to be cost-effective should be installed.

Use energy-efficient chillers

Energy-efficient chillers use larger heat exchange areas and more efficient compressors to achieve more efficient overall operation. Table 8 lists efficiency requirements of positive displacement and centrifugal water-cooled chillers under full and partial loads. Replacing existing chillers with energy-efficient chillers has an average payback period of about 4.5 years (IAC 2024).

Table 8: Efficiency requirements for water-cooled electric chillers (kW/ton) (FEMP 2024)

Chiller Type	Capacity (tons)	Full-Load Optimized Applications (products must meet both levels)		Part-Load Optimized Applications (products must meet both levels)	
		Full Load Efficiency	Integrated Part-Load Value (IPLV)	Full Load Efficiency	Integrated Part-Load Value (IPLV)
Positive Displacement	< 75	0.73	0.60	0.78	0.50
	75 to 149	0.71	0.56	0.75	0.49
	150 to 299	0.63	0.54	0.68	0.44
	300 to 599	0.61	0.52	0.63	0.41
	≥ 600	0.56	0.50	0.59	0.38
Centrifugal	< 150	0.61	0.55	0.70	0.44
	150 to 299	0.54	0.55	0.64	0.38
	300 to 399	0.54	0.52	0.60	0.37
	400 to 599	0.54	0.50	0.59	0.36
	≥ 600	0.52	0.50	0.59	0.33

Use absorption chillers when waste heat is available

Typical absorption chillers require approximately 1.6 Btu of thermal energy delivered to the chiller to remove 1 Btu of energy from the chilled water. Vapor absorption chillers use heat to transfer the refrigerant between areas of different temperatures and pressure (Evans 2018). They are energy efficient when waste heat from the process or a CHP engine can be captured and used to generate chilled water. CHP engines are often coupled with an absorption chiller that uses waste heat from combustion. Absorption chillers could replace mechanical chillers to limit the facility's electricity use and provide a hedge against peak electric demand charges. They use refrigerant water mixed with ammonia or lithium bromide, and they have two chambers: the top chamber comprises the condenser and the generator, and the bottom chamber comprises the evaporator and absorber. A heat exchanger improves the efficiency of the system. However, absorption chillers are not easy to operate and maintain and require a skilled maintenance staff that many facilities do not have.

Use electric-drive centrifugal chillers

Modern electric-drive centrifugal chillers require 0.2 Btu of electrical energy to remove 1 Btu of energy from the chilled water (0.7 kW/ton) (Sullivan et al. 2010). Also, they are relatively easy to maintain.

Use magnetic-drive chillers

Magnetic-drive chiller compressors operate more efficiently than reciprocating and screw compressors. The magnetic bearings operate without oil for lubrication, reducing energy losses due to friction. It also increases the heat transfer efficiency because no oil enters the evaporator or the condenser. Oil maintenance also is eliminated, resulting in O&M savings. The U.S. Navy's Techval program had three different projects where magnetic-bearing chiller compressors were installed between 2005 and 2007. The energy savings achieved were between 40% and 65%, and the payback period calculated was between 3.8 and 8.4 years (FEMP n.d.).

Cooling Towers

Use a cooling tower instead of a chiller

Cooling towers, when correctly operated, are simpler and more efficient than chillers (Jordan 2021). Temperature specifications of 85°F (29°C) or 90°F (32°C) can usually be met by installing a cooling tower or by using natural water. The main drawback is that they are not suitable for providing chilled water at temperatures below 50°F (10°C) in temperate climates (Jordan 2021). Replacing a refrigeration system with a cooling tower or an economizer has a payback time of about 2.3 years (IAC 2024).

Use ASDs on cooling tower fans

ASDs adjust the fan speed to maintain the same flow required when external conditions change. It reduces energy consumption by slowing the motor. A fan's power varies proportionally with the cube of its speed, meaning that a slight speed reduction causes a significant power reduction. For example, a reduction of 80% in speed causes a 50% reduction in energy consumption (Koepke 2009). Therefore, it is more energy efficient to run all existing fans at a slower speed than turn off some of the fans and run the others at full capacity.

Run pumps without fans when weather conditions permit

During cold weather, and if the ambient air flow is not reduced, cooling towers can cool the water below the desired supply temperature. This can upset industrial processes and result in unnecessary power consumption (Pontes et al. 2019). In this case, cooling tower fans should operate with reduced speed, or, if weather conditions permit, cooling tower pumps can be run without the fans to reduce electrical power consumption.

Schedule cleaning and maintenance

Cooling towers use heat transfer and evaporation to cool water. One percent of water is lost for every 10°F of cooling. Scale and fouling are left behind when water evaporates, which affects efficiency in the heat transfer. If maintenance and cleaning are not performed, the temperature of the water exiting the cooling tower will rise. For every 2°F increase, the equipment's energy costs will increase by up to 6%. Performing scheduled maintenance and cleaning techniques can save facilities up to 15% on their electricity costs (tekWorx n.d.).

Monitor fill

The fill, also called "wet deck" or "surface," maximizes the contact between air and water, encouraging evaporation. It is covered in a textured pattern, usually ridges or wrinkles that leave open spaces for water and air to travel. It should be serviced or replaced in cooling towers to avoid fouling (tekWorx n.d.).

Use water treatment systems for water makeup

Using water treatment systems for cooling tower makeup reduces tower blowdown frequency and limits tower fouling, keeping cooling towers more efficient for longer.

Auxiliary Equipment

Optimize the performance of auxiliary equipment

Opportunities to improve the efficiency of the auxiliary equipment used in the chiller systems, such as compressors, pumps, motors, and fans, can be found in the previous sections of this guide.

Use a trim cooler when dry bulb temperature is high

A trim cooler adds a supplemental fluid cooler to a closed-loop system. It is typically used in a location with a high dry bulb temperature to provide the proper coolant temperature to the load. With an added liquid-to-liquid trim cooler, it is possible to use a water source to trim the temperature to the desired setpoint. It also is used to reduce reliance on city water as a coolant (Williams 2013).

Use a chilled water tank/ice storage

A water tank/ice storage serves to expand the total system volume and increase thermal inertia. It can improve performance by ensuring better temperature control, increasing chiller longevity, reducing condenser cycling, and improving system startup times. It is commonly used when large instantaneous cooling loads with defined periods of operation are needed. A water tank is used to spread instantaneous loads over longer periods, allowing a smaller chiller (Timms 2019).

Implement side-stream filtration systems

A heavily fouled cooling tower has poor heat transfer. Dirt and fouling also can damage analytical instrumentation, creating inaccuracies and premature failure. Manual cleaning can take days to be completed, contributing to downtime, instrumentation failure, decreased efficiencies, and increased water and chemical usage. There are four main solutions for side-stream filtration systems (DOE 2012s):

- **Screen filtration.** Automatic screen filters use system pressure to clean themselves. They are also known as self-cleaning screen filters. The cleaning cycle is short, less than 1 minute, and the amount of water used for cleaning is small, less than 1% of the total water flow.
- **Sand filtration.** Sand filter systems are very efficient at removing fine particles, down to 0.45 microns. However, they tend to be more expensive and larger than other side-stream filtration systems. There are two types mainly used in cooling towers: pressure sand filters and high-efficiency sand filters. The high-efficiency sand filters are similar to the pressure sand filters; however, the sand layer order is reversed (i.e., the top layer is composed of extra fine sand with the layers becoming gradually coarser when moving to the bottom).
- **Centrifugal separators.** These separators are more efficient for separating large and heavy particles. They remove particles with a size ranging between 40 and 75 microns and fine and coarse inorganic particles with a specific gravity of 1.62 or more. Because particles are not trapped to clog the system, the maintenance

requirements are low. As a consequence, centrifugal separators can be more economical to operate than other filtering systems for the same separation efficiency.

- **Disc filtration.** The disc filtration technology uses plastic discs made of polypropylene. The discs have grooves in different patterns that are stacked together under pressure. They can remove both solids and inorganic filter particles with a size down to 10 microns. They use much less water than other self-cleaning filters, and the maintenance requirements are low.

Install TCUs

TCUs help regulate process temperatures by circulating water or an oil-based fluid through the process application. The fluid temperature is controlled with a heater and a cooling valve. During operation, a temperature is set in the controller. The pump continually circulates the fluid from the TCU to the process and then back to the TCU. The temperature is controlled in the return line. If the temperature is higher than the set one, cooling is needed. Conversely, if the temperature is lower, heat is needed. The TCU does not generate the cooling itself. It utilizes a cooling source (e.g., chiller system, cooling tower system, city water). Selecting the right pump for each application is crucial as it is the heart of the system and essential for efficient and effective performance (see Chapter 7: Pump Systems). The pump chosen is directly related to the flow rates. High turbulence flows transfer more energy than low laminar flows; thus, the first is more effective (Stone 2021).

Use microchannel heat exchangers

Microchannel heat exchangers are used, especially in large (approximately 400 tons), air-cooled chillers using screw and centrifugal compression. They are optimized to use low-density, low-GWP refrigerants such as R-1234ze and R-515B. The system performance is sensitive to pressure drops because of the low density of these refrigerants. The microchannel tube geometry provides a balance between maximum heat rejection and internal refrigerant pressure drop. Microchannel heat exchangers reduce 30% of the refrigerant charge and increase efficiency by 10% compared with fin and tube heat exchangers (Process Cooling 2021).

Use pre-insulated ABS piping

Pre-insulated ABS piping is an energy-efficient solution for industrial applications in a temperature range from -58°F to 104°F (-50°C to 40°C) due to its low thermal conductivity. It is insulated with high-density, closed-cell polyurethane foam and protected with a watertight, ultraviolet-resistant black polyethene jacket. The system is vapor tight, showing no thermal bridges, which minimizes energy loss along the lines. Because of its properties, the piping is suited for beverage production (Sampaio 2018).

Insulate the cooling line and jacket

It is often cost-effective to insulate cooling lines, expansion valves, and evaporators if the lines are uninsulated and if there is a significant average temperature difference between the cooling lines and their surroundings (e.g., more than 15°F [-9°C]). If lines are already insulated, upgrading may not be cost-effective. Use an insulation material that resists being crushed (i.e., mineral fiber insulation) and that does not absorb moisture as condensation may form outside of the piping. Also consider easily removable insulation (i.e., thermal blanket insulation) on access points and some valves.

Refrigerants

Use low-GWP potential refrigerants

In addition to energy efficiency, using lower-GWP refrigerants can help manufacturing plants reduce GHG emissions. Refrigerants should be carefully chosen depending on their thermochemical parameters, safety (i.e., flammability and toxicity), and environmental impact (e.g., GWP and ozone depletion). Current refrigerants have a high GWP. For example, HFC blend R-404A generates 3,922 times more warming than carbon dioxide (CO_2). Current regulations aim to eliminate high-GWP refrigerants and substitute them with refrigerants with a lower GWP. Regulations change over time and from state to state. For updated information, visit www.epa.gov/climate-hfcs-reduction.

There is no simple substitute for refrigerants because lower-GWP options may be more expensive and increase flammability (Figure 11). Refrigerants are named by the letter R (as in "refrigerants") followed by a two- or three-digit number and, in some cases, one or two letters, such as RXYZ (SWEP 2021).

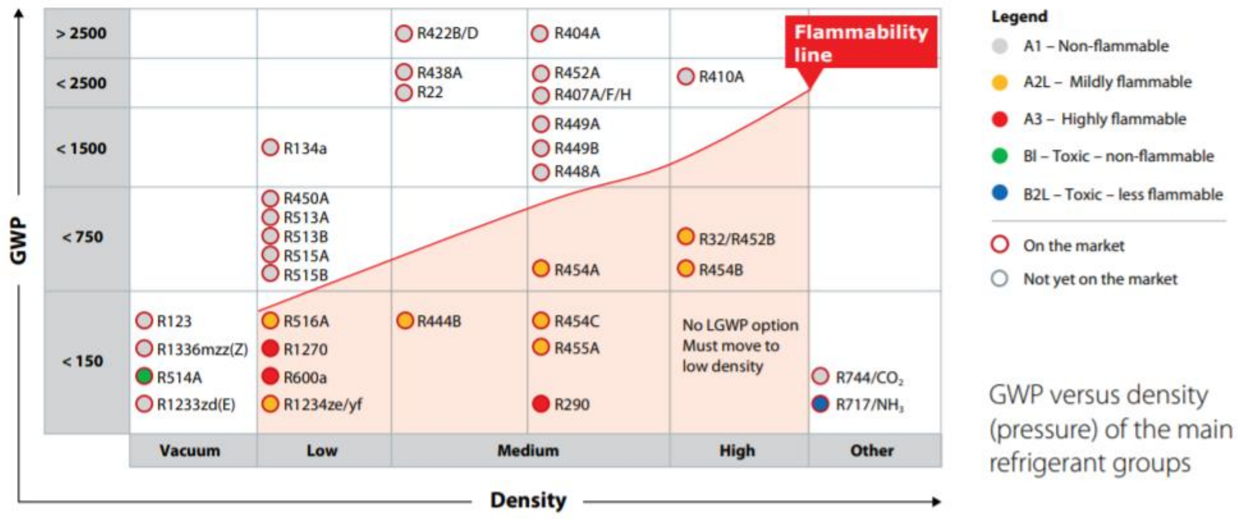


Figure 11: Carbon chain-based refrigerants (HCs, HFCs, and HCFCs), GWP versus density (pressure) (Danfoss 2021)

Table 9 compares various properties of current and next-generation refrigerants with low GWP. In general, refrigerants with lower GWP have lower efficiency. However, this should be studied in a comprehensive way as the tradeoff of lower efficiency brings lower GHG emissions.

Table 9: Comparison of refrigerant properties (adjusted from Trane, 2022)

		Low pressure refrigerants (larger centrifugal compressors)			Medium pressure refrigerants (screw compressors and smaller centrifugal compressors)						High pressure refrigerants (scroll compressors and unitary and packaged equipment)				
		R-123	R-514A	R-1233zd(E)	R-134a	R-513A	R-515B	R-1234yf	R-1234ze(E)	R-717 Ammonia	R-410A	R-454B	R-32	R-290 Propane	R-744 CO_2
Flammability/ ASHRAE® Class		1	1	1	1	1	1	2L	2L	2L	1	2L	2L	3	1
Toxicity	**ASHRAE® Class**	Higher (B)	Higher (B)	Lower (A)	Lower (A)	Lower (A)	Lower (A)	Lower (A)	Lower (A)	Higher (B)	Lower (A)	Lower (A)	Lower (A)	Lower (A)	Lower (A)
	OEL	50	320	800	1,000	650	810	500	800	25	1,000	850	1,000	1,000	5,000
Efficiency (COP)		8.95	8.91	8.87	8.47	8.27	8.32	8.17	8.45	8.77	7.99	8.16	8.22	8.34	4.41
Capacity Change		baseline	~5% loss	~35% gain	baseline	similar	~25% loss	~5% loss	~25% loss	~70% gain	baseline	~3% loss	~8% gain	~40% loss	~330% gain
GWP		77	1.7	1	1,430	630	298	6	4	0	2,088	467	675	3	1
Atmospheric Life		1.3 years	22 days	26 days	13.4 years	5.9 years	3.1 years	11 days	18 days	<1 day	17 years	3.6 years	5.2 years	13 days	20-200 years

OEL: Occupational exposure limit

Some suitable refrigerants for chlorine liquefaction with a low GWP and low ozone depletion potential (ODP) are ammonia, carbon dioxide, chlorine, and water. The choice of refrigerant for chlorine liquefaction depends on the liquefaction pressure. Table 10 shows the advantages and disadvantages of these four refrigerants.

Table 10: Advantages and disadvantages of refrigerants with a low GWP and ODP used in the chlor-alkali industry (Brinkmann et al. 2014)

Low-GWP, ODP refrigerant	Advantages	Disadvantages
Ammonia (R-717)	Excellent thermodynamic and thermophysical properties, inexpensive	Toxic, flammable, explosive if mixed with chlorine, two cooling circuits required
Carbon dioxide (R-744)	Non-toxic, non-flammable, inexpensive	Asphyxiant, low critical temperature
Chlorine	No cross-contamination	Larger amounts of chlorine in the production unit
Water (R-718)	Non-toxic, non-flammable, inexpensive (no vapor-compression refrigeration cycle)	High boiling and freezing point, therefore higher pressures for liquefaction needed

Changing the refrigerant from HCFCs/HFCs to either chlorine, water, ammonia, or carbon dioxide in existing plants will usually require a major rebuild of the liquefaction unit. The investment needed for a plant with a chlorine capacity of 66,000 tons/yr. was $21 million in 2012 (€16 million in 2012; $/€ rate=0.7781) (Brinkmann et al. 2014).

Monitor refrigerant charge

A low refrigerant charge can exist in many small direct expansion systems and also can exist without obvious indicators on larger flooded or recirculation systems. Without proper monitoring to ensure that refrigerant is charged to the appropriate level, significant amounts of energy can be wasted in a refrigeration system. Scott (2004) estimates that 1 in 6 direct expansion systems has a low refrigerant charge (or sometimes overcharge), which is sufficient to increase energy usage by 20%. Monitoring of refrigerant charge generally is not necessary for large ammonia systems.

Monitor refrigerant contamination

Periodic monitoring for contaminants (e.g., oil, water) in refrigerants should be performed to ensure early detection of system operating and maintenance problems. Oil can hinder heat transfer and reduce system capacity. Moisture on the other hand, when mixed with refrigerants, forms acid, which can cause damage to system components. Energy savings due to the implementation of this measure are estimated at 2%.

Cooling System Configurations

Convert systems from constant to variable flow

A variable flow system consumes less energy as the cooling water supply matches the cooling water demand. Replace three-way with two-way valves and install VFDs on pumps to convert chilled and condensing water systems from constant to variable flow. Two-way valves are needed as three-way valves are designed to open as the load is reduced, resulting in constant pump flow. Monitor and control the system to automatically match the cooling water supply with the cooling water demand.

Inspect frequently

Daily, weekly, and monthly visual inspection of your cooling system's fans, motors, belts, and pumps reduces inefficiencies due to improperly working equipment. Loose belts or improperly working fans prevent smooth flow through the system, reducing efficiencies and increasing operational costs. Regular inspection of basins, drains, and nozzles prevents the buildup of minerals, debris, and dirt that clog the system, increase energy consumption, and reduce overall system efficiency (tekWorx n.d.).

Use infrared cameras to spot losses

An infrared device is a non-contact temperature measurement tool that detects all infrared energy emitted, transmitted, or reflected. A temperature change would show that there is a leak or an uninsulated spot. This technology helps to identify cold and heat losses.

Improve O&M

Often it is possible to achieve energy savings at low investment costs with attention to improved O&M (Browning et al. 2010). Such improvements can include shutting doors, setting a correct head pressure, maintaining proper refrigerant levels, effectively maintaining cooling towers, and selecting and running appropriate compressors for partial load. Energy savings also can be achieved by cleaning the condensers and evaporators.

Any deposits on the surface of condensing coils reduce the ability of the condenser to remove heat. Condenser tubes with 1/32" of mineral scale have a 27% lower heat transfer capability. In the absence of additional condensing capacity, the compressor is forced to work against higher head pressures, using more energy (7% higher) and reducing the refrigeration output (1% lower). For 1/16" of scale, 13% more energy is used while the output reduces by 2% (Browning et al. 2010). If the heat transfer capabilities become very low, the compressor will shut down due to the high head pressure. For deposits containing microbiological slime, the impact on heat transfer efficiency is even more significant as it is 3 to 4 times more insulating than mineral scale (Browning et al. 2010). Water treatment and deposit control can significantly reduce scale.

Use glycol refrigerant for systems that must reach temperatures below -4°F (-20°C)

A solution with ethylene glycol or propylene glycol is commonly used as the heat transfer fluid in chillers. Ethylene glycol is not food grade and should not be used in food or beverage applications; only propylene glycol can be used in food or beverage applications. It is diluted with water and enables your chiller system to maintain a range temperature of 25°F to 27°F (-4°C to -3°C). It is recommended to use glycol solutions up to ~50% to operate chilling systems down to -4°F (-20°C) and to move away from glycols to other fluids for operating temperatures below this. The reason is mainly due to the high viscosities from increasing glycol mixture percentages and reduced temperatures. Pumping viscous fluids inside heat exchangers is difficult, causing operational difficulties that outweigh the benefits.

Frequently double-wall heat exchangers are utilized, preventing contamination. In select warmer temperature applications, a glycol-to-water heat exchanger is used with pressure higher on the waterside to mitigate the potential for contamination (Bimbo Bakeries USA, pers. comm., 2021). Primary glycol cooling could be used in mixer jackets; cream yeast systems; chilled ingredient water; process tanks; coolers; heat exchangers; and, depending on the application of the thermal process, environmental control.

Replace glycol solution with water during warm months

If a glycol solution in water is used as the cooling media to prevent freezing during cold months, consider draining the system and using water during warmer months. Glycol solution systems have a slightly lower heat transfer coefficient than water and require more energy to cool. Install a glycol storage tank to hold the drained glycol solution and refill the cooling system during cold months.

Use refractometers to adjust the solution concentration

A refractometer is used to measure concentrations of liquids using the refractive index. It is possible to correlate the refractive index with the concentration of a solution. For example, a 35% propylene glycol mixture should correlate to readings of 24.75°Brix or a 2°F freezing point. To check the concentration, a sample of the chiller reservoir or process piping should be taken. To ensure a well-mixed solution, ensure that the solution has time to circulate before taking the sample (Terrien 2020).

Recover waste heat

Heat recovery systems can extract heat from the chilled liquid that can be used along with the energy of compression to warm the circuit water for reheat and cooling. The energy that normally would be expelled into the atmosphere can be captured and used for other processes. There exist two possibilities: One possibility is using a heat exchanger that recovers heat from the condenser water. The other possibility is to use an additional condenser placed directly in the refrigeration circuit (Jia 2006).

Monitor the overall system and individual equipment efficiency

The introduction of automatic monitoring on refrigeration systems can help energy managers and facilities engineers track energy consumption, diagnose poor performance, optimize system performance, and identify problem areas before major repairs are needed. Automated monitoring of energy performance is not yet common but can be very beneficial in exposing poor part-load efficiency and in identifying system deterioration, such as the effects of low refrigerant charge. The cost of automated monitoring is proportional to the size of the system and might be minor on new systems, where much data often can be obtained from control systems. The monitoring system should have the ability to provide system- and component-level information to operating staff, as well as high-level performance summaries for management. It is estimated that 3% of refrigeration energy can be saved by applying this measure.

Use controls to optimize the system

Control and optimization help to regulate and efficiently equilibrate energy consumption. Different types of controls for cooling systems exist. For example, an early warning system can be implemented that sends a message to staff when equipment is operating outside expected parameters. Different algorithms continuously adjust cooling equipment operations and key setpoints based on different parameters, such as occupancy level and outdoor temperature, maximizing system efficiency in real time. Algorithms optimize the condenser water temperature by balancing auxiliary equipment power with chiller power to operate the chillers based on ambient conditions and load efficiency. Fault detection and diagnostic systems can also monitor and trend heat exchanger performance and identify fouling and prevent inefficiencies. Also, it is possible to optimize cooling tower isolation valves (cells) by sequencing them to flow water over the maximum amount of cooling towers without falling below the minimum flow rate of these tower cells (tekWorx n.d.). Green Proving Ground recommends considering chiller plant optimization for all plants with loads greater than 3 million ton-hours. It is possible to obtain 35% cooling savings with an average plant efficiency of 0.64 kW/ton. The payback is less than 5 years (GSA 2016).

Integrate with the BMS

A BMS is a critical component to managing energy demand; one is often implemented in projects with large mechanical, HVAC, and electrical systems. The systems included in a BMS represent 40% of a building's energy usage; it could go up to 70% if the lighting is included. An improperly configured BMS is believed to account for a 20% loss of building energy usage, or approximately 8% of total energy usage in the United States (Brambley et al. 2005).

Consider tri-generation

Many new CHP systems offer the option of tri-generation, which provides cooling in addition to electricity and heat. Cooling can be provided using either absorption or adsorption technologies, which both operate using recovered heat from the cogeneration process.

Chapter 9: Hot Water and Steam Systems

In this chapter:	
Steam Supply—Boiler	
Match steam demand	Control boiler allocation
Install boiler flue shutoff dampers	Perform maintenance
Improve or repair mechanical insulation	Reduce fouling/clean boiler heat transfer surfaces
Optimize the boiler blowdown rate	Reduce excessive flue gas quantities
Reduce excess air	Monitor flue gas
Install turbulators on two- and three-pass fire-tube boilers	Use an economizer
Use a deaerator tank	Recover heat from boiler blowdown
Recover condensate	Install a modulating burner on the boiler
Consider electric boilers	Consider once-through boilers
Switch to more efficient and lower-carbon fuels	Consider solar-powered boilers
Steam Supply—Combined Heat and Power (CHP)	
Install gas turbines	Use reciprocating engines
Convert waste heat to power	
Steam Distribution	
Shut off excess distribution lines	Properly size piping
Insulate steam lines and vessels	Check and monitor steam traps
Use thermostatic steam traps	Shut off steam traps
Reduce distribution pipe leaks	Recover low-pressure waste steam through vapor recompression
Recover flash steam	Perform total site pinch analysis

In a chlor-alkali plant, large steam quantities are used to heat the brine, evaporate the brine (applicable to membrane and mercury plants that use solution-mined brine), and support caustic soda evaporation. Other uses of steam can be to heat caustic soda storage tanks and to thaw frozen caustic barges or railcars. Many plants also use cogeneration to generate a part of the electricity and heat requirements. This section discusses general energy saving opportunities in boiler and steam systems.

While the exact size and use of a modern steam system varies greatly, there is an overall pattern that steam systems follow (see Figure 12). Treated cold feedwater is fed to the boiler, where it is heated to form steam. Chemical treatment of the feedwater is required to remove impurities because impurities would otherwise collect on the boiler tube walls. Even though the feedwater has been treated, some impurities remain and can build up in the boiler water. Thus, water is periodically drained from the bottom of the boiler in a process known as blowdown. The generated steam travels along the pipes of the distribution system to get to the process where the heat will be used. Sometimes the steam is passed through a pressure reduction valve if the process requires lower pressure steam. In steam transport, the steam loses heat by radiation through the pipe wall and condenses without temperature changes, and some of it is condensed. Condensate is removed by a steam trap that allows condensate to pass through to the drain while the steam is blocked. Traditionally, boilers fed by fossil fuels have been used; however, with the need to reduce CO_2 emissions, the use of electric boilers has been increasing.

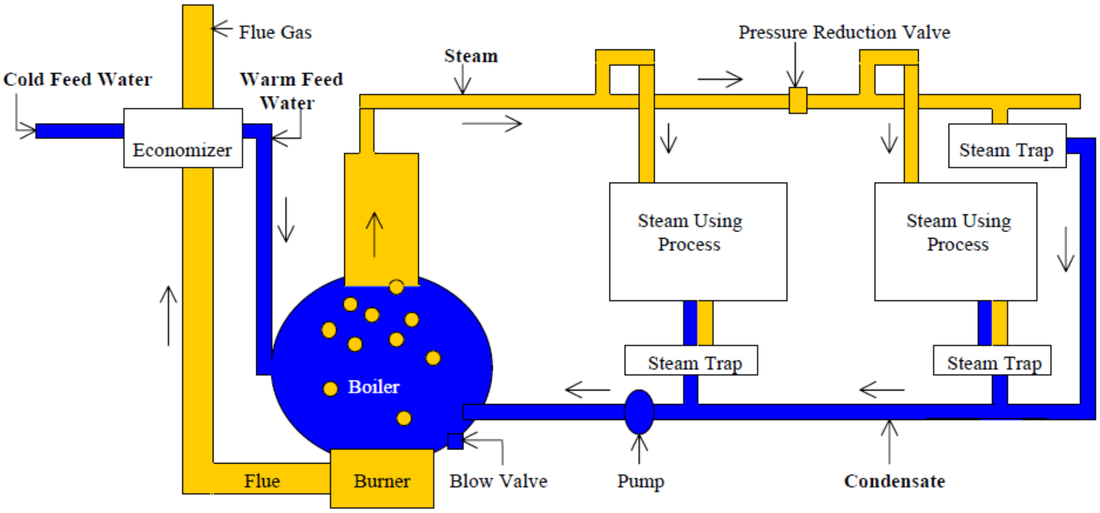


Figure 12: Schematic presentation of a steam production and distribution system

Steam flow meters are commonly used to help evaluate the performance of the steam system. They retrieve information on the boiler performance, calculate boiler efficiency, and determine the amount of steam needed by the system (DOE 2012a). In addition, their use can facilitate benchmarking the steam system and help identify opportunities for energy efficiency improvements.

There are two basic steam flow meter types (Parker et al. 2015):

1. *Differential pressure meters* rely on the relationship between the pressure difference through an element used in the steam flow to define steam velocity. The main types are the orifice, annubar, and spring-loaded variable.
2. *Velocity meters* directly measure the velocity of the steam flow. The main types are the turbine and vortex-shedding meters. Because velocity meters directly measure the velocity of the flow, they are more accurate than differential pressure meters.

Maintenance

Lack of proper maintenance can, within a period of only 2 to 3 years, result in 20% to 30% increased energy costs.

The orifice differential pressure meter is the steam meter most commonly used. Unfortunately, in many cases, meters are neglected and need to be frequently recalibrated to obtain correct readings (Parker et al. 2015).

For accurate readings, proper maintenance is crucial. Differential pressure systems should be checked monthly for properly connected and sealed pressure taps. Annual maintenance should include a thorough checkup of the state of the orifice and pressure taps. In the case of velocity meters, annual maintenance should include checking the impeller blades and the bearings for any wear or damage (Parker et al. 2015).

Because of the larger heating requirement, industrial hot water boilers are much larger than domestic boilers. In general, the concept design is very similar to steam boilers, with the main difference that hot water boilers are filled with water, while steam boilers also have space for the generated steam. A burner—typically using natural gas, liquefied petroleum gas, or oil—fires into the boiler furnace and tubes to heat the water inside the boiler shell. The heated water is then delivered to the processes with the use of a circulating pump and pipework and returned to the boiler to be heated again. To avoid corrosion, the fresh water added to compensate for any water losses must be chemically treated.

Energy Savings Checklist: Steam Systems

Steam Systems Checklist	✓
Are steam flow meters properly maintained?	
Is the whole system properly maintained?	
Does the burner use the proper air-to-fuel ratio?	
Is the system (e.g., boiler size, distribution lines) properly sized?	
Is waste heat recovered and reused?	
Are heat losses minimized?	
Do the steam turbines operate under optimum condition?	
Is the energy embodied in the pressure drop utilized?	

Best Practices for Energy-Efficient Steam Systems

Steam Supply—Boiler

- **Match steam demand.** Use the right size boilers in the high-fire setting to improve energy efficiency.
- **Control boiler allocation.** Employ automatic controllers for all boilers in systems that use multiple boilers to shift the loads and maximize efficiency. Install automatic flow valves to shut off unused boilers.
- **Install boiler flue shutoff dampers.** Reduce hot air losses by fitting fully closing stack dampers.
- **Perform maintenance.** Properly maintain the burner and condensate return systems to reduce energy consumption by 10%.

- **Improve or repair mechanical insulation.** Improve insulation and heater circuit controls and reduce energy use by 6% to 26%.
- **Reduce fouling/clean boiler heat transfer surfaces.** Remove scale deposits built on the waterside of the boiler to improve heat transfer and reduce fuel use by up to 5%.
- **Optimize the boiler blowdown rate.** Optimize the blowdown rate to reduce energy losses, makeup water, and chemical treatment costs.
- **Reduce excessive flue gas quantities.** Repair leaks in the boiler and the flue that can lead to excessive flue gases.
- **Reduce excess air.** Check the burner air-to-fuel ratio on a regular basis to reduce the amount of wasted heat. Controlling the combustion process digitally can improve energy efficiency by 3% to 5%.
- **Monitor flue gas.** Adopt flue gas monitoring to optimize the air-to-fuel ratio and detect scale deposition to improve efficiency.
- **Install turbulators on two- and three-pass fire-tube boilers.** Place turbulators into the boiler tubes to improve heat transfer and improve boiler efficiency.
- **Use an economizer.** Preheat boiler feedwater from flue gases in an economizer and reduce fuel use by 5% to 10%.
- **Use a deaerator tank.** The water thermal treatment to remove dissolved oxygen in the makeup water will reduce the use of chemicals and the boiler blowdown rate.
- **Recover heat from boiler blowdown.** Use the heat from boiler blowdown for space heating or feedwater preheating to improve energy efficiency.
- **Recover condensate.** Install a condensing economizer and improve overall heat recovery and system efficiency by up to 10%.
- **Install a modulating burner on the boiler.** It adjusts the flame based on steam demand.
- **Consider electric boilers.** If operated on renewable electricity, these reduce CO_2 emissions.
- **Consider once-through boilers.** These are more efficient than standard boilers in specific circumstances; a once-through boiler can lead to reduced fuel losses at startup, especially for boilers that are cycled often.
- **Switch to more efficient and lower-carbon fuels.** By shifting from coal and oil to gas, up to a 30% reduction of CO_2 emissions can be realized. Changing to (self-generated) biogas may further reduce emissions and energy costs.

Reduction of excess air

As a rule of thumb, boiler efficiency can increase by 1% for each 15% reduction in excess air.

- **Consider solar-powered boilers.** Industrial solar-powered boilers (> 10 MW) use the energy from the sun to directly transfer energy to a heating medium.

Steam Supply—Combined Heat and Power (CHP)

- **Install gas turbines.** Install a gas turbine to meet your power needs and recover the gas turbine exhaust to generate high-pressure steam or use it in heating or drying applications.
- **Use reciprocating engines.** Use modern reciprocating engines to generate electricity and recover the heat from the engine exhaust, cooling water, and lubricating oil to generate steam or to heat water.
- **Convert waste heat to power.** Capture discarded process heat to generate electricity.

Steam Distribution

- **Shut off excess distribution lines.** Reduce steam distribution losses in a cost-effective manner by shutting off excess or unused lines.
- **Properly size piping.** When designing new steam distribution systems, account for the velocity and pressure drop and avoid high heat losses, pressure drops, and erosion.
- **Insulate steam lines and vessels.** Reduce energy use by properly insulating the distribution system and by regularly inspecting and repairing worn mechanical insulation.
- **Check and monitor steam traps.** Adopt a scheme of regular steam trap checkups and follow-up maintenance to save up to 10% of energy. Managing steam traps also avoids the risk of water hammer and process low efficiency.
- **Use thermostatic steam traps.** Install thermostatic element steam traps and reduce energy use while improving reliability.
- **Shut off steam traps.** Shut off steam traps on superheated lines when not in use and save energy. Traps should be ready to work when the steam returns to distribution.
- **Reduce distribution pipe leaks.** Create a program of leak detection and maintenance on distribution pipes to decrease losses.
- **Recover low-pressure waste steam through vapor recompression.** Compress low-pressure waste steam to higher pressures so that it can be reused. Recompression will only need 5% to 10% of the energy required to raise an equivalent amount of steam in a boiler.
- **Recover flash steam.** Use a heat exchanger to recover the heat in flash steam to use it for space heating, feedwater preheating, or in a lower pressure steam process.
- **Perform total site pinch analysis.** Identify optimum site-wide utility levels by integrating the demands for heating and cooling and reduce the energy consumption by 20% to 30%.

Steam Supply—Boiler

Match steam demand

A boiler is more efficient in the high-fire setting. Since heating demands may change over time, situations can occur in which a boiler is operating beneath its optimum efficiency. Also, boilers may have been oversized because of anticipated additions or expansions that never occurred, or later, equipment may have been replaced or discarded from the boiler. Energy conservation or heat recovery measures also may have reduced heat demand. Thus, a facility may have multiple boilers, each rated at several times the maximum expected load (DOE 2012e). Another common problem with oversized boilers is boiler "short cycling," which occurs when an oversized boiler quickly satisfies process or space heating demands and then shuts down until the heat is again required. Efficiency losses occur, to some extent, because the fixed losses are higher when boilers operate at low loads. At full load, the radiation losses from the boiler enclosure are 1%, at half-load 2%, and at one quarter-load 4% (DOE 2012e).

Fuel savings can be achieved by adding a smaller boiler to a system, sized to meet average loads at a facility, or by re-engineering the power plant to consist of multiple small boilers. Multiple small boilers offer reliability and flexibility to operators to follow load swings without over-firing and short cycling. Facilities with large seasonal variations in steam demand should operate small boilers when demand drops rather than operating large boilers year-round. Electric boilers may be ideal for this situation since these are more energy efficient than fuel-fired boilers, help to reduce onsite emissions, and fit in long-term climate goals. See "Consider electric boilers" below for more information.

Measures to run boilers on the high-fire setting have an average payback time of slightly less than 1 year. Installing smaller boilers to increase the high-fire duty cycle has an average payback time of about 4.6 years (IAC 2024).

Steam accumulators can be used to supply steam load to the batch process and peak demands to allow stable operation of the steam boiler.

Control boiler allocation

Systems containing multiple boilers offer energy saving opportunities by using proper boiler allocation strategies. This is especially true if multiple boilers are operated simultaneously at low-fire conditions.

Automatic controllers determine the incremental costs (change in steam cost/change in load) for each boiler in the facility and then shift loads accordingly. This maximizes efficiency and reduces energy costs. If possible, loads should be scheduled to optimize boiler system performance.

The efficiency of hot water boilers can improve with automatic flow valves. These valves shut off boilers that are not being used, preventing hot water from the fired boiler from cooling as it passes through unused boilers in the system. If the plant runs equipment mostly in batches, and the fuel consumption is high between the shutdowns, the steam supply should completely stop by closing the steam valves (TLV n.d.).

Install boiler flue shutoff dampers

Where boilers are regularly shut down due to load changes, heat loss to the chimney can be significant. A solution for stopping hot air loss is to fit stack dampers that can be partially or fully closed, conserving energy when the boiler is not fully in use or shut down.

Perform maintenance

In the absence of a good maintenance system, the burners and condensate return systems can wear out or go out of adjustment. A simple maintenance program ensures that all components of the boiler are operating at peak performance and can result in substantial savings and reduce air pollutant emissions. Some of the activities performed during preventative maintenance include changing pump seals, adjusting controls and burners, testing safety valves, and cleaning probes and boiler tubes (Merritt 2015). Establishing a maintenance schedule for boilers has an average payback time of 0.7 years (IAC 2024).

Improve or repair mechanical insulation

New boilers are typically well insulated. Old boilers, however, can profit from improved insulation materials with sufficient heat transfer resistance, especially if the insulation is damaged or degraded. There are several types of boiler insulating materials, including brick, refractory, insulation, and lagging. Poor insulation can result in up to 10% shell losses (EECA 2010). Except from the type of insulation, heat losses due to radiation and convection will also depend on the operating loads. For a not-well-insulated boiler operating at full load, radiation and convection amount to 2% of total fuel consumption. The losses for the same boiler will be 4% when operating at half load and 8% when operating at a quarter-load. For a well-insulated boiler, the losses are 0.2% to 0.3% when at full load and 0.5% to 1.0% at half load (Barma et al. 2017).

Reduce fouling/clean boiler heat transfer surfaces

Fouling of the fireside of the boiler tubes and scaling waterside of the boiler should be controlled. Scale deposits occur when calcium, magnesium, and silica, commonly found in most water supplies, react to form a continuous layer of material on the waterside of the boiler heat exchange tubes. Even a thin scale layer can reduce heat transfer. As shown in Table 11, a scale layer of 0.03” (0.8 mm) can result in 3% fuel losses. If the scale has a high iron content, the losses are 4.7%. In fire-tube boilers, scaling can lead to fuel waste of up to 5% (DOE 2012f). In fire-tube boilers, scaling can lead to fuel waste of up to 5% (DOE 2012f). Moreover, scaling may result in tube failures.

Table 11: Fuel losses (%) in fire-tube boilers due to scale (DOE 2012f)

	Fuel losses (%) per scale type[1]		
Scale thickness (inches)	**“Normal”**	**High iron**	**Iron plus silica**
0.02	1.0	1.6	4.5
0.03	2.0	3.1	7
0.05	3.0	4.7	-
0.06	3.9	6.2	-

[1] “Normal” scale is the scale found in low-pressure applications, while the high iron and iron plus silica scale is found in high-pressure applications.

Scale removal can be achieved by mechanical means or acid cleaning. The presence of scale can be indicated by the flue gas temperature or be determined by visual inspection of the boiler tubes when the unit is shut down for maintenance. Fouling and scaling are more of a problem with coal-fed boilers than natural gas or oil-fed units. Boilers that burn solid fuels like coal should be checked more often as they have a higher fouling tendency than liquid fuel boilers (Hare et al. 2010).

Optimize the boiler blowdown rate

Insufficient blowdown may lead to carryover of boiler water into the steam or the formation of deposits. Excessive blowdown wastes energy, water, and chemicals. The optimum blowdown rate is determined by various factors, including the boiler type, operating pressure, water treatment, and quality of the makeup water.

Blowdown rates typically range from 1% to 8%, depending on the boiler feedwater flow rate; however, it can be as high as 20% when makeup water has a high solids content (DOE 2012g). Minimizing the blowdown rate can substantially reduce energy losses, makeup water, and chemical treatment costs. The reduction of the blowdown rate has an average payback time of 1.3 years (IAC 2024).

Optimum blowdown rates can be achieved with an automatic blowdown control system. In many cases, the savings due to such a system can provide a simple payback of 1 to 3 years (DOE 2012g). One thing that can reduce boiler blowdown is the degree and quality of water treatment of the boiler feedwater. This is done using treatment chemicals and/or reverse osmosis systems.

Reduce excessive flue gas quantities

Often, excessive flue gas results from leaks in the boiler and the flue, reducing the heat transferred to the steam and increasing pumping requirements. These leaks are often easily repaired. This measure consists of a periodic repair based on visual inspection or on flue gas monitoring, which is discussed below.

Reduce excess air

The more air used to burn the fuel, the more heat that is wasted by unnecessarily heating the excess air. However, too little air may cause higher combustion temperatures, leading to emission of nitrogen oxides (NOx). The most efficient air-to-fuel ratio depends on the type of fuel and air density. Poorly maintained boilers can have up to 140% excess air, leading to excessive amounts of waste gas. An efficient natural gas burner requires 2% to 3% excess oxygen, or 10% to 15% excess air in the flue gas to burn fuel without forming carbon monoxide (DOE 2012i). A rule of thumb is that boiler efficiency can be increased by 1% for each 15% reduction in excess air, or a 40°F (22°C) decrease in stack gas temperature (DOE 2012h). The air-to-fuel ratios of the burners should be checked regularly. On average, the analysis and adjustment of a proper air-to-fuel ratio has a payback time of 0.8 years (DOE 2012i).

An efficient burner provides the proper air-to-fuel ratio throughout the full range of firing rates, without constant adjustment. Traditionally, this mixture was controlled using linkages or cables to position the air and fuel valves. These are subject to wear, repeatability difficulties, and a limited amount of adjustment. Modern burners are an alternative to complex linkage designs and are increasingly using servomotors with parallel positioning to independently control the quantities of fuel and air delivered to the burner head. These controls provide consistent performance and repeatability as the burner adjusts to different firing rates (DOE 2012i). Implementing automatic control of the combustion process leads to an improved energy efficiency of about 4% (Suntivarakorn and Treedet 2016). Replacement of inefficient obsolete burners averages a payback period of about 2.4 years (IAC 2024).

Using a combination of carbon monoxide and oxygen readings, it is possible to optimize the air-to-fuel ratio for a high flame temperature (and thus the best energy efficiency) and low emissions.

Monitor flue gas

The oxygen content of exhaust gas is a combination of excess air (which is deliberately introduced to improve safety or reduce emissions) and air infiltration (air leaking into the boiler). By combining an oxygen monitor with an intake airflow monitor, it is possible to detect small leaks. An acoustic imaging detector, used for detecting compressed air leaks, can also be used to detect small air leaks in the boiler. Using a combination of carbon monoxide and oxygen readings, it is possible to optimize the air-to-fuel mixture for a high flame temperature, best energy efficiency, and low emissions. The payback of installing flue gas analyzers to determine proper air-to-fuel ratios, on average, is about 0.7 years. For two chlor-alkali plants, the average payback time was 1.1 years (IAC 2024).

Monitoring flue gas temperature also can help to indicate scaling since the flue gas temperature is an indirect indicator of scale or deposit formation. If the flue gas temperature rises (with boiler load and excess air held constant), the effect is likely due to the presence of scale.

The percentage of oxygen in the flue gas can be measured by inexpensive gas-absorbing test kits. More expensive handheld, computer-based analyzers (ranging in cost from $500 to $1,000) display the percentage of oxygen, stack gas temperature, and boiler efficiency. They are a recommended investment for any boiler system with annual fuel costs exceeding $50,000 (DOE 2012h).

Install turbulators on two- and three-pass fire-tube boilers

The packaged fire-tube boiler is the most common boiler design used to provide heating or process steam in industrial and heavy commercial applications. In a fire-tube boiler, hot combustion gases pass through long, small-diameter tubes where heat is transferred to the water through the tube walls. These gases enter the tubes in a turbulent flow regime. Within a few feet, laminar flow begins and a boundary layer of cooler gas forms along the tube walls. This layer serves as a barrier, retarding heat transfer. Turbulators, which consist of small baffles, angular metal strips, spiral blades, or coiled wire, may be inserted into the boiler tubes to break up the laminar boundary layer (DOE 2012j). This increases the turbulence of the hot combustion gases and convective heat transfer to the tube surface. The result is improved boiler efficiency. Turbulator installers also can balance gas flow through the tubes by placing longer turbulators in the uppermost tubes. This practice increases the effectiveness of the available heat-transfer surface by eliminating thermal stratification and balancing the gas flow through the fire tubes.

The cost of installing turbulators is about $10 to $15 per boiler tube, and the average payback time is about 1.4 years (IAC 2024).

Use an economizer

The heat from flue gases can be used to preheat boiler feedwater in an economizer. By preheating the water supply, the temperature of the water at the inlet to the boiler is increased, reducing the amount of heat necessary to generate steam and save fuel. While this measure is common in large boilers, there often is the potential to increase heat recovery.

The limiting factor for flue gas heat recovery is the economizer wall temperature that should not drop below the dew point of acids in the flue gas. Traditionally, this is done by keeping the flue gases at a temperature significantly above the acid dew point. However, the economizer wall temperature is more dependent on the feedwater temperature than on the flue gas temperature because of the high heat transfer coefficient of water. Thus, it makes more sense to preheat the feedwater to close to the acid dew point before it enters the economizer. This allows the economizer to be designed so that the flue gas exiting the economizer is just above the acid dew point.

Generally, boiler efficiency can be increased by 1% for every 40°F (22°C) reduction in flue gas temperature. By recovering waste heat, an economizer often can reduce fuel requirements by 5% to 10% and pay for itself in less than 2 years (DOE 2012k).

Use a deaerator tank

A feed tank is the meeting place for cold makeup water and condensate return. The makeup water, as it is cold, absorbs free oxygen and other gases that are liberated when heated. It is essential to remove the dissolved oxygen before it is released in the boiler to prevent corrosion. Oxygen in feedwater can be “driven off” by heating and “absorbed” by chemical treatment. By heating the feedwater, typically to 185°F (85°C), to remove the bulk of the oxygen, the amount of scavenging chemicals required can be reduced by up to 75%. This also can improve boiler efficiency by reducing the blowdown requirements.

Also, it is possible to use a deaerator head that mixes the cold makeup water with its high oxygen content with the flash steam from the condensate and blowdown heat recovery. Oxygen and other gases are liberated from the cold water and can be removed from the system through a vent before entering the tank. The benefits are that dissolved oxygen entering the boiler is kept as low as possible, chemical dosing costs are kept to a minimum, there is high and steady feedwater temperature to the boiler, and there is maximum use of heat in the condensate return and from blowdown heat recovery. Typically, the oxygen content of the water entering the tank is 8-10 µg/l. After the water is treated in the deaerator, the oxygen content decreases to less than 0.02 µg/l (Spirax Sarco 2014).

Recover heat from boiler blowdown

When the water is blown from the high-pressure boiler tank, the pressure reduction often produces substantial amounts of steam. Up to 90% of the heat in the discharge is recoverable with the use of a makeup water heat exchanger (DOE 2012l). The recovered heat can subsequently be used for space heating and feedwater preheating, increasing the efficiency of the system. Any boiler with continuous blowdown exceeding 5% of the steam rate is a good candidate for the introduction of blowdown waste heat recovery. If there is a non-continuous blowdown system, then consider the option of converting it to a continuous blowdown system coupled with heat recovery (DOE 2012l). Larger energy savings occur with high-pressure boilers. The use of heat from boiler blowdown, on average, has a payback period of about 1.9 years (IAC 2024).

Recover condensate

By installing a condensing economizer, companies reduce their fuel requirements by 5% to 10% (DOE 2012q). Many boiler applications can benefit from additional heat recovery. Condensing economizers require site-specific engineering and design, and a thorough understanding of the effect they will have on the existing steam system and water chemistry.

Hot condensate can be returned to the boiler to save energy and reduce the need for treated boiler feedwater since condensate, being condensed steam, is extremely pure and has high heat content. Increasing the amount of returned condensate has an average payback period of about 1.6 years (IAC 2024). Condensate also has been used to provide hot water supply. This measure had an average payback period of 2.3 years (IAC 2024).

Care should be taken to prevent the forming of corrosion. Corrosion in condensate systems can limit the quality or quantity of returned condensate; may contain iron and copper corrosion products; and can deposit the corrosion products on boiler heat transfer surfaces, reducing heat transfer efficiency. In addition, corrosion may cause steam leaks, increasing maintenance and equipment costs.

Condensate return will reduce water, chemicals, and fuel consumption by recovering water and heat and reducing chemical treatment needs and blowdown rate.

Install a modulating burner on the boiler

Boilers do not always run at full capacity. A typical steam boiler fires up when the pressure drops below the setpoint, meaning that more steam is needed, and it fires down once the setpoint threshold has been reached. The burner is either fully on or fully off. But every time the burner is ignited or extinguished, there is a loss of efficiency. A modulating burner adjusts the flame based on steam demand rather than being either fully on or off; the burner monitors the rate at which the pressure changes and adjusts the amount of fuel accordingly. As pressure equalizes, it provides just enough fuel to maintain a constant pressure. Modulating burners will not fix an undersized boiler, but they allow boilers to be more efficient during periods of low demand. The burner itself also does not require more room or a complete retrofit of the boiler.

Consider electric boilers

Electric boilers are highly efficient, often reaching 95% efficiency. The two main types of electric boilers use either resistance heating or electrode heating, where the current is passed through the water. Induction and infrared also can be used but are available for small-scale applications only. Typical capacities of electric boilers are up to 5 MWe, while electrode boilers can have capacities up to 70 MWe, producing hot water or (superheated) steam (up to 660°F [350°C]). In combination with heat storage, electric boilers can take advantage of low off-peak power rates. Electric boilers are very reliable, need limited maintenance, emit no air pollutants, and have lifetimes of at least 15 years. Many suppliers sell electric boilers for varying capacities and steam qualities.

CASE STUDY

In 2022, an electric boiler was installed at the Nobian chlor-alkali plant at the Mariager site in Denmark. The boiler has three electrode bundles. It operates at 10,000 V and can convert about 1,800 ft^3 (50 m^3) of water into steam within an hour. This is the total steam demand for the salt multistage evaporation process when running at full pressure. The electric boiler can help stabilize the grid when excess electricity from renewable sources is available and can reduce the natural gas consumption by up to 250 million ft^3 (7 million m^3) a year.

Source: Nobian. (2022). Sustainability report 2022. https://cms.nobian.com/uploads/Downloads/Sustainability-Report-Nobian-2022.pdf

Consider once-through boilers

In once-through boilers, water passes from the liquid to the vapor stage without the use of a steam drum. The removal of the steam drum enables the boiler to operate at supercritical pressures and much higher steam temperatures than with drum-type boilers, resulting in significantly improved unit efficiency (Lindsley et al. 2018). Once-through boilers have low losses during startups and when operated at low loadings.

Switch to more efficient and lower carbon fuels

CO_2 emissions per unit of energy produced are different for every type of fuel. The amount of carbon in the fuel is directly related to the amount of CO_2 that will be emitted when combusted. The amount of heat that is generated is determined by the carbon (C) and hydrogen (H) content of the fuel. Energy is released when C and H react with oxygen (O) during combustion. Also, water and various elements, such as sulfur and noncombustible elements in some fuels, reduce their heating values and increase their CO_2-to-heat contents. Methane (CH_4) has a higher energy content relative to other fuels. Table 12 shows the amount of CO_2 emitted per unit of energy output or heat content for different fuels (EIA 2020).

Table 12: Carbon dioxide emissions coefficients for various fuel; based on EIA 2020

	CO_2 Emissions Coefficients (lb. CO_2/MBtu)
Coal (anthracite)	229
Coal (bituminous)	206
Coal (lignite)	215
Coal (subbituminous)	214
Diesel fuel and heating oil	161
Natural gas	117

The change to a less carbon-intensive fuel would lead to lower CO_2 emissions for the same energy use. For example, switching from coal to natural gas could reduce CO_2 emissions by approximately 50%. Another strategy is to shift to a renewable source using biomass, such as wood and byproducts from the production. To be a renewable source, it is important that the biomass is sustainably grown. While biomass may be less carbon intensive in some scenarios, combusting solid fuel produces air pollutants.

Consider solar-powered boilers

Solar-powered boilers use concentrated solar power (CSP) to generate steam. CSP uses mirrors or lenses to concentrate a large area of sunlight onto a receiver and generate heat. The payback depends heavily on the price of the fuel that solar is replacing and the direct irradiation of solar light. Hence, this technology would be more applicable in areas with high direct irradiation (e.g., in the U.S. Southwest).

Steam Supply—Combined Heat and Power (CHP)

CHP is an efficient and clean approach to generating electric power and useful thermal energy from a single fuel source. CHP is used either to replace or supplement conventional separate heat and power. Instead of purchasing electricity from the local utility and burning fuel in an onsite furnace or boiler to produce thermal energy, facilities can use CHP onsite to provide both energy services in one energy-efficient process. In this way, and by avoiding distribution losses, CHP can achieve total efficiencies of more than 80%, compared with 50% for conventional technologies (i.e., grid-supplied electricity and an onsite boiler).

Applications with a steady demand for electricity and thermal energy are potentially good economic targets for CHP deployment. Industrial applications, particularly in industries with continuous processing and high steam requirements, tend to be the most economical and represent most existing CHP capacity (EPA 2015).

Properly sized and configured CHP systems can effectively insulate facilities from a grid failure, providing continuity of critical operations. The design elements that are necessary so that a CHP system can be isolated from the grid (i.e., operate in “island” mode) are system specific and include additional controls and switchgear equipment (ORNL 2013).

The cost benefits of power exported to the grid will depend on regulations where the industry is located but can provide a major economic incentive. Not all states allow wheeling of power (i.e., sales of power directly to another customer using the grid for transport), and for the states that do allow wheeling, regulations also may differ with respect to the tariff structure for power sales to the grid operator.

Most CHP systems consist of several individual components—prime mover (heat engine), generator, heat recovery, and electrical interconnection—configured into an integrated system. The type of equipment that drives the overall system (i.e., the prime mover) typically identifies the CHP system (EPA 2015). Five technologies are represented by 95% of the CHP projects in place today and 99% of the total installed CHP electric capacity. These technologies are reciprocating engines, gas turbines (including gas turbine/steam turbine combined cycles), boiler/steam turbine, microturbine, and fuel cells (EPA 2015).

CHP systems are classified either as topping cycle or bottoming cycle CHP. In topping cycle CHP systems, fuel is used to generate electricity. Waste heat from the prime mover is then recovered and used for steam, hot water, process heating, and/or cooling applications. In bottoming cycle CHP systems, high-temperature thermal energy is first used for industrial applications, such as metal smelting furnaces, and the waste heat is then recovered and used to drive a turbine to produce electric power.

The technology choice for a CHP facility depends on available fuel and the amount of generating capacity needed (EIA 2012). For more information on the type of technologies, see the Oak Ridge National Laboratory Combined Heat and Power report (ORNL 2008).

Install gas turbines

Gas turbines are used to meet many different power needs, including propulsion, direct-drive, and stationary electricity generation. Gas turbines are well suited for industrial CHP applications because the high-temperature gas turbine exhaust can be used to generate high-pressure steam, or it can be used directly for heating or drying applications. Some industrial CHP systems use gas turbine exhaust to heat the input of a furnace or to preheat combustion air. This option may require replacing existing furnaces since the radiative heat transfer from gas turbine exhaust gases is much smaller than from combustion gases due to their lower temperature. Gas turbines can range from 1 MW to hundreds of megawatts, and they can be utilized as simple cycle turbines or as part of a combined cycle where recovered steam is used to power a secondary steam turbine. Some recent designs use a Cheng cycle that injects steam directly into the gas turbine to boost power output. Electric efficiencies for simple cycle gas turbines can approach 40% high heating value (HHV); however, efficiency degrades quickly as the load is decreased, so gas turbines are best suited for applications where the system operates at near-constant full load.

Use reciprocating engines

There are two primary reciprocating engine designs relevant to stationary power generation applications—the spark ignition Otto cycle engine and the compression ignition diesel cycle engine. For baseload power and CHP applications, spark ignition natural gas-fueled engines tend to be used, with capacities ranging from 10 kW to 10 MW.

Reciprocating engines represent more than 50% of all installed CHP systems, with engines fueled by natural gas and other gaseous fuels accounting for most of the installed capacity. Modern reciprocating engines are some of the most efficient CHP technologies, reaching more than 40% electric efficiency and 80% total CHP efficiency (HHV). Thermal energy can be recovered from three sources: (1) engine exhaust, (2) cooling water, and (3) lubricating oil. Steam can be produced from the exhaust of some larger engines; however, thermal energy from cooling water and lubricating oil can only be used to produce hot water (or chilled water with an absorption chiller).

Convert waste heat to power

Waste heat to power (WHP) is the process of capturing heat discarded by an existing industrial process and using that heat to generate power (EPA 2012). Waste heat streams can be used to generate power in what is called bottoming cycle CHP. In this configuration, fuel is first used to provide thermal energy in an industrial process, such as a furnace, and the waste heat from that process is then used to generate power. The key advantage of this type of WHP system is that waste heat utilization, which would otherwise be wasted, is used to produce electricity or mechanical power instead of purchasing power. Most WHP systems use the Rankine cycle, either with steam or with an organic fluid when the waste heat source has a lower boiling point. The latter is called the Organic Rankine Cycle (ORC). A Rankine cycle normally operates with water and therefore a steam temperature in the range of 265°F to 355°F (130°C to 180°C), but can be used at temperatures as low as 140°F to 160°F (60°C to 70°C) (SWEP 2019).

Depending on the electricity prices, the payback periods range from 2.4 to 9.5 years, with an average of about 6 years (for an average electricity price of $0.06-0.08/kWh and investment cost for a waste heat system of $1,500-2,500/kW) (Thekdi et al. 2021). For ORC systems, the largest part of the investment is for the turbine and the heat exchange devices.

Steam Distribution

Shut off excess distribution lines

Installations and steam demands change over time, which may lead to under-utilization of steam distribution capacity and extra heat losses. It may be too expensive to optimize the system for changed steam demands. Still, checking for excess distribution lines and shutting off those lines is a cost-effective way to reduce steam distribution losses.

Properly size piping

When designing new steam distribution systems, it is very important to account for the velocity and pressure drop. This reduces the risk of oversizing a steam pipe, which is not only a cost issue but would also lead to higher heat losses. Installing pipes with larger diameters can help create less pressure drop and also reduce noise related to steam flow (DOE 2012a).

Insulate steam lines and vessels

Mechanical insulation can typically reduce energy losses by 90% and help ensure the proper steam pressure for plant equipment (DOE 2012n). The application of insulation can lead to significant energy cost savings with relatively short payback periods. For example, the average payback period of insulation on steam and hot water lines, condensate lines, and feedwater tanks is 1.6, 2.0, and 1.1 years, respectively (IAC 2024). The improvement of existing insulation can often lead to further savings. This measure consists of applying more or better insulating material. Crucial factors in choosing insulating material include low thermal conductivity, dimensional stability under temperature change, resistance to water absorption, and resistance to combustion.

During maintenance, insulation that covers pipes, valves, and fittings is often damaged or removed and not replaced. Repairing faulty insulation saves energy and has an average payback time of 1.2 years (IAC 2024). It is also possible to use removable and reusable insulating pads, which are available to cover almost any surface. Reusable pads are flexible and vibration-resistant, and can be installed vertically or horizontally depending on the application. They can also contain built-in acoustical barriers when important for the specific application (DOE 2012m).

Check and monitor steam traps

Steam traps capture condensate while keeping the steam in the piping. Sometimes the valves in the trap will get stuck or fail, resulting in lost steam and increased energy costs.

Steam trap performance can be assessed by observing the temperatures at different parts of the trap. If both the steam and condensate sides of the trap are the same temperature, there is a problem: The trap is either stuck open and blowing steam or is not in operation. A simple laser thermometer or an infrared camera can be used to observe any temperature differentials across the trap.

A program of checking steam traps to ensure proper operation can save significant amounts of energy. If the steam traps are not maintained for 3 to 5 years, 15% to 30% of the traps can be malfunctioning, thus allowing live steam to escape into the condensate return system (DOE 2012o). Also, in plants with no active steam trap testing and repair program in place, about 50% of the traps are blowing steam. With monthly inspections and repair, this number can decrease to less than 3% (Fuhr 2010). Regularly detecting and repairing leaks can decrease the energy use by up to 20% (Gooding 2020). In systems with a regularly scheduled maintenance program, leaking traps should account for less than 5% of the trap population. Repairing and replacing steam traps have an average payback time of about 0.7 years (IAC 2024). In a steam system that has not been maintained for 3 to 5 years, about 15% to 30% of the steam traps may have failed and are leaking (DOE 2012o).

Attaching automated monitors to steam traps in conjunction with a maintenance program can save even more energy without significant added costs. Such a system is an improvement over steam trap maintenance alone because it gives quicker notice of steam trap malfunction or failure. Using automatic monitoring is estimated to save an additional 5% over regular steam trap maintenance, with a payback of about 1 year.

Use thermostatic steam traps

Thermostatic traps distinguish between steam and condensate from the temperature difference. For the trap to open, the condensate will need to cool below the steam temperature. Thermostatic traps are considered more efficient compared to other trap types (i.e., mechanical and thermodynamic) because they can back up a sufficient amount of condensate and, as a result, the steam is unable to reach the trap. The valve is actually flooded with condensate and there is no steam loss through the trap. However, they can also adversely affect the system efficiency if the condensate backup moves into a heat exchanger (Emerson 2017).

For light to moderately high condensate loads, thermostatic traps can offer several advantages, such as low initial investment, energy savings, and ease in application and maintenance. Thermostatic traps are not recommended when there are high condensate requirements (more than 7.7 tons/hr) (Bhatia 2020). Also, because they can rapidly purge air from a system, they are favored in operations with frequent startups and shutdowns (Emerson 2017).

Shut off steam traps

Energy savings can come from shutting off steam traps on superheated steam lines when they are not in use. This measure has an immediate payback (IAC 2024).

Reduce distribution pipe leaks

As with steam traps, the distribution pipes themselves often have leaks that go unnoticed unless there is a program of regular inspection and maintenance. On average, leak repair has a payback period of 0.4 years (IAC 2024).

Recover low-pressure waste steam through vapor recompression

Low-pressure steam exhaust from industrial operations is usually vented into the atmosphere or condensed in a cooling tower. Simultaneously, other plant operations may require intermediate-pressure steam at 20 to 50 psi. Instead of letting down high-pressure steam across a throttling valve to meet these needs, low-pressure waste steam can be mechanically compressed or boosted to a higher pressure so that it can be reused. Recovery of the latent heat content of low-pressure steam reduces the boiler load, resulting in energy and fuel cost savings. Potential uses of low-pressure steam include driving evaporation and distillation processes, producing hot water, space heating, producing a vacuum, or chilling water.

Vapor recompression relies on a mechanical compressor or steam jet ejector to increase the temperature of the latent heat in steam to render it usable for process duties. It is noted that the steam jet ejector is known for its simple construction, insensitivity to fouling, easy installation, low capital and installation costs, easy maintenance with no moving parts, and long useful operating life.

Recompression typically requires only 5% to 10% of the energy required to raise an equivalent amount of steam in a boiler. Vapor recompression can be used in steam distribution systems to boost system pressures that have dropped to unacceptably low levels (DOE 2012g).

Recover flash steam

When a steam trap purges condensate from a pressurized steam distribution system to ambient pressure, flash steam is produced. Depending on the pressures involved, the flash steam contains approximately 10% to 40% of the energy content of the original condensate. This energy can be recovered by a heat exchanger and used for space heating or feedwater preheating (DOE 2012p). The potential for this measure is site-dependent, as it is unlikely that a plant will build an entirely new system of pipes to transport this low-grade steam unless it can be used close to the steam traps. Sites using multi-pressure steam systems can route the flash steam formed from high-pressure condensate to reduced pressure systems.

The flashing of high-pressure condensate can regenerate low-pressure steam. Low-pressure process steam requirements are usually met by throttling high-pressure steam; however, a portion of the process requirements can be achieved at a low cost by flashing high-pressure condensate. Flashing is particularly attractive when it is not economically feasible to return the high-pressure condensate to the boiler. The economics of heat recovery projects are most favorable when the waste steam heat content is high and the flow continuous. Seasonal space heating is not the most desirable end use. Flashing of high-pressure condensate to regenerate low-pressure steam has an average payback period of about 0.9 year (IAC 2024).

Perform total site pinch analysis

Process integration, or pinch analysis, refers to the exploitation of potential synergies that are inherent in any system that consists of multiple components working together. In plants that have multiple heating and cooling demands, the use of process integration techniques can significantly improve efficiencies.

Developed in the early 1970s, process integration is now an established methodology for continuous processes (Linnhoff et al. 1992). The methodology involves the linking of hot and cold streams in a process in the thermodynamic optimal manner (i.e., not over the so-called “pinch”). Process integration is the art of ensuring that the components are well suited and matched in terms of size, function, and capability. Pinch analysis takes a systematic approach to identifying and correcting the performance-limiting constraint (or pinch) in any manufacturing process (Kumana 2000). Since its development, the pinch approach has been extended to resource conservation in general, whether the resource is capital, time, labor, electrical power, water, or a specific chemical compound or element such as hydrogen (in refineries).

The critical innovation in applying pinch analysis was the development of “composite curves” for heating and cooling, which represent the overall thermal energy demand and availability profiles for the process as a whole. When these two curves are drawn on a temperature enthalpy graph, they reveal the location of the process pinch (the point of closest temperature approach) and the minimum thermodynamic heating and cooling requirements. These are called the energy targets. The methodology involves first identifying the targets and then following a systematic procedure for designing heat exchanger networks to achieve these targets. The optimum approach temperature at the pinch is determined by balancing the capital versus energy tradeoffs to achieve the desired payback. The procedure applies equally well to new designs, as well as to the retrofit of existing plants.

The analytical approach used in pinch analysis has been widely documented in the literature since the 1970s (Klemes 2013). Energy savings potential using pinch analysis far exceeds that from well-known conventional techniques such as heat recovery from boiler flue gas, insulation, and steam trap management; energy savings averaging 30% have been identified on processes thought to be already optimized (Kemp 2006). Several case studies assess the potential for energy savings from pinch analysis. Heat integration through pinch analysis could decrease energy costs by about 6% in an ethylbenzene plant (Yoon et al. 2007), 40% in a cheese plant (Becker et al. 2012), 45% in a crude distillation unit (Mrayed et al. 2021), and 28% through heat pump integration in a chocolate plant (Bhadbhade et al. 2024).

Chapter 10: Lighting

In this chapter:	
Turn off lights in unoccupied areas	Use occupancy sensors and other lighting controls
Upgrade exit signs to LED signs	Use LED lighting
Update conventional lights	Replace magnetic ballasts with electronic ballasts
Reduce lighting system voltage	Use daylighting
Use brighter or more reflective finishes	Use photocell sensors for outdoor lighting

Lighting is used either to provide overall ambient lighting throughout the manufacturing, storage, and office spaces or to provide low bay and task lighting to specific areas. For many chlor-alkali plants, rail yards are another area with high lighting needs. High-intensity discharge (HID) sources are used for the former, including metal halide, high-pressure sodium, and mercury vapor lamps. In 2018, 68% of commercial buildings used standard fluorescent lights, dropping from 84% in 2012. LED lighting was used in more than 44% of the buildings, significantly increasing since 2012 (9%). Due to increased use of LED lighting, the use of all other types of lighting is rapidly decreasing (EIA 2021).

Energy Savings Checklist: Lighting

Lighting corresponds to significant energy use and cost for many manufacturers and is an area with numerous opportunities for savings. Use the checklist below to find new ways to save energy and costs with lighting changes.

Lighting Checklist	✓
Are unoccupied areas lit?	
Are lights left on during non-work hours?	
Are parts of the facility overlit?	
Can existing technology be made more energy efficient?	
Are exit lights using old technology?	
Can daylighting be used?	
Are the lighting controls in use?	
Is there a periodic review of lighting technology to ensure that the most efficient technology is in use?	

Opportunities for Energy Efficiency

There are many options and choices for providing appropriate lighting for specific settings. When the opportunity to install new or replace and upgrade existing lighting presents itself, understanding the various energy requirements, lifetime, uses, and so forth for the numerous types of lighting sources can be an important part of energy management and savings in a manufacturing facility. Table 13 compares the efficacy of various lighting sources.

Table 13: Efficacy comparison between top best-in-class LED lamps and conventional lamps (Pattison et al. 2018; Turner and Doty 2013)

Lighting type	Luminous efficacy (lumen/watt)	Usable lifetime (hours)[1]
2016 Top Performing LED lamps[2]		
LED A19 lamp (dimmable, 2,700 K)	100	25,000
LED PAR38 lamp (3,000 K)	88	25,000
LED T8 tube (4,000 K)	149	50,000
LED 6 downlight (3,000 K)	86	50,000
LED troffer 2 × 4 (3,500 K)	129	50,000
LED high/low-bay fixture (4,000 K)	136	60,000
LED street light (5,000 K)	118	60,000
Conventional Lighting lamps		
Incandescent A19	15	1,000
Halogen A19	20	8,400
CFL A19 replacement	70	12,000
CFL (dimmable) A19 replacement	70	12,000
Linear fluorescent system	108	25,000
T12	*49-97*	*20,000*
T8	*53-98*	*18,000-30,000*
T53	*96-104*	*20,000*
T5HO	*83-94*	*20,000*
HID (high-watt) system+	115	15,000
HID (low-watt) system+	104	15,000
Mercury	32-58	50-1,000

[1] For LED lights, the usable lifetime is reported in L70 values (i.e., the time at which the lights produce 70% of the initial light level).

[2] The top-performing LED lamps include the 90th percentile of ENERGYSTAR®-qualified lights (A19, PAR38 and 6” downlight) and of DesignLights Consortium-qualified lights.

Best Practices for Energy-Efficient Lighting

- **Turn off lights in unoccupied areas.** An easy and effective measure is to encourage personnel to turn off lights in unoccupied building spaces.
- **Use occupancy sensors and other lighting controls.** Lights can be shut off during non-working hours by automatic controls, such as occupancy sensors that turn off lights when a space is unoccupied.
- **Upgrade exit signs to LED signs.** Energy costs can be reduced by switching from incandescent lamps to LEDs or radium strips in exit sign lighting.
- **Use LED lighting.** LED lights use far less energy to emit the same lumens of light.
- **Update conventional lights.** When switching to LED lights is not possible, use other lighting alternatives to decrease the electricity use.
- **Replace magnetic ballasts with electronic ballasts.** Electronic ballasts require 12% to 30% less power than magnetic ballasts.
- **Reduce lighting system voltage.** Voltage controllers reduce voltage and save energy in HID or fluorescent lighting systems without losing light.
- **Use daylighting.** Increasing levels of daylight within rooms can reduce electrical lighting loads by up to 70%.
- **Use brighter or more reflective finishes.** Increasing the reflective properties of surfaces improves lighting conditions.
- **Use photosensors for outdoor lighting.** Reduce electricity use by using artificial lighting only when needed.

Use photocell sensors for outdoor lighting. Reduce the use of artificial lighting when natural light is available. Turn off lights in unoccupied areas

An easy and effective measure is to encourage personnel to turn off lights in unoccupied building spaces. An energy management program that aims to improve the awareness of personnel with regard to energy use can help staff get in the habit of switching off lights and other equipment when not in use.

Use occupancy sensors and other lighting controls

Lights can be shut off during non-working hours by automatic controls, such as occupancy sensors, which turn off lights when a space is unoccupied. Manual controls also can be used in addition to automatic controls to save additional energy in smaller areas. Numerous case studies throughout the United States suggest that the average payback period for occupancy sensors is approximately 1.4 years (IAC 2024).

Manual controls can be used in conjunction with automatic controls to save additional energy in smaller areas. One of the easiest measures is to install switches that allow occupants to control lights. Other lighting controls include daylight controls for indoor and outdoor lights, which adjust the intensity of electrical lighting based on the availability of daylight.

A daylight responsive dimming system (DRDS) utilizes the daylight incident to an indoor working area to dim the lights and reduce the energy use (see Figure 13). It measures the daylight with the use of a solar radiation sensor and the incident daylight into the working area with the use of photosensors that are attached to the lighting or the ceiling. If the predicted illuminance in the working area exceeds a target value, the lighting is turned off; if it meets the target value, the lighting is adjusted with a dimmer. The average power savings can reach 77% (Kim et al. 2018).

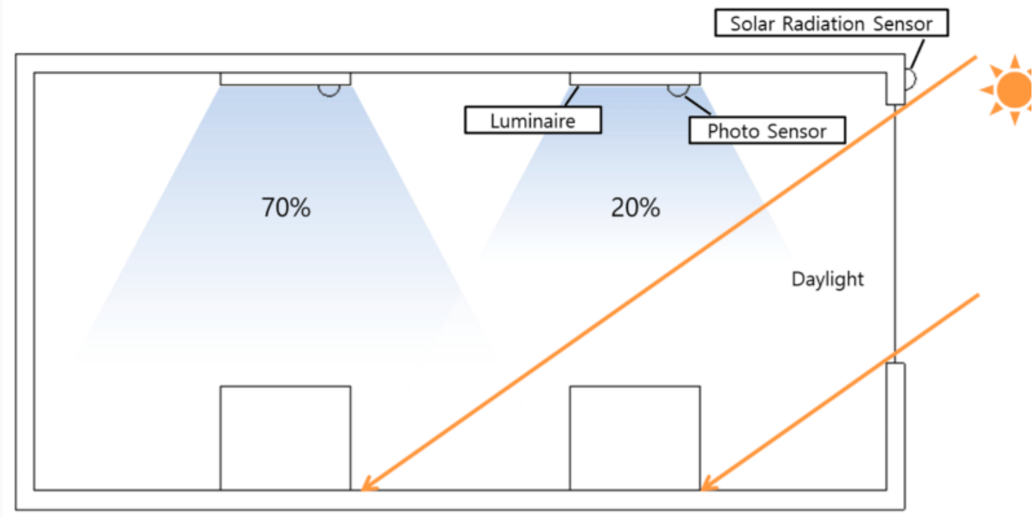


Figure 13: The concept of DRDS system (Kim et al. 2018)

Upgrade exit signs to LED signs

Energy costs can be reduced by switching from incandescent lamps to LEDs or radium strips in exit sign lighting. An incandescent exit sign uses about 40 W, while LED signs may use less than 4 W, reducing electricity use by 90%. Fluorescent exit signs are more efficient than incandescent signs but still use 2 times more electricity (10 W) than LED signs (see Table 14). The lifetime of an LED exit sign is more than 10 years, compared with 8 months for incandescent signs and less than 2 years for compact fluorescent signs, which can reduce exit sign maintenance costs considerably (Turner and Doty 2013; EPA 2003). In addition to exit signs, LEDs are increasingly being used for path marking and emergency wayfinding systems. Their long life and cool operation allow them to be embedded in plastic materials, which makes them well suited for such applications.

New LED exit signs are inexpensive, with prices typically starting at around $20. The EPA's ENERGY STAR program website provides a list of suppliers of LED exit signs.

Tritium exit signs are an alternative to LED exit signs. Tritium signs are self-luminous and thus do not require an external power supply. The light, however, dissipates with time. They have a high initial cost of more than $200, and at the end of their lifetime there can be an additional cost for disposing of them (NRC 2024). Electroluminescent signs consume very little energy; however, the light output depreciates rapidly (Turner and Doty 2013).

Table 14: Types of exit signs (Turner and Doty 2013)

Light source	Watts	Life	Replacement
Incandescent (long life)	40	8 months	Lamps
Compact Fluorescent	10	1.7 years	Lamps
Incandescent Assembly	8	3+ years	Light source
LED	< 4	10+ years	Light source
Electroluminescent	1	8+ years	Panel
Self-luminous (tritium)	0	10-20 years	Luminous tubes

Use LED lighting

LED technology is currently the most energy-efficient and rapidly developing lighting technology. Due to its high-efficiency and directional nature, LED lighting is ideal for many industrial applications such as task lighting, outdoor lighting, and refrigerated case lighting. The early technology LED lamps produced a cool, bright light. However, due to technological developments, LED lights can now produce warmer color temperatures equivalent to the color temperatures of conventional lighting (Carbon Trust 2017). LEDs have the highest efficacy and lamp life (see Table 13), they are reliable, and they require no warming up. Depending on the conventional lighting technology they replace, such as halogen, T-12 linear fluorescent, and metal halide, adopting LED technology can reduce electricity use for lighting by up to 80%. Replacing T8 and T5 fluorescent lights with LED will result in smaller energy savings but still has a good rate of return.

Update conventional lights

When it comes to lighting, LED lights are the most efficient. However, if it is not possible to replace all of your lighting system, there are some other alternatives that reduce the electricity use.

Where color rendition is critical, metal halide lamps can replace mercury or fluorescent lamps with significant energy savings. Ceramic metal halide lamps have an efficacy of 50-113 lumen/watt (Carbon Trust 2017) compared with an efficacy of 32-58 lumen/watt for mercury lamps (Turner and Doty 2013). Where color rendition is not critical, high-pressure sodium lamps with an efficacy of 85-150 lumen/watt is an energy-efficient option (see Table 15). A plant-wide energy assessment at the Ford Cleveland Casting Plant in Cleveland, Ohio, identified the potential for 282,000 kWh savings in electricity consumption by replacing the 400 W mercury lights with 360 W metal halide lights. The payback period was estimated to be 3.7 years (DOE 2003a).

Table 15: Performance of different lighting sources (Carbon Trust 2017)

	Lamp life (hr)	Color temperature (K)	Color rendering (Ra)	Efficacy (lumen/watt)
Standard Incandescent	2,000-3,000	2,500-3,000	100	5-20
Tungsten Halogen	2,000	3,200	100	15-24
Tubular Fluorescent	10,000-12,000	2,700-6,500	> 85	60-105
Compact Fluorescent	6,000-15,000	2,700-4,000	> 85	45-80
High Pressure Sodium	12,000-30,000	2,000-2,700	25-85	85-150
Metal Halide	6,000-20,000	3,000-6,000	65-93	50-113
LED	25,000-75,000+	2,700-8,000	65-97	70-150+

Also, when it is not possible to replace traditional HID lighting, such as mercury vapor and metal halide, with LEDs, they can be replaced with high-intensity T-5 fluorescent lighting. These systems incorporate high-efficiency fluorescent lamps, electronic ballasts, and high-efficacy fixtures that maximize output to the work plane. Some of the advantages are lower energy consumption, lower lumen depreciation over the lifetime of the lamp, better options for dimming and occupancy sensors, faster startup and restrike capability, better color rendition, higher pupil lumen ratings, and less glare (Martin et al. 2000; DOE 2011). High-intensity fluorescent systems yield 50% electricity savings over standard metal halide HID. Dimming controls that are impractical in the metal halide HIDs also can save significant energy. In addition to energy savings and better lighting qualities, high-intensity fluorescents can help improve productivity and have reduced maintenance costs.

Fluorescent T12 lamps and ballasts were phased out in 2012 and are no longer legal to be produced or imported. But still some facilities could use them. T-12 refers to the diameter in 1/8-inch increments (T-12 means 12/8-inch- or 3.8-cm-diameter tubes). These lights are very energy intensive and have poor efficacy, lamp life, lumen depreciation, and color rendering index. Because of this, maintenance and energy costs are high. Replacing T-12 lamps with T-8 lamps (smaller diameter) provides more lumens while it uses less energy. Typical energy savings from the replacement of a T-12 lamp with a T-8 lamp are around 30%. However, switching to LED or T-5 tubes lights leads to even higher energy savings (see Table 13). In addition, using electronic ballasts with a low ballast factor (BF) (lower than 0.85) can reduce the energy use of fluorescent lighting by up to 40% (NREL 2011).

Replace magnetic ballasts with electronic ballasts

A ballast is a mechanism that regulates the amount of electricity required to start a lighting fixture and maintain a steady output of light. Electronic ballasts operate at a higher frequency than magnetic ballasts, have lower flickering and noise, and require 25% less power than their magnetic predecessors (Kaya et al. 2021). Because electronic ballasts have smooth and silent dimming capabilities, the actual energy savings can be higher. In addition, they have faster run-up times and generate less heat than magnetic ballasts (Kaya et al. 2021; Perdahci et al. 2018). New electronic ballasts also have automatic switch-off capabilities for faulty or end-of-life lamps.

Reduce lighting system voltage

Reducing lighting system voltage can also save energy. A Toyota production facility installed reduced-voltage HID lights and realized a 30% reduction in lighting energy consumption (Galitsky et al. 2005). Commercial products are available that attach to a central panel switch (controllable by computer) and constrict the flow of electricity to lighting fixtures, thereby reducing voltage and saving energy with an imperceptible loss of light. Voltage controllers work with both HID and fluorescent lighting systems and are available from multiple vendors.

Use daylighting

Daylighting involves the efficient use of natural light to minimize the need for artificial lighting in buildings. Using dimmable and on/off daylight systems can result in significant electricity savings ranging between 10% and 90% (IEA 2016). Unlike conventional skylights, an efficient daylighting system may provide evenly dispersed light without creating heat gains, which can reduce the need for cooling compared with skylights. Daylighting differs from other energy efficiency measures because its features are integral to the architecture of a building; therefore, it is applied primarily to new buildings and incorporated at the design stage. However, existing buildings can sometimes be cost-effectively refitted with daylighting systems.

Daylighting can be combined with lighting controls to maximize its benefits. Because of its variability, daylighting is almost always combined with artificial lighting to provide the necessary illumination on cloudy days or after dark. Daylighting technologies include properly placed and shaded windows, atria, clerestories, light shelves, and light ducts. Clerestories, light shelves, and light ducts can accommodate various angles of the sun and redirect daylight using walls or reflectors. Slatted daylight blinds can be used to direct sunlight up to the ceiling where it is reflected throughout the working area without decreasing employee comfort (Carbon Trust 2017).

Using daylighting whenever possible in lieu of artificial lighting has a payback period of 1.7 years (IAC 2024).

Use brighter or more reflective finishes

Brighter or more reflective wall, ceiling, and floor finishes can improve lighting without consuming energy. According to Makaremi et al. (2019), increasing the reflective properties of surfaces can decrease electricity use by up to 45%. A ceiling with a reflectance of 0.89 versus 0.75 can increase the light level by 25% when indirect lighting is used, 18% when a combination of direct/indirect lighting is used, and up to 4% when only direct lighting is used (Katunský et al. 2022).

Use photocell sensors for outdoor lighting

Photocell sensors can be added to detect natural sunlight or other light sources present in the premises, limiting the use of artificial lighting and reducing electricity use.

Chapter 11: Building HVAC

In this chapter:

- Employ an energy-efficient system design
- Install energy monitoring and advanced control systems
- Repair leaks
- Install adjustable-speed drives (ASDs)
- Modify your fans
- Install efficient exhaust fans
- Employ solar air heating
- Install low-emittance (Low-E) windows
- Consider recommissioning before replacing
- Adjust non-production setback temperatures
- Consider variable air volume systems
- Consider heat recovery systems
- Use ventilation fans
- Add building insulation
- Modify building reflection

HVAC stands for heating, ventilation, and air conditioning and refers to the equipment, distribution network, and terminals used either collectively or individually to provide fresh filtered air, heating, cooling, and humidity control in a building. The main goals of HVAC are to provide comfort and indoor air quality. It is used throughout the buildings, the warehouses, and the plant itself when temperature and humidity need to be controlled.

Energy Savings Checklist: HVAC Systems

HVAC systems can be a significant energy load, so it is important to ensure that these systems are operating efficiently. Use the checklist below to identify new ways to save energy and costs with HVAC system changes.

HVAC Checklist	✓
Are temperature setpoints turned back during non-production hours?	
Are temperature setpoints at the right level?	
Is ductwork leaking?	
Is the building well insulated?	
Are the HVAC systems programmed correctly and operating according to the manufacturer's instructions?	
Are coils cleaned regularly?	
Are air filters changed appropriately and regularly?	
Can existing technology be made more energy efficient?	
Are economizer control and models functioning properly?	
Have burners been maintained properly and calibrated annually?	
Have V-belts been replaced with energy-efficient belts (i.e., cog belts)?	

Best Practices for Energy-Efficient HVAC Systems

- **Employ an energy-efficient system design.** Sizing equipment properly and designing energy efficiency into a new facility minimizes the energy consumption and operational costs of HVAC systems from the outset.
- **Consider recommissioning before replacement.** Recommissioning identifies problem areas that may be reducing building efficiency and can help avoid the cost of new equipment.
- **Install energy monitoring and advanced control systems.** These systems monitor, control, and track energy consumption to optimize consumption and help identify system problems.
- **Adjust non-production setback temperatures.** Adjusting temperatures during periods of non-use can significantly reduce HVAC energy consumption.
- **Repair leaks.** Steam leaks in radiator control valves and humidifiers can add marginal heat losses to the system. Repairing duct leaks can reduce HVAC energy consumption by up to 30%.
- **Consider variable air volume systems.** These systems match the HVAC load to heating and cooling demands and reduce energy use.
- **Install ASDs.** ASDs minimize consumption based on system demand to save energy.
- **Consider heat recovery systems.** These systems reduce the energy required to heat or cool intake air.
- **Modify your fans.** Changing the size or shape of the sheaves of a fan optimizes fan efficiency and airflow and reduces energy consumption.
- **Use ventilation fans.** Ventilation fans reduce the load on heating systems and lead to better air circulation.
- **Install efficient exhaust fans.** Impeller exhaust fans are up to 25% more efficient than centrifugal fans.
- **Add building insulation.** Insulation is an easy and effective way to reduce utility bills.
- **Employ solar air heating.** These systems use solar radiation for insulation and provide clean, fresh air.
- **Modify building reflection.** Use reflective roofing, “green” roofing, or shading/windbreaks to increase energy efficiency.
- **Install Low-E windows.** Insulating ability is increased through these windows.

Employ an energy-efficient system design

For HVAC systems in new industrial facilities, the greatest opportunities for energy efficiency arise at the design stage. Sizing equipment properly and designing energy efficiency into a new facility generally minimizes the energy consumption and operational costs of HVAC systems from the outset. This practice often saves money in the long run, as it is generally less expensive to install energy-efficient HVAC equipment during construction than it is to upgrade an existing building with an energy-efficient system later on, especially if those upgrades lead to downtime. One design option for new plants or rebuilt plants is radiant heating systems that supply heat directly to the floor, ceiling, or walls and are more energy efficient than baseboard heating and forced-air heating.

Consider recommissioning before replacing

Before replacing HVAC system components to improve energy efficiency, explore the possibility of HVAC system recommissioning. Recommissioning is essentially the same process as commissioning, but it is applied to a building's existing HVAC, controls, and electrical systems (EPA 2008). Depending on the region and the heating and cooling systems to be replaced, replacement with higher-energy-efficiency equipment can reduce the energy use for electric heating and cooling systems by 50% and the energy use in gas furnace heating systems by 10% (EERE n.d.).

Commissioning is the process of verifying that a new building functions as intended and communicating the intended performance to the building management team. This usually occurs when a new building is turned over for occupancy. In practice, commissioning costs are not included in design fees and often compete with other activities, so commissioning is seldom pursued properly. To ensure that energy performance and operational goals are met, however, the building must be commissioned. To achieve this, ENERGY STAR recommends the following:

- Communicate your energy performance goals during commissioning to ensure that the design target is met. Encourage energy use tracking so that performance comparisons are made over time.
- Specify detailed commissioning activities in project contracts. Seek separate funding for commissioning work to ensure that it will get done and be done well.
- Hire building commissioning experts. Include the commissioning firm as part of the design team early in the project.
- Finalize and transfer a set of technical documents, including manufacturers' literature for systems and components. Supplement technical literature with summaries on how to operate and manage the systems. Provide an additional explanation for innovative design features.

Recommissioning involves a detailed assessment of existing equipment performance and maintenance procedures. This is compared with the intended or design performance and maintenance procedures to identify and fix problem areas that might be hampering building energy efficiency. Recommissioning can be a cost-effective retrofit, sometimes generating more savings than the cost of the retrofit measure. For example, recommissioning may help avoid the need to install new or additional equipment, leading to savings in capital investments.

Install energy monitoring and advanced control systems

An energy monitoring and control system supports the efficient operation of HVAC systems by monitoring, controlling, and tracking system energy consumption. Such systems continuously manage and optimize HVAC system energy consumption while also providing building engineers and energy managers with a valuable diagnostic tool for tracking energy consumption and identifying potential HVAC problems. Several projects indicate that the average payback period for HVAC control systems is about 1.5 years (IAC 2024).

Adjust non-production setback temperatures

Setting back building temperatures (i.e., adjusting building temperatures down in the winter or up in the summer) during periods of non-use, such as weekends or non-production times, can significantly reduce HVAC energy consumption.

Lowering the temperature during wintertime has a payback period of 0.2 years. Lowering the temperature during winter in a chlor-alkali plant in Ohio reduced natural gas costs by approximately $46,000 in 2007 prices (IAC 2024). No investment was required.

Repair leaks

Leaking air ducts can waste significant amounts of energy. Install duct insulation and perform regular duct inspection and maintenance, including ongoing leak detection and repair. According to a study by Lawrence Berkeley National Laboratory (LBNL), repairing duct leaks in industrial and commercial spaces can reduce HVAC energy consumption by up to 30% (Galitsky et al. 2005). The study also showed that duct tape should not be used for leak repair; aerosol sealants are preferable.

Consider variable air volume systems

Variable air volume systems adjust the rate of airflow into a room or space based on the current airflow requirements of that room or space. Variable air volume systems, therefore, work to match HVAC load more closely to heating and cooling demands, which reduces energy use.

Install ASDs

ASDs can be installed on variable-volume air handlers and recirculation fans to precisely match the flow and pressure requirements of air handling systems. Energy consumed by fans can be lowered considerably since they do not constantly run at full speed. ASDs can also be used on chiller pumps and water system pumps to minimize power consumption based on system demand.

Consider heat recovery systems

Heat recovery systems reduce the energy required to heat or cool facility intake air by recovering the thermal energy of the exhaust air. Common heat recovery systems include heat recovery wheels, heat pipes, and run-around loops. Heat pipes recover about 45% to 65% of the exhaust heat, while the efficiency of run-around loops can be in the 55% to 65% range.

Modify your fans

In belt-driven fans, changing the size or shape of the sheaves of a fan can help optimize fan efficiency and airflow, reducing energy consumption. Toyota optimized the sheaves of its fans instead of installing ASDs on fans, finding better savings and payback periods than expected (Scott 2004).

Use ventilation fans

Ventilation fans installed in the ceilings of work areas can help destratify workspace air, leading to better circulation of cool air in summer and warm air in winter, as well as more even temperature distributions from floor to ceiling. Such fans can help reduce the load on building heating systems by helping to "push down" warm air that rises during heating months. The average payback time of using destratification fans for improved air circulation is about 2 years (IAC 2024).

Install efficient exhaust fans

Exhaust fans are standard components in any HVAC system. Mixed-flow impeller exhaust fans offer an efficient alternative to traditional centrifugal exhaust fans. Table 16 shows the efficiencies of common fan types used in building ventilation.

Table 16: Common fans used in building ventilation and typical peak efficiencies (Radgen et al. 2008)

Fan type	Fan total efficiency (%)
Centrifugal	
Aerofoil	88
Backward-curved	84
Backward-inclined	80
Forward-inclined	70
Axial	
Vane-axial	85
Tube-axial	75
Propeller	55
Mixed-flow	75
Tangential	25

Add building insulation

Adding insulation will reduce utility bills. Older buildings are likely to use more energy than newer ones, leading to very high heating and air conditioning bills. However, even in new buildings, adding insulation may reduce utility bills enough to pay for itself within a few years.

Various states have regulations and guidelines for building insulation (e.g., California's Building Energy Efficiency Standards for Residential and Nonresidential Buildings, Title 24). Going beyond regulated insulation levels may be economically beneficial and should be considered as part of a new building's design, as well as for reconstruction of existing buildings. For refrigerated warehouses, much higher levels of insulation are preferred.

Insulating walls, ceilings, and roofs has a payback period of 3.2 years (IAC 2024).

Employ solar air heating

Solar air heating systems, such as SolarWall®, use conventional steel siding painted black to absorb solar radiation for insulation. Fresh air enters the bottom of the panels where it is heated as it passes over the warm absorber. Fans distribute the air. This technology could produce up to 600 W/m^2 of thermal energy (1.5 to 3.5 GJ/m^2 per year), depending on the weather and geographical conditions. On a sunny day, this air will be heated to temperatures of 59°F to 104°F (15°C to 40°C) above ambient. In a SolarWall 2-stage system, the pre-heated air is further heated as it passes through the SolarWall® absorber. This can increase the temperature 36°F to 85°F (20°C to 47°C) above the ambient temperature on a sunny day. The thermal energy delivered is up to 50% higher than in the conventional SolarWall® system (SolarWall 2018).

Using this technology, Toyota Motor Corporation in Valenciennes, France, turned one of the south walls of its plant into a huge solar collector. Annual energy savings were estimated to be over 25% compared with conventional gas air systems The Solarwall® system can raise the temperature of the air entering the plant during winter by 16°F (9°C). In addition to energy savings, the system can reduce CO_2 emissions by 20% (SolarWall 2011). In another case study, the SolarWall system saved $6,100 (2006 prices) on natural gas at the 3M manufacturing plant in Perth, Ontario, Canada (SolarWall 2009). This measure is only of interest for buildings in cold climates, and the potential benefits should be analyzed based on the local conditions of each site.

This technology also could be used for cooling, where systems, such as NightSolar®, remove energy from the air to cool buildings without the use of compressors or refrigeration systems. Since many chlor-alkali plants are in the warm Gulf Coast region, this technology could be of particular interest. This solar cooling technology is based on the scientific principle of nocturnal radiation cooling, which can cool a roof by as much as 18°F (10°C) below ambient temperature on a clear night. As warm night air touches the cooler surface of the panel, heat is transferred to the surface, which cools the air by radiating the heat to the cold night sky. The chilled air is then drawn in through perforations in the collector and enters the HVAC unit via an economizer cycle. This cooling can reduce or even displace conventional air conditioning from sunset to sunrise. The result for the building owner could be up to 50% in energy savings that occurs from reducing onsite cooling and heating. This would depend on the availability of solar radiation and the gradient of temperatures.

The installation of a damper/economizer on the HVAC unit has an average payback time of 2 years (IAC 2024).

Modify building reflection

Reflective roofing. Using a reflective coating on the roofs of buildings in sunny, hot climates can save on air conditioning costs. Using reflective roofings in a cold storage industrial building in California reduced the average peak power demand of the chiller between 6% and 7% while the average daily energy savings amounted to 3% to 4% (Akbari et al. 2004). For colder climates, the heat lost due to cool roofs (in winter, for example) needs to be considered, as it could negate savings.

In addition to location and weather, other primary factors (such as roof insulation, air conditioning efficiency, and building age) also influence energy savings. Reflective roof materials are available in different forms and colors.

"Green" roofs. Roof gardens on a flat roof improve the insulation of buildings against both hot and cold by providing heat in winter and air conditioning in summer. In winter, "green" roofs can freeze, so they carry a slight heating penalty but still often yield net energy savings. In addition, a roof garden can increase the lifetime of the roof, reduce runoff to local storm drains, and lower air pollution and dust.

Shading and windbreaks. Shade trees reduce the need for cooling in hot climates. Shade trees should be deciduous (providing shade in the summer and none in the winter) and planted on the west and southwest sides of the building (based on the path of the summer sun). Trees planted on the north side of the building in cold climates can reduce heating in winter by shielding the building from the wind. Vines can provide both shade and wind shielding. Planting trees or shrubs near windows has a payback period of 0.6 years (IAC 2024).

Install low-emittance (Low-E) windows

Low-E windows are another effective strategy for improving building insulation. Low-E windows can lower the heat transmitted into a building to increase its insulating ability. There are two types of Low-E glass: high solar transmitting (for regions with higher winter utility bills) and low solar transmitting (for regions with higher summer utility bills). The ENERGY STAR website includes a selection of rated Low-E windows. New window and glazing technologies are being developed worldwide.

Energy Efficiency Technologies for Chlor-Alkali Plants

There are three main manufacturing steps used for chlorine production in all chlor-alkali plants: (1) brine preparation, (2) brine electrolysis, and (3) final product treatment. The method of brine electrolysis used, either mercury,[4] diaphragm, or membrane cells, dictates the exact steps in upstream and downstream processes. This is because each type of electrolysis cell has different brine quality requirements and results in products with dissimilar properties. For example, the brine used in membrane cells needs to be of higher purity than the brine used in diaphragm and mercury cells, requiring an extra purification step during brine preparation. Similarly, the caustic soda produced in diaphragm and membrane cells has a lower concentration than the one produced in mercury cells and needs to be concentrated.

The key processes, along with the main subprocesses and the type of equipment used in the U.S. chlor-alkali industry, are outlined below:

- **Brine preparation:** The brine is prepared based on electrolytic cell requirements. Key steps are saturating and resaturating the salt with water or depleted brine in vessels; removing impurities via precipitation and filtration; and, if brine is recirculated, dechlorinating the depleted brine. Finally, the brine undergoes acidification to protect the anode coatings of the electrolytic cell.

---

[4] Mercury plants are being phased out since the Minamata Convention entered into force: UNEP Global Mercury Partnership: Chlor-alkali sector - World Chlorine Council. Most mercury plants will cease operating in 2025. Two plants, both outside the U.S., have a 5-year extension to 2030.

- **Electrolysis:** The brine is electrolyzed in the electrolytic cell.
- **Product processing:** Main products (i.e., chlorine, caustic soda, and hydrogen) are prepared for storage or further use. The chlorine extracted from all types of cells undergoes cooling, drying, and cleaning to avoid corrosion in downstream equipment, compression, and, if not used on site, liquefaction. The caustic soda is cooled and concentrated, depending on the use of the caustic. When caustic soda is produced in mercury cells, further concentration is not needed. Hydrogen is typically cooled and cleaned.

Generally, most fuel used on-site is for generating electricity and steam. Steam is used to heat the brine, dry the chlorine, and concentrate the caustic soda. Electricity is used throughout all processes, but the most significant consumer by far is the electrolytic cell. Other equipment with significant electricity use are compressors and chillers used for compressing and cooling the chlorine, chillers for cooling the caustic soda, and the rectifiers for providing direct current to the electrolytic cell.

The following three chapters describe energy saving practices and technologies that can be implemented in chlor-alkali plants to reduce energy use and GHG emissions. The previous chapters provided energy saving opportunities for technologies that are commonly found in plants, such as motors, pumps, and cooling towers. While these technologies also are found within key production processes, the subsequent chapters discuss energy saving opportunities more holistically within each of the key chlor-alkali production processes. Where available, case studies that present the results of specific measures (e.g., achieved cost savings and payback periods) are discussed.

Chapter 12: Brine Preparation

In this chapter:	
Use high-purity brine	Employ nanofiltration
Use iron (III) meso-tartrate for anticaking	Avoid salt pile dissolving
Use fluidized salt saturators	Minimize fouling
Recover waste heat from electrolysis products for brine heating	Recover waste heat from cell rooms for brine heating
Adjust the brine recirculation process to limit brine heating	Minimize clarifier and dissolver heat losses
Use online impurity control	Use a once-through brine system
Use multiple effect evaporation	Use mechanical vapor recompression
Use thermal vapor recompression	

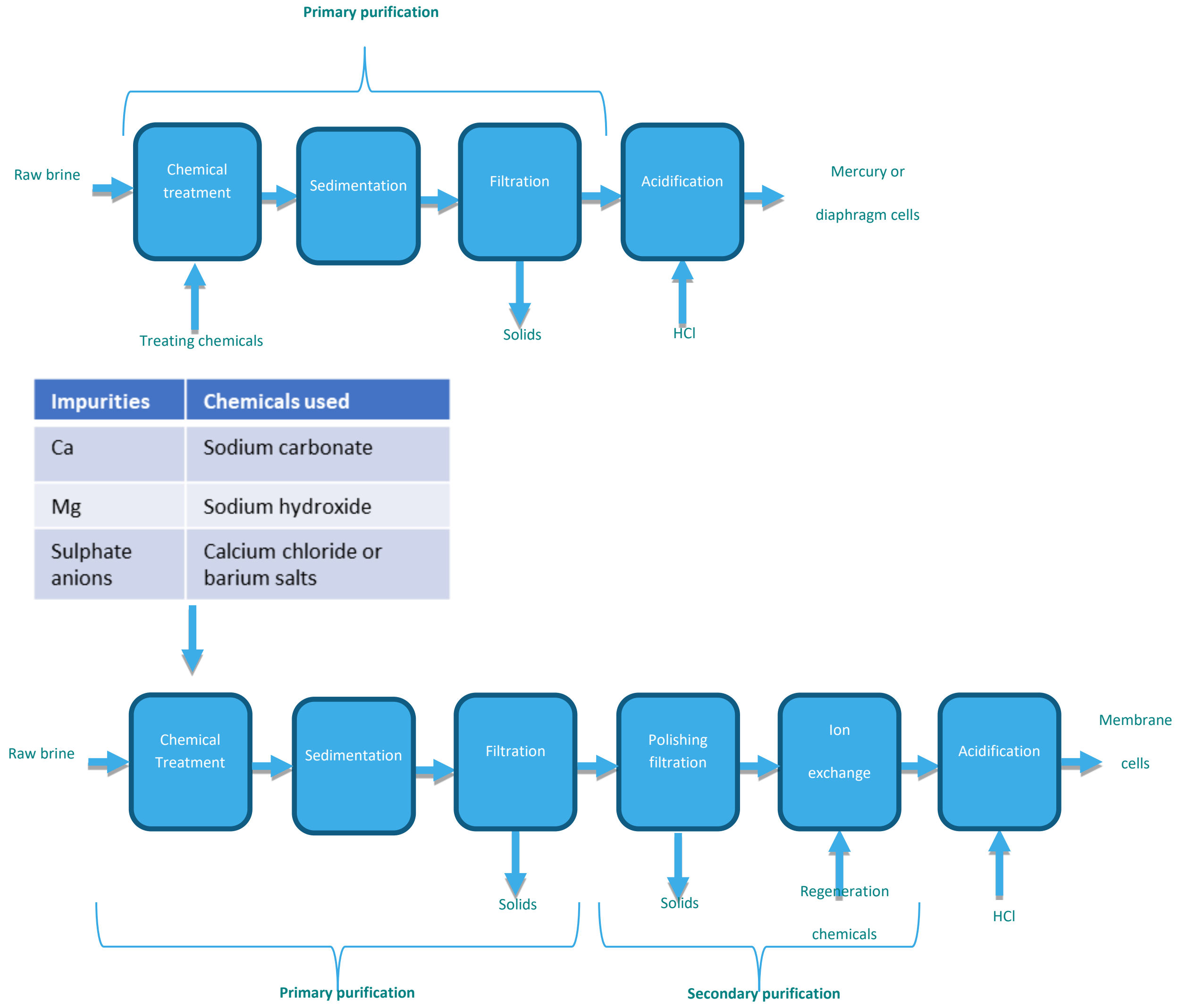
The first step in chlorine manufacturing is preparing the brine. To make the brine, dry salt needs to be mixed with water and/or with depleted brine that is recycled from the electrolysis cell. Chlorine plants operating diaphragm cell technology use brine as the raw material.

Brine saturation and resaturation takes place in brine dissolvers. Throughout this report, dissolvers might also be referred to as *saturators* or *resaturators*. In older plants, the open pits used for salt storage serve also as dissolvers, while newer plants use closed vessels (Schmittinger et al. 2011). Dissolvers are typically classified, based on the direction of flow of the brine, into upflow or downflow (O'Brien et al. 2005). In upflow dissolvers, water or diluted brine is introduced with a distributor (e.g., a sparger pipe) into a bed of salt at the bottom of the vessel. The brine becomes saturated as it rises from the bottom of the vessel. In downflow dissolvers, the water/diluted brine direction is the opposite. Other dissolvers combine an upflow and downflow design where the brine flows in more than one direction. The dissolver most commonly used in the chlor-alkali industry is the upflow type (O'Brien et al. 2005). Chlor-alkali plants operate several dissolvers as occasional shutdowns are needed to remove sludge.

For an efficient electrolytic process, the brine needs to be free of impurities. Brine impurities can affect the electrode kinetics, cell performance, condition of certain cell components, and product quality (O'Brien et al. 2005). Two main impurities are calcium (Ca) and magnesium (Mg), which damage the electrodes and the membranes. Energy efficiency is also affected by impurities. Operating with partially blocked membranes increases cell electricity consumption and limits the lifetime of membranes.

In mercury and diaphragm cells, brine impurities are removed in a primary purification process while a secondary purification step is needed for membrane cells. Figure 14 shows the different primary and secondary purification steps. In primary brine purification, the raw brine is treated with chemicals, mainly sodium hydroxide and sodium carbonate, to remove Ca and Mg impurities. Several methods are used to remove sulphate ions, such as using barium salts (not recommended in the case of membrane cells), purging a part of the brine, and nanofiltration. Sulfate removal is not needed in the case of diaphragm cells. In a secondary purification step, impurities are further removed by passing the brine through polishing filters and an ion exchange unit (for more details, see the Brine purification section in Appendix A: The Chlor-Alkali Industry). After purification, the brine needs to be acidified to extend the lifetime of the anodes and increase the purity of the chlorine.

Mercury and membrane plants recirculate depleted brine while diaphragm cells do not. Before its use in the brine system, the depleted brine needs to be dechlorinated. Membrane plants dechlorinate the full recirculated brine volume, as chlorine can harm the resins used in secondary purification, while mercury plants only partially dechlorinate. During dechlorination, the depleted brine is first acidified with the use of hydrochloric acid (HCl) and then passed through a vacuum dechlorinator (O'Brien et al. 2005).



Impurities	Chemicals used
Ca	Sodium carbonate
Mg	Sodium hydroxide
Sulphate anions	Calcium chloride or barium salts

Figure 14: Primary and secondary purification in chlor-alkali plants

In a chlor-alkali plant, the brine preparation system typically accounts for about 15% of the overall capital cost and about 5% to 7% of the operating costs (O'Brien et al. 2005). With the use of membrane cells, brine specifications have tightened, increasing process complexity and brine treatment costs.

The brine preparation system in diaphragm plants is the least complex. Plants with diaphragm cells do not recirculate the brine, thus requiring no dechlorination, and the sulfates do not need to be removed. According to Schmittinger et al. (2011), the investment cost for the brine system in diaphragm plants accounts for 3% to 4% of the total capital investment, while for mercury and membrane cells the cost is similar and it accounts for 4% to 7% of the total capital investment. Although the brine system for membrane cells is the most complex, due to the greater brine depletion the brine system is smaller than in the mercury cells (Schmittinger et al. 2011).

To maintain the electrolysis process and create the desired conditions in the electrolysis cell, the brine and the brine equipment need to be heated (Brinkmann et al. 2014). The brine is usually heated with steam. In general, steam consumption for brine preparation is higher for membrane cell plants than for diaphragm cell plants due to the lower Joule heating.[5] In 2008, the average energy consumption for brine and brine equipment heating in European Union (EU) chlorine plants (all cell technologies included) was 0.6 MBtu/ton Cl_2. The lowest reported energy consumption was 0.24 MBtu/Cl_2 while the highest was 3.1 MBtu/ton Cl_2[6] (Brinkmann et al. 2014).

In a Dutch membrane plant, the heat use for brine preparation was 1.1 MBtu/ton Cl_2 and was provided either by a CHP plant operating on-site or by reusing heat from the electrolysis cells, and from the hydrogen and chlorine cooling units (Scherpbier and Eerens 2021). Modern plants use plate heat exchangers, often called "plate and frame heat exchangers," in and around the cell room for heat recovery (O'Brien et al. 2005). In addition, about 10 kWh/ton Cl_2 of electricity were used (Scherpbier and Eerens 2021).

In brine preparation, the electricity is primarily used in motors for mixing, dosing chemicals, and pumping brine through the different steps. In a chlor-alkali plant in India, about 2.6 kWh/ton NaOH is used in brine preparation equipment, of which 95% was used in pumps and the remaining 5% in mixers (NPC 2017).

Mercury and membrane cells cannot operate with solution-mined brine, unless the brine solution is evaporated to reduce the high water content. There are many solution-mining activities at the salt domes of the Gulf Coast, and the chlorine plants processing the extracted brine will need a salt evaporator/concentrator to reach the desired salt levels. Brine evaporation is especially relevant for the U.S. chlor-alkali industry if diaphragm cells are replaced with membrane cells and the source of salt remains the same (i.e., solution-mined brine).

---

[5] *Joule heating* is the heating taking place inside the cell by the heat released as the electric current passes through. It is also known as *resistive heating*.

[6] According to Brinkmann et al. (2014), the steam consumption reported by EU plants (all cell technologies included) ranged between 0.1 and 1.3 tons steam/ton Cl_2 produced, with the average consumption at 0.3 ton steam/ton Cl_2. The energy consumption is estimated for a boiler efficiency of 90% and exergy content of 2.1 MBtu/ton steam. Throughout this guide, *MBtu* refers to *million British thermal units*.

Energy Savings Checklist: Brine Preparation

Most energy in brine preparation is used in the form of steam for heating the brine. Operators should ensure that the steam systems operate efficiently; for energy efficiency measures in this area see Chapter 9: Hot Water and Steam Systems. Recovering heat from other processes to heat the brine will limit the need for burning fuels and increase the overall energy efficiency. Since electricity is mostly used for pumping brine, pump systems should also be efficiently operated. Chapter 7: Pump Systems is dedicated to energy efficiency measures for pumping.

The brine quality, which strongly depends on the impurity removal efficiency during brine purification, is closely related to the electricity consumption in the electrolysis cell. Carefully controlling brine purification and other brine parameters, such as temperature, will increase the plant's efficiency, as less electricity will be used in the electrolytic cell.

Brine Preparation Checklist	✓
Are the steam units operating efficiently?	
Is steam used efficiently?	
Can waste heat be recovered and reused for brine heating?	
Is pumping used efficiently?	
Can heat losses be minimized?	
Are there more efficient processes for brine purification?	
Can the brine purity be improved?	
Can the temperature be better controlled?	
Can the overall process be better controlled?	

Best Practices for Energy-Efficient Brine Preparation

Use high-purity brine

The brine needs to be sufficiently purified to minimize the contamination of electrodes, diaphragms, and membranes used in the electrolytic cells. If impurities are not kept at a low level, energy consumption in the electrolytic cell can increase.

Brine purity is usually determined based on the equipment specifications set by the manufacturer. In addition, a full characterization of the brine is carried out before designing the purification system, which is followed by pilot trials and equipment calibrations (Brinkmann et al. 2014).

Primary brine purification is performed in all chlor-alkali plants, while plants using the membrane process also use a second purification stage. Adding extra purification stages can increase the energy use for purification, increasing the use of ancillary materials while more waste might be generated (Brinkmann et al. 2014). Therefore, it needs to be carefully assessed whether the benefits from decreased cell electricity use and improved cell maintenance compensate for the additional purification costs.

Using high-quality resins in the ion exchange units in membrane cell plants will result in higher-purity brine, increased throughput, and extended membrane lifetimes.

CASE STUDY

A chlor-alkali plant in South India, with a caustic capacity of 210 kton per year, replaced the resins used in some of the ion exchange units with a newer resin design. The new resins had a much smaller particle diameter (0.39 mm instead of 0.65 mm). The result was a 49% increase in brine throughput, while the membrane lifetime was also extended due to the higher-purity brine.

Sources: LANXESS. (2018a). Case study about chlor-alkali brine purification in a chemical plant in south India. https://lanxess.com/en/Products-and-Brands/Brands/Lewatit/Case-Studies-and-Stories/Brine-purification-with-finely-dispersed-ixr

LANXESS. (2018b). Lewatit® MDS TP208 – Significant Cost Savings Offered by Chelating Resin with Special Small-sized Monodisperse Beads.

Employ nanofiltration

The salt used by the chlor-alkali industry contains impurities that can affect the efficient operation of the cells and increase electricity use (Schmittinger et al. 2011). One of these impurities is sulfate (SO_4^{2-}). High sulfate accumulation in the brine leads to precipitation on the anode and scaling and plugging of the ion exchange membrane (Kyburz et al. 2021; Zahedi et al. 2017). Damaged anodes increase overvoltage, and when impurities are deposited in the membrane, the resistance increases and thereby the cell voltage. Current efficiency also declines as the membranes lose their ability to reject anions (Schmittinger et al. 2011). In addition, the lifetime of the anodes and the membranes decreases.

Especially in plants with brine recirculation, such as membrane plants, sulfate is recycled with the depleted brine and builds up in the brine system. Currently, sulfate removal is achieved by purging a part of the brine, precipitation with barium and calcium salts, an ion-exchange process, or membrane nanofiltration (Schmittinger et al. 2011). Purging a part of the brine is the method predominantly used as the use of barium salts is increasingly prohibited due to environmental concerns (Kyburz et al. 2021).

Compared to the other methods, using membrane nanofiltration to treat a part of the recirculated brine can have several environmental benefits such as lower volumes of wastewater and reduced emissions. Nanofiltration employs a type of membrane filtration system with membrane pore sizes of about 1 nm. To guarantee good performance of the membranes, the depleted brine undergoes pH adjustment, cooling, chlorine removal, filtration, and compression (Brinkmann et al. 2014). The cooled, high-pressure, depleted brine is then fed to the nanofiltration unit, which consists of several stages and operates in cross-flow mode. The nanofiltration membranes selectively reject sulfate anions while chloride and chlorate are allowed to pass through. The permeate from each filtration stage is then gathered and recirculated into the brine system while the sulfate-rich brine is purged. The sulfate concentration achieved in the purge is more than 100 g Na_2SO_4/L (Brinkmann et al. 2014).

Using nanofiltration to concentrate and remove sulfate from the brine purge instead of simply employing brine purging results in up to 90% lower volumes of wastewater while the chloride emissions also decrease by the same rate (Brinkmann et al. 2014). In addition, salt consumption decreases by more than 20%. With lower raw salt consumption, the need for primary brine treatment also is lowered as the Mg and Ca impurities that enter the brine system are reduced. When compared to the use of barium salts, the main benefits of using a nanofiltration system are the eradication of handling toxic barium salts and the disposal of barium sulfate sludge (Brinkmann et al. 2014). Also, barium impurities in the recirculated brine have a negative impact on the cell voltage.

The main costs associated with nanofiltration are the electricity costs for operating the high-pressure pumps, estimated at about 5 kWh/ton chlorine, and the membrane costs. The lifetime of membranes is about 2 years. Nanofiltration is applicable to all membrane plants, new and existing ones, while diaphragm plants cannot profit from this measure as brine is not recirculated and the sulfate is normally removed during caustic soda concentration.

The operational cost benefits will depend on the sulfate content and the other impurities (e.g., Mg and Ca) in the salt used; the industrial salt used; whether barium salts were used before; water, membrane, and electricity prices; and the costs of waste disposal. When barium impurities are eliminated, energy efficiency gains are possible due to the improved cell operation. Note that if the original barium sulfate precipitation process is efficient, no energy savings are expected (Brinkmann et al. 2014).

Newer, high-temperature nanofiltration membranes can withstand brine temperatures as high as 160°F (70°C) (Lenntech n.d.; Maycock et al. 2007). In this way, membrane nanofiltration becomes more efficient as heat losses are avoided, and the heat exchangers to cool and reheat the sulfate-free recirculated brine are not needed.

The first industrial unit was installed in 1997 at an Occidental Chemical chlor-alkali plant in Delaware (Maycock et al. 2007). Since then, more than 70 chlor-alkali plants worldwide have installed nanofiltration using a variety of membranes reported to achieve sulfate retention levels ranging from 85% to 99% (Kyburz et al. 2021).

Use iron (III) meso-tartrate as an anticaking agent

During storage, the salt crystals can absorb moisture that forms a brine film on the crystal surface. Changes in air humidity and temperature can cause water evaporation and recrystallization of the brine film with the crystals bonding together. Also, evaporated salt[7] that exits the dryers tends to undergo increased caking when left to cool in silos. To prevent caking and ease salt handling, an aqueous ferrocyanide solution is frequently sprayed onto the salt (Brinkmann et al. 2014). However, the use of ferrocyanide has several adverse effects and it is currently rarely used. The iron is transferred to the electrolysis cell where it tends to accumulate in the anode and form a brown deposit at the anode/membrane interface, which leads to shorter lifetimes (for both membranes and anodes), lower product qualities, and increased energy consumption (Brinkmann et al. 2014; O'Brien et al. 2005). The typical upper limit of the iron content is 0.0-0.1 ppm, while higher iron concentrations can be allowed in non-acidified brines (Brinkmann et al. 2014).

---

[7] Evaporated salt is salt made by an evaporation process using water and steam, which produces salt in a crystallized form.

An alternative anticaking agent has been available since 2004, iron (III) meso-tartrate. Because the iron precipitates as hydroxide during primary brine purification, it is not transferred into the electrolytic cell. The residual tartrate reaches the cell, but it is fully oxidized to hydrochloric acid and carbon dioxide.

Replacing ferrocyanide with iron (III) tartrate in a Dutch chlor-alkali plant operated by AkzoNobel (now Nobian), resulted in a 50 mV lower overvoltage. The electricity savings expected are about 5% in plants using brine acidification, while the lifetime of membranes and anodes increases. When an alkaline brine is used, no significant savings are expected. The main drawback is the larger volume of solid wastes; the iron content of the salt increases by about 15% compared to when using ferrocyanide (Brinkmann et al. 2014).

Avoid salt pile dissolving

In some older chlor-alkali plants, salt is dissolved by spraying water on top of the salt piles (Schmittinger et al. 2011). This practice, although simple in operation, has several drawbacks. The two main issues are the unevenly dissolved salt and the hard-to-control impacts of rainfall (O'Brien et al. 2005). Impurities can also accumulate on the pile surface and on partly dissolved finer particles, resulting in the formation of channels and the production of unsaturated brine.

Using below-grade pits is better than salt pile dissolving (O'Brien et al. 2005). In this case, the fluid, water or depleted brine, can be introduced via spargers placed below the salt surface. Using closed vessels for brine resaturation avoids environmental pollution. Feeding the processes with evenly dissolved brine with low impurities is important for the smooth and efficient operation of both the brine preparation system and the electrolytic cell.

Use fluidized salt saturators

When salt is saturated in outdoor locations, the brine temperature varies greatly. If depleted brine, typically used at process temperatures, is used for salt saturation, then significant heat losses can occur (O'Brien et al. 2005). In plants operating with hot brine processes, fluidized bed resaturators may be used. In fluidized bed resaturators, an internal cone holds a recirculating salt slurry. Fresh, undersaturated brine enters the cone and saturated brine falls to the bottom section of the vessel (O'Brien et al. 2005).

Minimize fouling

When untreated brine is heated, either with steam or by interchange with hotter brine, sulfates or carbonates may deposit on the heat exchanger surface (O'Brien et al. 2005). Also, shell and tube units should be regularly cleaned with inhibited acid. Plate heat exchangers should be designed to minimize fouling. Decreasing the surface area increases the fluid velocity and decreases fouling (Kananeh and Peschel 2012).

Recover waste heat from electrolysis products for brine heating

To enter the cell, the brine needs to have a temperature of 149°F to 158°F (65°C to 70°C); thus, it needs to be heated. Heat from the products (chlorine, hydrogen) can be recovered to preheat the brine.

Diaphragm cell plants use direct contact heat exchangers to heat brine by cooling the generated hydrogen. Heat is saved while the chlorine contained in the gas remains inside the process (O'Brien et al. 2005). Deposit formation is not very common when heating brine with direct contact.

CASE STUDY

Heat from the chlorine gas can be used to raise the brine temperature. In the Travancore-Cohin Chemicals (TCC) Ltd plant in Kerala, India, about 794 lb. of steam per ton caustic (397 kg of steam/tonne caustic) were used to raise the brine temperature from 140°F (60°C) to 194°F (90°C). By using the hot chlorine gas at 176°C (80°C) coming out of the electrolyzer in a recuperator, the feed brine could be preheated from 140°F (60°C) to 154°F (68°C), reducing steam consumption by 63%. The investment had a payback time of 0.9 years.

Source: National Productivity Council (NPC). (2017). Good practices manual: Chlor-alkali sector.

https://www.npcindia.gov.in/NPC/Uploads/Competencies/Manual%20Chlor-alkali%20Sector.pdf

Recover waste heat from cell rooms for brine heating

The brine temperature decreases due to heat losses in the brine system and the addition of dissolving water at a lower-than-the-process temperature. Heat can be added to the brine, using either shell-and-tube-type or plate-type heat exchangers. A robust operation can be achieved with cupronickel tubes in carbon steel shells (shell-and-tube-type) and stainless steel and titanium (plate-type) heat exchangers. In modern plants, the trend is to use plate-type heat exchangers in and around the cell area (O'Brien et al. 2005).

In membrane cell plants, some of the waste heat generated on the cathode is usually removed by interchanging the circulating caustic solution with brine. For this application plate heat exchangers are the most efficient (O'Brien et al., 2005).

A Dutch chlorine plant recovers about 1.5 MBtu/ton Cl_2 (1.7 GJ/tonne Cl_2) from the membrane cells and uses it to heat the brine and concentrate part of the caustic solution (Scherpbier and Eerens 2021).

Adjust the brine recirculation process to limit brine heating

Chlor-alkali plants can use waste heat from the cells or from the cell products to heat the brine. It is worth checking, however, whether the brine recirculation process can be adjusted to limit the temperature drop of the hot depleted brine. Limiting the temperature drop will decrease the need for brine heating.

CASE STUDY

The chlor-alkali plant Shriram Alkali & Chemicals in Bharuch Gujarat (India) produces 69,000 tons of chlorine annually. The plant uses membrane cells. To remove the impurities, the brine undergoes primary and secondary purification, as is typical for membrane cell plants. For an optimum operation of the ion exchanger, the brine is fed at a temperature of approximately 140°F (60°C).

To maintain the brine temperature at the inlet of the ion exchange unit at 140°F (60°C), the temperature of the depleted recirculated brine was raised from a range of 162°F to 165°F (72°C to 74°C) at the exit of the dechlorination unit to 176°F (80°C) in a plate-type heat exchanger. The temperature would then drop by about 36°F (20°C) during saturation and primary brine purification (see Figure 15). However, at low load operation, because there was not enough waste steam available, an oil burning brine heater was used to raise the temperature. The burner consumed 230 tons oil/yr.

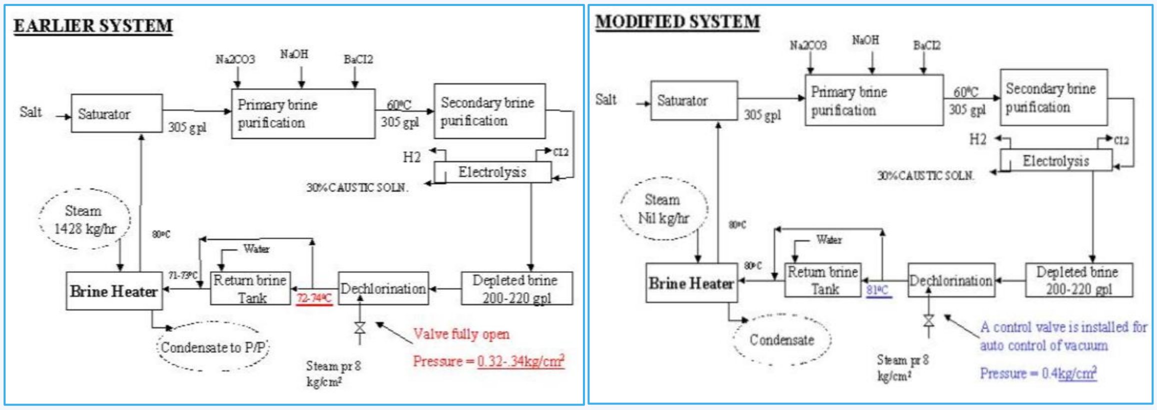


Figure 15: Original and modified brine recirculation system (PCRA n.d.)

By installing a pressure control valve in the steam line for auto control of the pressure, the pressure increased from an average 4.7 psi (0.33 kg/cm^2) to 5.7 psi (0.40 kg/cm^2), which corresponded to a brine temperature at the dechlorination outlet of 178°F (81°C). With this adjustment, the plant was able to eliminate the need to further raise the brine temperature after dechlorination, thereby eliminating oil consumption and improving steam economy. The payback time was less than 1 month.

Source: Petroleum Conservation Research Association (PCRA). (n.d). Reduction in furnace oil consumption in auxiliary boiler by process modification.

Minimize clarifier and dissolver heat losses

Due to their large size, salt clarifiers used in the chlor-alkali industry can have significant heat losses. Heat losses result in greater steam consumption for reheating brine used in the cells, but also in an uneven temperature distribution inside the clarifier (O'Brien et al. 2005). The temperature gradients can create thermal convection currents that disrupt the settling of particles.

If clarifiers are open, most of the heat losses occur at the top. By adding floating insulators (plastic foam pieces) at the top, or a cover, heat losses can be significantly reduced (O'Brien et al. 2005). Insulating the clarifier walls, with rubber for example, is another way to significantly limit heat losses.

Another source of heat losses are brine dissolvers (Brinkmann et al. 2014). Similar gains are expected if dissolvers are insulated.

Use online impurity control

Brine impurities, such as calcium and magnesium, affect the performance of membranes and can also damage the electrodes. This results in higher electricity costs and an additional cost associated with replacing the membranes more often.

Brine impurities are therefore monitored. Calcium and magnesium are measured hourly by titration, and chlorate and sulfate are also measured by titration once a day (Schmittinger et al. 2011). Sodium chloride concentrations are monitored by measuring the density using several techniques such as vibration, hydrometry, or weighing (Schmittinger et al. 2011).

The main drawback of laboratory titration is that it does not provide the results in a timely manner as brine enters the cell before the results are ready. Using online process analysis, the brine can be monitored continuously. Process analyzers monitor the hardness of the brine and can signal when impurity levels have exceeded a predefined level after the ion exchange membrane, enabling action to be taken before the membranes are affected (Lanciki 2019; Metrohm n.d.).

CASE STUDY

Andhra Sugars Ltd at the Saggonda Chemical Complex in Andhra Pradesh (India) was using a semi-automatic control system for controlling the brine temperature. By replacing it with fully automatic controls, the brine temperature could be more accurately controlled. Using a temperature of 192°F (89°C) instead of 194°F (90°C) decreased the electricity use for electrolysis by 13.2 kWh/ton NaOH. The annual cost savings reached $62,000 (5,075,000 rupees in 2017), and the investment required was about $120,000 (10,000,000 rupees in 2017). The payback period was almost 2 years.

Source: National Productivity Council (NPC). (2017). Good practices manual: Chlor-alkali sector.

https://www.npcindia.gov.in/NPC/Uploads/Competencies/Manual%20Chlor-alkali%20Sector.pdf

Use a once-through brine system

In membrane plants that use solution-mined brine as the raw material, an evaporation step is typically required to reduce the water content and reconcentrate the depleted brine. Evaporation can take place either in a vacuum plant outside the chlor-alkali plant or in an evaporation unit as part of the plant's recirculated brine treatment process. By adopting a once-through brine process, (i.e., no recirculation of depleted brine) the evaporation step can be eliminated, resulting in lower energy consumption for brine preparation (Brinkmann et al. 2014). Figure 16 shows the brine process with and without recirculation (once-through).

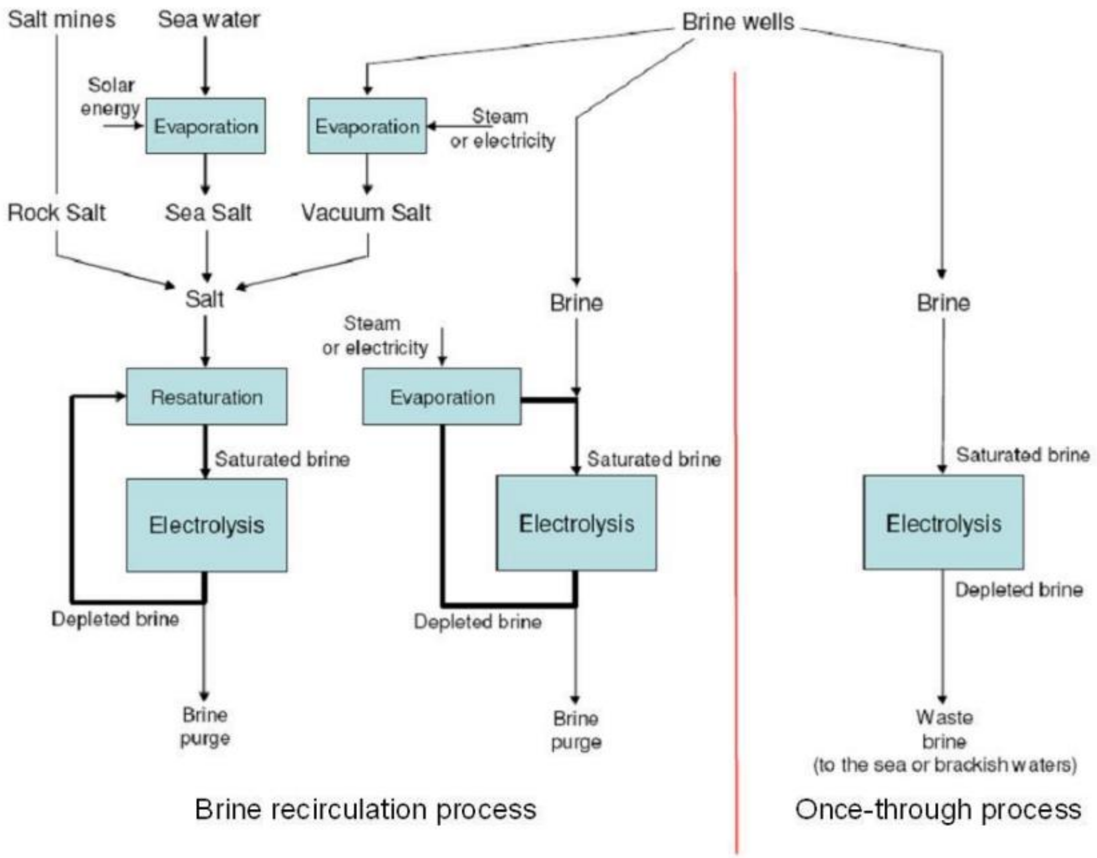


Figure 16: Schematic presentation of the brine recirculation and once-through brine process (Brinkmann et al. 2014)

To produce 1 ton of chlorine, about 1.7 tons of salt are needed. Solution-mined brine has a high water content (about 3 tons water for each ton of salt). By eliminating the evaporation step, the energy consumption can decrease. Depending on the number of evaporation stages used, energy consumption can be reduced by 1.8-3.0 MBtu/ton Cl_2 (2.1-3.5 GJ/tonne chlorine produced) (Brinkmann et al. 2014).

However, more energy will be needed to preheat the entire brine volume prior to entering the cell compared to recirculation plants that only preheat the make-up brine. Electricity use for once-through brine systems is up to 3% higher than in recirculation brine systems. This is because the cells need to operate with a lower flow rate to limit material consumption. With a lower brine temperature, this translates into a higher electricity use for electrolysis (Brinkmann et al. 2014).

A disadvantage of the once-through brine system is that it uses twice as much salt, while about half of the salt is discharged as depleted brine. Recirculation plants use 1.7 ton/ton Cl_2 while once-through plants use about 3.1-3.8 ton/ton Cl_2 and discharge larger volumes of water (9-11 ton/ton Cl_2). In addition, effluent pollution, such as chlorate, bromate, and chloride, is higher (Brinkmann et al. 2014).

The once-through method can also be applied in mercury plants; however, due to the mercury (Hg) releases from the system, this method is not currently used (O'Brien et al. 2005).

Use multiple effect evaporation

In mercury and membrane plants that use solution-mined brine as raw material, brine resaturation is achieved with evaporation. Brine evaporation is very energy intensive. The latent heat required to separate 1 ton of dry sodium chloride (NaCl) from a saturated brine solution is 5.6 MBtu/ton (6.5 GJ/tonne) (O'Brien et al. 2005). Multi-effect evaporation decreases the energy needs for evaporation. In multi-effect evaporation, the vapor produced from the solution is exploited as a source of heat, limiting steam consumption (i.e., the vapor produced in the initial evaporation unit is condensed in the heating area of the next evaporator). In this way, the latent heat of the vapor heats the second evaporation stage. Using the generated vapor as a source of heat can continue for several stages.

Table 17: Steam and energy use in multi-effect brine evaporation (Brinkmann et al. 2014)

	Number of effects		
	3	**4**	**5**
Steam use (ton/ton H_2O evaporated)	0.38	0.29	0.23
Steam use (ton steam/ton Cl_2 produced)	1.25	0.93	0.75
Fuel use[1] (MBtu/ton Cl_2)	3.0	2.2	1.8

[1] Assuming 2.1 MBtu/ton steam and a boiler efficiency for steam generation of 90%.

The number of effects that can be employed economically are usually three to six (O'Brien et al. 2005). For every new effect, the energy efficiency increases by about 10% (Scherpbier and Eerens, 2021). The energy use for three-effect, four-effect, and five-effect brine evaporation is about 3.0 MBtu/ton Cl_2 (3.5 GJ/tonne Cl_2), 2.2 MBtu/ton Cl_2 (2.6 GJ/tonne Cl_2), and 1.8 MBtu/ton Cl_2 (2.1 GJ/tonne Cl_2), respectively (Brinkmann et al. 2014).

Use mechanical vapor recompression

In mechanical vapor recompression (MVR), the vapor generated in the evaporator unit is reused by compressing it in a compressor. The steam economy in MVR can be very high, similar to a 10- or 20-effect evaporation system (O'Brien et al. 2005). There is a tradeoff between pressure increase and the heat transfer area. For lower pressure increases, electricity use is lower, but the required heat-transfer area will be larger (O'Brien et al. 2005).

Electricity use of MVR is estimated at 132 kWh/ton Cl_2 produced, or 41 kWh/ton water evaporated (Brinkmann et al. 2014). Assuming an efficiency for electricity generation of 40%, about 1.1 MBtu/ton of fuel are needed, about 48% less fuel than a three-effect evaporation unit (see Table 17). Total energy demand can be reduced by outfitting the unit with efficient synchronous motors. Electricity use can also be replaced with high-pressure steam, if available, and a steam turbine (see below under thermal vapor recompression [TVR]).

Use thermal vapor recompression

When high-pressure steam is available, TVR can be used instead of mechanical recompression (O'Brien et al. 2005). Steam pressures should exceed 3 bar and be preferably above 7 bar (NPC 2017). In TVR, a portion of the steam generated in the evaporator goes through a booster jet for recompression. Because the booster also consumes some steam, the overall steam economy in thermal vapor recompression is lower than in mechanical vapor recompression systems. A single-effect evaporation unit with TVR will have a steam economy equal to a two-effect evaporation unit (O'Brien et al. 2005). To increase steam efficiency, a hybrid system can be employed, where the excess steam is used to drive a second evaporation effect (NPC 2017; O'Brien et al. 2005).

Chapter 13: Electrolysis

In this chapter:	
Electrolytic cell	
Switch to bipolar membrane electrolyzers	Operate bipolar electrolyzers in series
Convert from asbestos diaphragm to membrane technology	Use asbestos-free diaphragms
Use high-performance membranes (zero-gap electrolysis)	Replace aging membranes with new ones
Convert to oxygen depolarized cathodes (ODCs)	Recoat cathodes and anodes when needed
Consider adding cells to lower the current density	Improve cell control
Increase electrolyte temperature	Decrease electrolyte concentration
Accurately control the brine flux	Maintain and control the structural and contact voltage drop
Avoid fluctuations	Use high-performance electrodes and coatings
Transformer-rectifier	
Use energy-efficient transformers	Place transformers closer to the load
Connect transformers in parallel	Operate transformer-rectifier systems close to the designed capacity
Use energy-efficient rectifiers	Install capacitors to improve the power factor
Install harmonic filters	

After purification, the brine is fed to the electrolytic cell. There are three main cell technologies used in chlor-alkali plants to form chlorine and caustic soda:

- Mercury cells
- Diaphragm cells
- Membrane cells

These three cell technologies differ in terms of electrode reactions and the way the products (i.e., chlorine, caustic soda, and hydrogen) are kept separate. A full description of the cell components and cell reactions classified by technology is found in Appendix A: The Chlor-Alkali Industry.

In 2020, 49.7% of U.S. chlorine capacity used diaphragm cells, 48.6% used membrane cells, 0.5% used mercury cells, and 0.9% used a different technology that electrolyzes magnesium chloride ($MgCl_2$) to produce chlorine (The Chlorine Institute 2022).

Brine electrolysis is the most energy-intensive step in chlorine and caustic soda manufacture. The most modern and energy-efficient electrolysis process is membrane electrolysis. Since its commercialization in 1975 as the first pollution-free chlorine manufacturing process (O'Brien et al. 2005), membrane electrolysis has continuously improved. Currently, membrane cells consume on average 2,000-2,400 kWh/ton Cl_2 (2,200-2,600 kWh/tonne Cl_2) (Schmittinger et al. 2011). State-of-the-art membrane cells consume a little more than 2,000 kWh/ton Cl_2, e.g. INEOS BICHLOR technology is at 2,008 kWh/ton Cl_2 (2,213 kWh/tonne Cl_2) (INEOS 2024) and e-BitaC v7 is at 2,006-2,026 kWh/ton Cl_2 (2,211-2,234 kWh/tonne Cl_2) (Thyssenkrupp, 2023) at 6 kA/m^2. Nevertheless, it is still an energy-intensive process, and any further reduction in electricity consumption will yield major economic and environmental benefits.

Diaphragm cells are generally more energy intensive than membrane cells, consuming approximately 2,100-2,600 kWh/ton Cl_2 (2,300-2,900 kWh/tonne Cl_2) (Schmittinger et al. 2011). However, diaphragm cells can be less energy intensive than membrane cells (< 2,180 kWh/ton Cl_2) if they are operated under low current densities, less than 1 kA/m^2 (Brinkmann et al. 2014). Although the electricity intensity can be lower or comparable to membrane cells, the diaphragm plant's overall energy intensity will be higher due to the higher steam needs for caustic soda concentration. Diaphragm cell plants require about 4.1 MBtu/ton Cl_2 for caustic soda concentration while membrane cell plants need 1.0 MBtu/ton Cl_2.

Mercury cells, with an electricity use of 2,800-3,100 kWh/ton Cl_2 (3,100-3,400 kWh/tonne Cl_2) are the most energy-intensive electrolysis technology (Schmittinger et al. 2011).

Energy Savings Checklist: Electrolysis

The energy source for brine electrolysis is 100% electricity to operate the electrolytic cell. For an efficient and stable cell operation, certain key conditions should be controlled and optimized: current density, concentration of anolyte and catholyte, brine impurities, and temperature (Schmittinger et al. 2011). In addition to the efficient operation of existing equipment, installing new, more energy-efficient cell components, e.g., advanced membrane and electrode designs, will reduce electricity use considerably. Furthermore, since transformers and rectifiers handle all the power consumed, even an incremental rectifier efficiency change can result in significant energy savings.

Two technologies have the potential to substantially decrease electricity consumption in chlor-alkali plants: The first is ODCs, where oxygen is added to the cathode to reduce H_2 to water and which can decrease electricity use by 30%; the second are fuel cells, which transform the H_2 generated as a byproduct into electricity and can offer a 20% reduction in electricity use (Delfrate and Schmitt 2010). The first technology is described in this chapter, while the second is described in Chapter 14: Product Processing.

High brine purity is key in membrane cell operations. A very pure brine at the right flow rate minimizes membrane blockages and allows the sodium to penetrate freely, increasing the current efficiency. Improving brine purity and certain brine parameters (i.e., brine temperature and flux) can decrease electricity use for electrolysis. All measures concerning improved brine preparation practices for energy-efficient electrolysis are described in Chapter 12: Brine Preparation.

Electrolysis Checklist	✓
Are cell conditions optimized?	
Are cell conditions adequately controlled?	
Are there energy-efficient technologies available?	
Can diaphragm cells be converted to membrane cells?	
Can high-performance membranes be adopted?	
Can improved cathode designs be adopted?	
Can improved electrolyzer designs be adopted?	
Are aging cell components replaced at the end of their lifetime?	
Does the transformer-rectifier system operate efficiently?	

Best Practices for Energy-Efficient Electrolysis

Switch to bipolar membrane electrolyzers

The electrolyzers used in both diaphragm and membrane cells can be classified as either monopolar or bipolar (Schmittinger et al. 2011). The predominant type used in chlor-alkali plants is monopolar (Schmittinger et al. 2011), with diaphragm plants operating more monopolar electrolyzers than the membrane plants (Brinkmann et al. 2014).

The electrolyzer refers to the different cell components and their connection. In bipolar electrolyzers, the anode of one cell unit is directly connected to the cathode of the adjacent cell unit (see Figure 17). With this construction, the intercell voltage is minimized (Schmittinger et al. 2011). These units are typically assembled in series, and the voltage of the electrolyzer is equal to the sum of the individual cell voltages (created between the anode and the cathode of each cell). Bipolar electrolyzers have high voltages and low current, resulting in lower rectification costs.

In monopolar electrolyzers, the anodes and cathodes of the different cell units operate in parallel and are not directly connected. Due to the cell arrangement, monopolar electrolyzers have low voltage and high amperage. Because the current travels longer distances, the current must be connected to every anode and cathode; thus, the voltage drop[8] in monopolar cells is higher than in bipolar cells. Ohmic losses[9] in monopolar electrolyzers are 74-93 kWh/ton Cl_2 (82-102 kWh/tonne Cl_2 or 80-100 kWh/tonne NaOH [100%]) (Schmittinger et al. 2011). The voltage drop can be limited by reducing the cell size and by placing copper contactors internally to reduce resistance (Schmittinger et al. 2011).

---

[8] Voltage drop occurs when the voltage at the end of the electrolyzer is lower than at the beginning.

[9] Ohmic losses represent the voltage drop across the electric circuit.

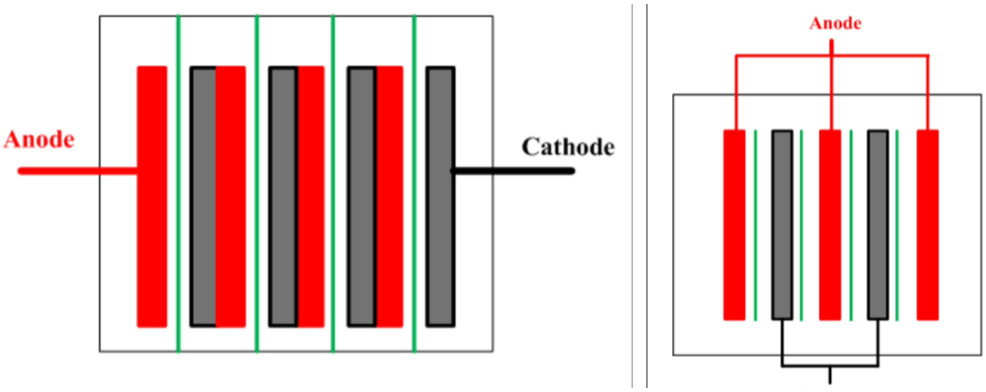


Figure 17: Bipolar (left) and monopolar (right) electrolyzers (Bommaraju and O'Brien 2015)

The first monopolar electrolyzers had a maximum current density of 4 kA/m^2. In 2011, monopolar electrolyzers were only manufactured to maintain existing plants and new plants with small capacities (Brinkmann et al. 2014). Currently, bipolar electrolyzers can be operated with a current density of 6-7 kA/m^2. The ability to increase the current densities has caused a trend toward use of bipolar electrolyzers.

The electricity use in monopolar membrane cells ranges between 2,500 and 2,720 AC kWh/ton Cl_2, with the median being 2,540 kWh/ton Cl_2, for current densities between 1.0 and 4.0 kA/m^2 (Brinkmann et al. 2014). In bipolar membrane cells, electricity use ranges between 2,090 and 2,630 AC kWh/ton Cl_2, with the median at 2,270 AC kWh/ton Cl_2 for current densities between 1.4 and 6.5 kA/m^2.

Replacing old bipolar electrolyzers (1985 technology) with new bipolar electrolyzers (2008 and later technology) can reduce electricity consumption by at least 8% to 11% at current densities 3-4 kA/m^2 (Brinkmann et al. 2014). Table 18 lists the electricity use of bipolar electrolyzers under optimal conditions.

Table 18: Electricity use[1] in bipolar electrolyzers depending on the current density (INEOS 2024; Thyssenkrupp 2023)

		Current density (kA/m^2)
Manufacturer		**6**
INEOS	DC kWh/ ton NaOH (100%)	1,780
Thyssenkrupp		1,796
INEOS	DC kWh/ ton Cl_2[2]	2,008
Thyssenkrupp		2,026
INEOS	AC kWh/ ton Cl_2[3]	2,068
Thyssenkrupp		2,087

[1] Excluding electricity use in auxiliary equipment and downstream processes (cooling of products, liquefaction etc.)

[2] Assuming 1.128 tons of NaOH (100%) produced per ton of Cl_2.

[3] Assuming electricity losses due to electrical connections and transformer/rectifier losses of 3%.

Switching from a monopolar membrane cell or a diaphragm cell to a new bipolar membrane cell with an energy use of 2,180 AC kWh/ton Cl_2 (6 kA/m^2), electricity savings of about 360 AC kWh/ton Cl_2 are expected. Investments are estimated at \$600/ton Cl_2 (2014\$) (Brinkmann et al. 2014). Payback time will depend on the electricity prices. For current electricity prices at 8.5₵/kWh (EIA 2022a), a payback time of 16 years is expected. In the case of diaphragm cells, the energy savings will be higher due to the lower needs for caustic soda concentration, resulting in better economics.

This technology can also be used as a retrofit. In the case of existing membrane cells and if the new electrolyzers are compatible with the existing ones, only modifications on auxiliary equipment will be needed, reducing the payback considerably. For existing older technology monopolar membrane cells or diaphragm cells, transformers, rectifiers, and electrical facilities such as busbars need to be replaced (Brinkmann et al. 2014).

Operate bipolar electrolyzers in series

Although installing bipolar electrolyzers in parallel might be economically justified, there are disadvantages (O'Brien et al. 2005). Because the current flow within each cell is not always the same, when they are installed in series, and if one of the electrolyzers is damaged, there will be a current mismatch. A 10% current difference is common for such arrangements (O'Brien et al. 2005).

To maintain the same total current, the voltage will increase. In addition, because the electrolyzer damage can affect current efficiency, the current will need to increase to maintain the same throughput level. Damaged membranes need to be replaced. However, when small damages occur, electricity consumption can increase when the electrolyzers are placed in parallel. The change in electricity use is not very large, but for large chlor-alkali plants, even a 0.1% difference can cause 500 MWh/yr. higher power use (O'Brien et al. 2005).

Convert from asbestos diaphragm to membrane technology

Switching from the traditional asbestos diaphragm cell technology to the membrane cell technology can result in significant electricity and steam savings but requires a large investment due to the significant plant modifications needed. Besides the electrolyzers, other important changes concern the more sophisticated brine purification needed for use in membranes (diaphragm plants do not recirculate brine) and the handling of the higher-concentration caustic solution produced in membrane cells.

Converting to the membrane cell technology involves (Brinkmann et al. 2014):

- Changing the electrolyzers.
- Adding a second brine purification step, involving the installation of polishing filtration and ion exchangers. Sulfate removal may be needed.
- Adding brine dechlorination to protect the ion-exchange resin used in secondary brine purification.
- Modifying the caustic soda evaporators to accept high-strength, salt-free caustic soda.
- Changing transformers, rectifiers, and other equipment in the cell room.

Converting asbestos diaphragm cells to membrane can be attractive due to the lower electricity consumption, the higher concentration of caustic soda generated (33 wt.% in membrane cells, 10 wt.% in diaphragm cells), the lower steam use for evaporation when high purity 50 wt.% is needed, and the elimination of asbestos waste and asbestos emissions. The evaporative load reduces by a factor of 5 to 6, while steam use increases by the same factor (O'Brien et al. 2005). However, diaphragm plants can still be economic. This is especially the case when low-priced brine is available, energy costs are low (e.g., due to cogeneration), and there is a market for lower-concentration caustic soda (Schmittinger et al. 2011).

Currently in the United States, 50% of chlorine production takes place in diaphragm cells, of which, 91% use asbestos diaphragms and 9% use asbestos-free diaphragms (Vallette et al. 2018) (see also Table 27 in Appendix A: The Chlor-Alkali Industry). In the past decades, two U.S. plants phased out the asbestos diaphragm cells. OxyChem's Taft, Louisiana, facility, phased out the obsolete diaphragm cells in 1984 and added new membrane cells (Vallette et al. 2018). In 2014, Olin's Freeport, Texas, facility completed a new membrane chlor-alkali manufacturing plant and replaced the same amount of asbestos diaphragm capacity (Dow 2014). The same plant eliminated another 220,000 tons of asbestos diaphragm capacity in 2016. A recently issued EPA final rule will require industry to phase out asbestos diaphragm technology over the next several years (89 FR 21970).

The investment cost is significant, ranging from \$360-\$480 (2014\$) per ton yearly chlorine capacity. The conversion to membrane cells at the Anwil plant in Wloclaek, Poland, decreased electricity use by 5% and steam use by 50%. At the INEOS ChlorVinyls plant in Rafnes, Norway, electricity use was decreased by 15% and steam use by 65% (Brinkmann et al. 2014).

Use asbestos-free diaphragms

Another option in the transition away from asbestos diaphragms is the use of asbestos-free diaphragms. Main benefits are eliminating asbestos emissions and asbestos waste, and lower energy consumption and maintenance needs. De Nora Tech's Polyramix®/PMX® asbestos-free diaphragms, are composed of (1) fibers with a polytetrafluoroethylene (PTFE) polymer backbone with zirconia (ZrO_2) particles embedded in and on the PTFE and (2) free zirconia particles.

The average lifetime of non-asbestos diaphragms can exceed five years while the lifetime of asbestos diaphragms ranges from 200 to 500 days. Another advantage of asbestos-free diaphragms is stable operation even after repeated shutdowns. Non-asbestos diaphragms can be used in a zero-gap cell design with the use of expandable anodes. In this case, electricity use is about 100-150 kWh/tonne Cl_2 lower than using asbestos diaphragms. About one-third of the energy reduction is due to the new diaphragm, another third to the expandable anodes, and a final third to the improved cathodes. In addition, steam consumption for caustic soda evaporation can decrease as the cells can be operated with higher cell liquor strength (Brinkmann et al. 2014).

The total investment cost for this conversion ranges between \$11 and \$16 per tonne Cl_2 (1999\$) (Brinkmann et al. 2014). A conversion may include a diaphragm preparation facility, additional purification equipment, a polarization rectifier to avoid cathode corrosion, and a reducing agent injection system. In the United States, there are currently two plants using synthetic diaphragm cells. In 2010, Westlake's Lake Charles, Louisiana, plant converted to synthetic diaphragms, and in 2015, Westlake's Natrium, West Virginia, plant was partially converted (Vallette et al. 2018).

Use high-performance membranes (zero-gap electrolysis)

Membranes are the most important component of the membrane electrolysis cells. One side of the membrane is exposed to chlorine and anolyte and the other side to strong caustic solution at high temperatures of about 194°F (90°C). To be able to withstand such severe conditions, the ion-exchange membranes are made of perfluoropolymer (Schmittinger et al. 2011).

In general, the cell voltage of a membrane cell increases with current density and electrode distance. The cell voltage can be split into (Schmittinger et al. 2011):

i) Decomposition voltage (or reversible potential) (~2.2 V; depends on temperature, pressure, and concentration).
ii) Membrane potential between anolyte and catholyte (~0.08 V; represents the overpotential at the membrane surfaces).
iii) Electrode overpotentials for Cl_2 and H_2 (~0.05 V for Cl_2 and ~0.1 V for H_2).
iv) Ohmic drop[10] in the membrane (~0.25-0.30 V in modern cells at 3 kA/m^2).
v) Ohmic drop in the electrolytes (~0.26-0.35 V; depends on the gaps between the membrane and the two electrodes).
vi) Ohmic drop in electrodes and conductors (~20-40 mV in modern cells at 3 kA/m^2; represents the voltage drop due to unfavorable current paths along the metallic structure).

High-performance membranes are characterized by low voltage drop and high current efficiencies while they can maintain mechanical and chemical stability (Brinkmann et al. 2014). In a zero-gap membrane design, the electrolyte gap between the two electrodes and the membrane is eliminated. This eliminates the ohmic losses in the electrolytes (0.26-0.35 V). The membranes are covered with a hydrophilic layer to prevent the electrolytic gas bubbles from attaching. Zero-gap membrane cells have a cell voltage of about 2.9 V at a current density of 6.0 kA/m^2.

Existing membrane cells can be retrofitted with newer higher-performance membranes. The cost of membranes is about \$600/m^2. A bipolar electrolyzer operating at a current density of 6 kA/m^2 and with a 95% current efficiency produces annually 64 tonnes Cl_2/m^2. During a 4-year lifetime, the specific membrane costs are low, \$2/tonne Cl_2. For a monopolar electrolyzer, the membrane costs are 1.7 times higher (Brinkmann et al. 2014).

Reducing cell voltage may not be economically attractive if the steam costs in a plant are more significant than electricity costs (Brinkmann et al. 2014) because to maintain the operating temperature, additional brine heating will be needed.

Replace aging membranes with new ones

The ohmic drop in the membrane can be up to 10% to 15% of the total cell voltage (Brinkmann et al. 2014). Due to accumulation of impurities on the membrane, the ohmic drop increases, thereby increasing the total cell voltage. In addition, the accumulation of impurities decreases the lifetime of the membranes. Electricity use due to increased ohmic

---

[10] Ohmic drop, or ohmic polarization, is the voltage drop due to the resistance of the media during the current flow through the cell.

losses in the membrane and the aging of electrode coatings can increase by 3% to 4% after 3 years (Brinkmann et al. 2014). Another study (NPC 2017) estimates an annual increase in electricity use of 32 kWh/ton NaOH.

To maintain the designed ohmic drop, the membranes should be replaced at the recommended period (i.e., every 3 to 5 years).

Convert to ODCs

Along with the production of Cl_2 and NaOH, H_2 is also produced during brine electrolysis. For every ton of Cl_2 produced, about 0.028 tons of H_2 are produced. Production of hydrogen is an inefficiency. Forming H_2 consumes energy, estimated at about 890 kWh/ton Cl_2 (980 kWh/tonne Cl_2) (O'Brien et al. 2005). To reclaim some of the energy used in electrolysis, the H_2 generated can be used in fuel cells or combusted in burners (see Chapter 14: Product Processing for more information on H_2 use in burners and fuel cells). Hydrogen could potentially be sold into the growing hydrogen market after it is purified.

A more efficient way to operate, however, would be to avoid the generation of H_2 by accomplishing the following reaction at the cathode:

$$2H_2O+O_2+4e \rightarrow 4OH^-$$

ODCs, also called air cathodes, can facilitate the reaction. In practice, using ODCs reduces the voltage of a conventional membrane cell of 3.0 V with a current intensity of 4 kA/m^2 by about 30% (Moussallem et al. 2012). Electricity consumption is expected to decrease by 590-890 kWh/tonne Cl_2 (650-980 kWh/tonne Cl_2) (Li et al. 2014; O'Brien et al. 2005; Scherpbier and Eerens 2021). In addition, energy losses from handling (e.g., H_2 cooling) or using (burners or fuel cells) are also avoided. The need for oxygen limits the energy savings and cost advantages. The theoretical oxygen consumption is 0.225 tons/ton Cl_2 (O'Brien et al. 2005).

The investment needed is reported to be in the range of \$85-\$120/tonne Cl_2 (Brinkmann et al. 2014). Whether the technology is cost-effective or not will depend on the electricity prices, the costs for oxygen production, and whether H_2 is preferred as an electrolysis product (e.g., when used for chemical reactions).

According to Schmittinger et al. (2011), ODC cells have a simple operation as they are insensitive to current changes and can use less-expensive, off-peak-time electricity. The ODC electrolyzer is operated at 4 kA/m^2 and for a corresponding cell voltage of 2.0-2.2 V (Chavan et al. 2015). The first ODC membrane demonstration plant (annual capacity: 22,000 tons Cl_2) was put into operation in 2011 at the Covestro Krefeld-Uerdingen (formerly Bayer Material Science AG) plant in Germany (Covestro 2017). The technology was commercially implemented at Covestro's plant in Tarragona, Spain (see case study below). The ODC technology is exclusively marketed by Thyssenkrupp Nucera (Thyssenkrupp 2023).

CASE STUDY

In February 2023, the first industrial scale chlor-alkali plant that solely uses ODC technology started operation in Tarragona, Spain. Construction started in 2018. Because of the lower voltage needed, the electricity used for electrolysis is about 25% less than in conventional membrane cell plants. It is expected that the new plant will avoid about 24,250 tons (22,000 metric tonnes) of CO_2 (based on the plant's energy mix) annually.

The Cl_2 produced at the Tarragona industrial site is used to produce MDI, a material required to manufacture polyurethane foams used in building insulation and refrigerating devices.

Source: Covestro. (2023). Covestro successfully starts up a new world-scale chlorine plant in Tarragona.

https://www.covestro.com/press/covestro-successfully-starts-up-a-new-world-scale-chlorine-plant-in-tarragona/

Recoat cathodes and anodes when needed

Aside from replacing the membranes when necessary, the anode and cathode pans need to be recoated and replaced when their condition has deteriorated. In this way, the cell voltage can be maintained close to the design level. To maintain the voltage drop at the design level, anodes and cathodes should be recoated at the recommended period, about every 8 years (NPC 2017).

Consider adding cells to lower the current density

The electricity needed for electrolysis increases linearly with the operating cell current density. At higher current densities energy consumption is higher, and at lower current densities energy consumption is lower. The energy consumption can thereby decrease by operating the cells at lower current densities while adding more cells to maintain production at the same level.

The payback time for adding more cells depends on electricity prices. An India-based study estimated the payback time to be 3-4 years (NPC 2017).

Improve cell control

In addition to the cell configuration and type of cell components used, cell operating parameters significantly affect power consumption. Table 19 shows important operating conditions of membrane cell plants. To minimize electricity consumption during electrolysis, the operating conditions should be carefully controlled and cells configured appropriately.

Table 19: Typical operating condition in membrane cell plants (O'Brien et al. 2005)

Parameter	Allowable range	Typical value
Feed brine concentration	270-305 gpl	300 gpl
Exit brine concentration	190-230 gpl	200 gpl
Feed brine pH	< 11.6 at 73°F (23°C)	
Exit brine pH	> 2	2-4
Feed NaOH concentration	28-32% (w/w)	30%
Exit NaOH concentration	30-33% (w/w)	32%
Exit caustic solution temperature	176-194°F (80-90°C)	189°F (87°C)
Exit brine temperature	176-194°F (80-90°C)	189°F (87°C)
Differential pressure	5-30 mbar	20 mbar
Current density	1.5-6 kA/m^2	

Key parameters are current density, feed flow rate, brine and caustic soda concentrations, and operating temperature. Dias (2013) found that the optimum cell voltage value is obtained for higher feed flow rates (150mL/min), higher sodium chloride concentrations (300 g/L), lower sodium hydroxide concentrations (26 wt.%), and higher temperatures (167°F/75°C).

Increase electrolyte temperature

The electrolysis process should be conducted so that energy consumption is minimized. For the electrical conductivity to be high, membranes should operate at high temperatures (O'Brien et al. 2005). The parameters affecting power consumption the most are cell temperature and brine concentration (Dias 2013). The lower electricity consumption at higher temperatures can be explained by the improved internal kinetic processes and the higher conductivity of NaCl and NaOH.

Operating at high temperatures decreases the cell voltage drop. For every 1% of temperature increase, the cell voltage drops by 5 to 10 mV (NPC 2017). A temperature decrease of 2°F (1°C) of the feed brine or caustic solution can increase cell electricity consumption by 5-6 kWh/ton (IREDA 2003).

Decrease electrolyte concentration

Cell voltage changes with the electrolyte concentration. For every 1% increase in concentration, the cell voltage increases by about 20 mV (NPC 2017). Changing the concentration should be done carefully. Maintaining the correct level is critical to achieve the desirable rate of osmotic water transport and the right equilibrium water content in the polymer (O'Brien et al. 2005), see Table 19. A 1% higher caustic soda concentration can increase cell electricity consumption by 13-14 kWh/ton (IREDA 2003).

Accurately control brine flux

Another important parameter is the brine flow rate. The overall cell performance significantly increases as the brine concentration increases (Dias 2013). With high brine flow rates, the temperature and electrical conductivity of the medium increases. When the brine flow rates are too low, high cell voltages are created that are higher than the most efficient cell voltage (3.1-3.7V) (Hung et al. 2017).

In diaphragm cells, a major problem is the contamination of NaOH with chlorate. Contamination with chlorate inhibits hydrogen evolution and can increase the electricity use during electrolysis by more than 5% (Lima et al. 2010). Chlorate formation depends on the brine flux and caustic soda generation. At higher brine flow rates, with NaOH generation at low concentrations, the chlorate formation is low. When the NaOH concentrations increase, chlorate formation also increases. Improved control of the brine/liquor flux can help reduce chlorate formation and energy consumption (Lima et al. 2010).

Maintain and control the structural and contact voltage drop

At the commissioning of new chlor-alkali cells, the structural and contact voltage drops should be recorded and benchmarked (NPC 2017). Future voltage drops should then be compared at any point with the benchmarked values, and any deviations should be further assessed.

Avoid fluctuations

Fluctuations in the operating conditions will result in unstable cell operation with low current efficiency (Schmittinger et al. 2011). Caustic soda strength fluctuations above a certain optimum range should be especially avoided as NaOH highly affects electricity consumption. Upsetting the brine feed will also impact cell performance. Figure 18 shows the cell voltage and current efficiency under varying NaOH concentrations.

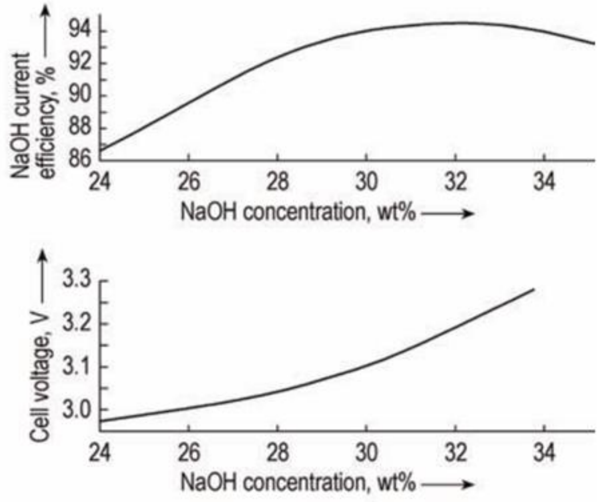


Figure 18: Impact of NaOH concentration on current efficiency and cell voltage (Schmittinger et al. 2011)

Use high-performance electrodes and coatings

As with membranes, using improved-performance electrodes and coatings can improve cell operation and decrease energy use. Electrodes and coatings can improve gas release and lower electrode potentials (Brinkmann et al. 2014).

In the case of diaphragm cells, using expandable anodes allows cell operation at a 3-mm gap between the two electrodes, resulting in significantly lower energy use. Currently, very few plants still operate without expandable anodes (Schmittinger et al. 2011).

In the case of membrane cells, the most important aspects are supporting the membrane and releasing the gas at the back of the cell. In this way the electrical resistance caused by gas bubbles can be reduced (Schmittinger et al. 2011). The eBiTAC-v7 has a fine anode mesh with a smooth surface that allows for a smoother gas release. This leads to an improved current distribution across the anode and a lower cell voltage.

Using active cathode coatings lowers the overpotentials by 200-280 mV (Schmittinger et al. 2011). Due to the high investment costs, changing the coatings is carried out when recoating is required (Brinkmann et al. 2014). The anode coatings of diaphragm cells have a lifetime of more than 12 years (Brinkmann et al. 2014). The anode and cathode coatings of membrane cells have a lifetime of more than 8 years.

CASE STUDY

Andhra Sugars Ltd at the Saggonda Chemical Complex in Andhra Pradesh (India) recoated the anodes and cathodes of the membrane cells and decreased cell voltage by 31 mV. The electricity use decreased by 18 kWh/ton of caustic. Changing the membranes decreased the electricity use by another 32 kWh/ton caustic. The investment cost was about $230,000 (12,500,000 rupees in 2017), and the payback time was 6.5 years.

Source: National Productivity Council (NPC). (2017). Good practices manual: Chlor-alkali sector.

https://www.npcindia.gov.in/NPC/Uploads/Competencies/Manual%20Chlor-alkali%20Sector.pdf

Increase capacity for peak shaving

The levels of chlorine production at a chlor-alkali plant can be adjusted to respond to electricity pricing. Reducing electricity consumption quickly during peak hours is called *peak shaving*. When electricity prices are high, chlorine production can be reduced. When electricity prices are low, production can increase. This practice is not only financially attractive, but it can also lead to a decrease in the indirect CO_2 emissions since the practice promotes the direct consumption of electricity generated from renewable sources.

Peak shaving requires the flexible operation of the chlorine plant. The flexibility of plant operations will depend on the available chlorine and caustic soda storage capacities and on the extra production capacity (Scherpbier and Eerens 2021). The investment costs needed involve the extra capacity that needs to be handled, such as extra storage, and investments in information and communication technology (ICT) (e.g., computers and software). After the initial investments have been made that make flexible operation possible, the main change on the operational costs will be for ICT.

CASE STUDY

The Nobian chlor-alkali plant in Rotterdam, the Netherlands, cooperated with an energy company, Vattenfall, to enable flexible chlorine production to match the availability of electricity supplied from renewable sources. The process is fully automated, and it facilitates the addition of up to 40 MW of renewable electricity to the grid.

Source: Nobian. (2021). Sustainability report 2021.
https://cms.nobian.com/uploads/Content%20pages/Sustainability/Sustainability-Report-Nobian-2021.pdf

CASE STUDY

The Nobian Delfzijl chlor-alkali plant in the Netherlands made changes in process control systems and increased automation to enable flexible operation. In 2022, the plant increased plant flexibility from 30% to 50% in just 15 minutes.

Source: Nobian. (2022). Sustainability report 2022. https://cms.nobian.com/uploads/Downloads/Sustainability-Report-Nobian-2022.pdf

Transformers-Rectifiers

Use energy-efficient transformers

There are two types of transformers used: high voltage power transformers that bring electricity to the plant and a series of lower voltage step down transformers that provide the voltage required to the electrolyzer. Old transformers have an energy efficiency of 93% while newer, energy-efficient transformers have efficiencies of 97% to 98% (NPC 2017; O'Brien et al. 2005). The chlor-alkali industry typically uses large transformer units with high efficiencies.

Place transformers closer to the load

Distribution losses in cables can be minimized by having the transformers closer to the loading center (NPC 2017).

Connect transformers in parallel

Under fluctuating loads, it is more efficient to use the transformers in parallel and not in series (NPC 2017). If the transformers are connected in parallel, when loads fluctuate, the load changes will be the same for all transformers. In this way all transformers will operate closer to their maximum efficiency.

Operate transformer-rectifier systems close to the designed capacity

Although a certain amount of current and voltage overdesign is needed for maintaining product throughput, it should be limited (O'Brien et al. 2005). With aging, the current efficiency of the electrolyzers decreases. To compensate for the lower production yield, the current needs to increase. In addition, the voltage might also need to increase due to aging but also if plant expansions have occurred.

Operating the transformer-rectifier at partial load causes the system to operate below its best efficiency. Operation at 80% of the designed capacity results in relatively small efficiency losses (typically less than 0.5%), while the losses become significant as the load drops further. The efficiency loss is more than 1% at 60% load and more than 2% at 40% load (O'Brien et al. 2005).

Use energy-efficient rectifiers

Rectifiers are used in chlor-alkali plants to convert the AC current to DC. Old diode-based rectifiers have a design energy efficiency of 91% to 94% while newer thyristor-based rectifiers are at about 97% to 98% (NPC 2017). Due the better control and faster response, chlor-alkali plant designers prefer the thyristor technology for new installations (O'Brien et al. 2005).

Using new energy-efficient rectifiers will result in lower eddy-current losses and lower inductance and power losses of busbars while improving the flow coefficient and power factors (Li et al. 2014).

Install capacitors to improve the power factor

The thyristor rectifier has gained a lot of favor in the electrochemical industry. Thyristor rectifiers eliminate the use of on-load tap changers and saturable reactors and can be more accurately controlled over a larger operation range than the diode rectifiers (Buddingh and Hagemoen 2001).

The main drawback of thyristor rectifiers is the low power factor and its association with the power system harmonics (Buddingh and Hagemoen 2001), which may result in additional power costs. In thyristor rectifiers, the current is controlled either with saturable reactors or by varying the triggering of thyristors (Buddingh and Hagemoen 2001). This causes a further drop in the power factor. To avoid power factor penalties while maintaining operations under different currents, capacitors can be used. Capacitors do not consume energy, but just store it and release it.

Optimizing the plant power factor has an average payback period of 2 years (IAC 2024). In an India-based study (NPC 2017), it was reported that the payback time for installing capacitors for power loss reduction was less than 6 months.

Install harmonic filters

Compared to diode rectifiers, thyristor rectifiers generate more harmonic distortion (O'Brien et al. 2005). Harmonic distortion is a distortion of the waveform due to the combination of high-frequency harmonics with the fundamental frequency (60 Hz).

Harmonics can create several problems (Buddingh and Hagemoen 2001). As the harmonic frequencies increase, capacitors can act like a short circuit, overheat, and fail. Harmonic currents can also confuse the control system and make it unstable. Another major problem is resonance can create a pulsing energy transfer that can destroy equipment. Lastly, harmonics also affect the power factor.

Having a configuration where the capacitors are combined with a reactor to form a harmonic filter can offset some of the power loss and all other negative impacts of harmonics (Buddingh and Hagemoen 2001; NPC 2017; O'Brien et al. 2005).

The payback period on installation of capacitors for power factor improvement can be as little as 6 months.

Chapter 14: Product Processing

In this chapter:	
Chlorine	
Employ high-pressure liquefaction	Employ multistage liquefaction
Use electronic expansion valves	Clean the condenser and the evaporator when needed
Employ closed-circuit direct chlorine cooling	
Caustic Soda	
Reduce the needs for 50 wt.% NaOH	Use a four-stage caustic soda evaporation system in membrane cell plants
Increase the effects in caustic soda evaporation for diaphragm cells	Use mechanical vapor recompression for caustic soda evaporation
Properly heat and insulate caustic soda storage tanks	Properly heat and insulate piping
Hydrogen	
Combust hydrogen (H_2) for heat generation	Use H_2 in fuel cells to generate electricity and heat

To meet commercial standards, the main electrolysis products exiting the cell (i.e., chlorine, caustic soda, and hydrogen) need to be further processed.

The caustic solution generated in diaphragm and membrane cells needs to be concentrated to 50 wt.% concentration. Mercury cells produce directly highly concentrated caustic solution. Steam consumption will depend on the outlet concentration and the number of evaporation stages used. Diaphragm cells generate caustic solution with a 10-12 wt.% concentration, while membrane cells produce caustic solution with about 31-33 wt.% concentration.

Diaphragm cell plants typically use one to four evaporation stages and steam consumption ranges of 2.4-4.7 tons of steam per ton of $NaOH_3$ (100%), with the average being 3.1 tons steam/ton $NaOH_3$ (Brinkmann et al. 2014). Evaporators need to be nickel plated due to the corrosiveness of the cell liquor that contains NaCl and $NaClO_3$ (Schmittinger et al. 2011). Membrane cells use one to three evaporation stages. The steam requirements range from 0.5 to 1.5 tons steam per ton $NaOH_3$ with an average of approximately 0.7 tons steam/ton $NaOH_3$ (100%) (Brinkmann et al. 2014). The evaporators in membrane cell plants can be made of stainless steel due to absence of salt, resulting in lower corrosivity, and are smaller than those found in diaphragm plants due to the lower evaporation needs (Schmittinger et al. 2011). The multistage evaporators for diaphragm caustic solution are responsible for 20% to 35% of the overall investment, while for membrane caustic solution they account for 3% to 4% (Schmittinger et al. 2011).

To facilitate transport, chlorine needs to be liquefied. Chlorine liquefaction is an energy-intensive process consuming between 9 and 180 kWh/ton Cl_2, with the average of 45 kWh/ton Cl_2.

For chlorine evaporation, the steam use ranges from 0.1 to 0.8 tons steam/ton Cl_2 vaporized, with the average of 0.2 ton/ton Cl_2 vaporized (Brinkmann et al. 2014). Chlorine evaporation is mostly conducted by the end-use chlorine customers outside the chlor-alkali facility.

The H_2 that is cogenerated in the electrolysis cell can be combusted to generate steam and/or electricity, used in fuel cells to produce electricity, or used as chemical feedstock (e.g., production of ammonia, methanol, and hydrochloric acid). By utilizing the generated H_2, instead of simply emitting it, energy consumption will decrease.

It is not known how many plants in the U.S. emit H_2 into the atmosphere. In the EU, however, only about 10% of chlorine plants do not utilize the generated H_2 and simply emit it. The majority of the plants use H_2 as a reagent or fuel. The H_2 could also be marketed as a separate product. However, this is deemed unattractive for most chlor-alkali producers due to the investment needed to ready the product for market (e.g., purification, compressors, bottling), operational costs, additional quality controls, and associated management and accounting for the rather limited volume of H_2 produced.

Energy Savings Checklist: Product Processing

Depending on the type of cell technology used, the energy consumption for processing chlorine, caustic soda, and hydrogen will differ. Most energy is used in the form of steam for evaporating the caustic soda. Electricity is mainly used in compression, cooling, and liquefaction. Plant managers should ensure that cross-cutting equipment, such as compressors and the cooling system, operate efficiently. Additionally, the steam system is of crucial importance. The checklist below can be used to prompt conversations around finding ways to save energy and costs in evaporation, liquefaction, cooling, and other processes in product handling.

Product Processing Checklist	✓
Does the steam system operate efficiently?	
Can the evaporation stages increase?	
Does the cooling system operate efficiently?	
Is there a more efficient way to cool chlorine?	
Do the chlorine compressors operate efficiently?	
Can waste heat be recovered and reused?	
Can process byproducts (i.e., H_2) be used more efficiently?	
Can liquefaction become more efficient?	

Best Practices for Energy-Efficient Product Processing

Chlorine processing

Employ high-pressure liquefaction

Chlorine liquefaction can be conducted under different temperature and pressure levels, from high to low. When liquefying chlorine under high pressure (i.e., 102-232 psi; 0.7-1.6 MPa) with a low temperature [59°F (15°C)] water/brine cooling has the lowest overall energy consumption of all liquefaction methods (Schmittinger et al. 2011). At higher pressures, the electricity needs for compression increase, but because no cooling plant is needed, the overall energy intensity is lower. Table 20 shows the typical electricity use for compression and cooling under different pressure levels.

Table 20: Electricity consumption for chlorine compression and liquefaction (Brinkmann et al. 2014)

	Liquefaction pressure (psi)			
	14.5	**43.5**	**116**	**232**
Compression energy (kWh/tonne)	5	23	42	57
Cooling energy (kWh/tonne)	87	68	27	3
Overall energy (kWh/tonne)	*92*	*91*	*69*	*60*
Starting temperature (°F)	-33	-18	77	127
Final temperature (°F)	-44	1	57	104

Employ multistage liquefaction

Most of the chlorine can be condensed under relatively mild conditions. By adopting a multistage liquefaction process, only part of the feed gas will be subjected to more vigorous liquefaction (either at higher pressure or lower temperature), saving energy (O'Brien et al. 2005). For example, in a two-stage liquefaction process, the feed gas is initially compressed to about 240 kPa. During this stage, about 84% of the chlorine condenses. The depleted gas moving to the second liquefaction stage is about 20% of the gas processed in the first stage. This lower volume gas is now compressed to 656 kPa. If a single-stage liquefaction process was used instead, then all the feed gas would have been compressed to 656 kPa. Using a two-stage process instead of single-stage process results in about 49% lower electricity consumption (O'Brien et al. 2005).

Another advantage of multistage liquefaction is the higher yield (Schmittinger et al. 2011). In single-stage liquefaction, only 90% to 95% of the gas can be condensed. This is to keep the H_2 concentration limit below the 6% explosion limit. By using a second stage to condense the chlorine from the depleted gas, in a low-volume, strong-construction liquefier, the overall yield increases to more than 99% (Schmittinger et al. 2011).

Use electronic expansion valves

Normally, chlorine liquefaction capacity is installed based on the site configuration and upon the total chlorine load. At low liquefaction needs, thermostatic valves may lead to supercooling and an unnecessarily higher electricity consumption. Using electronic expansion valves, the refrigerant flow is more optimally controlled and can cool chlorine to the set temperature.

Clean the condenser and the evaporator when needed

Operating with a dirty condenser can increase electricity use by 20%, and operating with a dirty evaporator can increase electricity use by 11%. The overall energy use for dechlorination can be 38% higher. Liquefiers should be cleaned approximately every 2 years.

Employ closed-circuit direct chlorine cooling

Chlorine gas can be cooled indirectly in tubular titanium heat exchangers, directly in packed towers, or with a combined method in a closed-circuit direct cooling system (Schmittinger et al. 2011). The indirect method uses tubular titanium heat exchangers. The main advantages are the low chlorine condensation and the low generation of chlorine saturated water (Brinkmann et al. 2014). The condensate can be either fed directly back to the brine system or, in the case of diaphragm cells, dechlorinated by evaporation. In the direct method, water or brine is sprayed into the top of packed towers and flows counter-currently to the chlorine gas. Main advantages are better mass transfer and higher thermal efficiencies. However, the main drawback is the higher energy consumption for wastewater dechlorination (Schmittinger et al. 2011).

In the closed-circuit direct cooling method, the chlorine-rich water leaving the cooling tower is cooled in titanium plate coolers to remove the heat and reused (Schmittinger et al. 2011). Surplus condensate is fed back to the brine system like in the case of indirect cooling. With this method, the advantages of direct and indirect cooling are combined (Schmittinger et al. 2011). The needs for dechlorination are not high, as the cooling water is recycled back to the cooling process and the thermal efficiency is high.

Caustic soda processing

Reduce the needs for 50 wt.% NaOH

Commercial-grade caustic soda concentration is typically around 50%. However, depending on the customer's intended use of the caustic soda, a lower concentration may be sufficient. Delivering a lower-concentration caustic soda solution will reduce energy used for evaporation and concentration of the solution. However, note that a lower concentration may result in increased energy use and costs for shipping. Hence, before implementing this opportunity, analyze the trade-offs. In practice, if the solution is piped to an on-site or nearby user, a lower concentration solution may be viable.

Use a four-stage caustic soda evaporator in membrane cells

The caustic solution from membrane cells has a concentration of 32±1% wt.% NaOH (Schmittinger et al. 2011). If a 50 wt.% caustic soda concentration is needed, then the solution needs to undergo concentration using evaporation. Evaporation is commonly achieved in two-stage or three-stage plate or shell-and-tube evaporators (Brinkmann et al. 2014). Due to the lower evaporation needs, the evaporators used to concentrate caustic solutions from membrane cells are typically smaller than the ones used in diaphragm plants (Schmittinger et al. 2011).

In general, the chlor-alkali industry uses up to three evaporation stages for concentrating caustic soda, while for concentrating solution-mined brine more than four stages are typically used. This is because caustic solutions are characterized by a much higher boiling point rise (BPR) than salt solutions. The BPR is the difference between the boiling temperature of the caustic solution and the boiling temperature (or condensing temperature) of pure water at the same pressure (O'Brien et al. 2005). A higher BPR means that there is a lower temperature differential for heat transfer. BPRs are highly affected by the solution concentration and to a lower extent by the operating conditions such as pressure (O'Brien et al. 2005).

The caustic solution exiting the membrane cells has a BPR of 68°F (20°C), and it increases further as the solution concentrates. In a triple-stage evaporator, the BPR consumes about 160°F (70°C) of the available temperature differential. Therefore, most plants use up to three evaporation stages (O'Brien et al. 2005). In 2014, the first four-stage caustic soda evaporation system was installed in Germany (AkzoNobel 2012). It is estimated that a four-stage evaporation system requires 20% to 25% less steam than a three-stage system (Kovacs 2015). The investment costs of evaporation units increase with the number of stages. The relative investment for one-, two-, and three-stage evaporators units are 100%, 160% and 230%, respectively (Brinkmann et al. 2014).

One- and two-stage evaporation systems require low-pressure steam (~3 bar), while three- and four-stage systems need medium-pressure steam (~10 bar) (Brinkmann et al. 2014). Although adding more evaporation stages will decrease steam use, operators of chlor-alkali plants with a cogeneration unit prefer one- or two-stage evaporation. This is because it costs less to cogenerate low pressure steam and electricity instead of medium-pressure steam for three- and four-stage evaporation (Brinkmann et al. 2014). Expanding steam from 10 to 3 bar generates about 20 kWh of power.

Increase the effects in caustic soda evaporation for diaphragm cells

The caustic solution from diaphragm cells has a lower caustic concentration (10-12 wt.%) than the caustic solution from membrane cells (~32 wt.%), and therefore a lower initial BPR (O'Brien et al. 2005). The BPR rise in multistage evaporation is also lower in the case of diaphragm solutions. A lower BPR means that there is a higher temperature differential that can be used for heat transfer. This can make the four-effect evaporation system more practical than the three-effect for diaphragm caustic solutions (O'Brien et al. 2005).

Table 21 shows the typical intermediate concentration increase when using multi-effect evaporators for membrane and for diaphragm caustic solutions.

Table 21: Typical intermediate NaOH concentrations (wt.%) in multi-effect evaporation systems (O'Brien et al. 2005)

	Intermediate concentrations	
Number of effects	**Membrane**	**Diaphragm**
Two-effect	39.0%	21.0%
Three-effect	36.4%	17.6%
	42.1%	26.0%
Four-effect	-	16.3%
	-	21.0%
	-	29.6%

Use mechanical vapor recompression for caustic soda evaporation

In Chapter 12: Brine Preparation, it was shown that mechanical vapor recompression (MVR) can be used to replace multistage brine evaporation. MVR is already widely applied for salt evaporation by the salt and chlor-alkali industry (van Delft and Kler 2017). Except for brine evaporation, MVR could also be used as an alternative to multi-effect caustic soda evaporation. However, due to the higher BPR, MVR for caustic soda concentration currently is unattractive and has not been applied yet (van Delft and Kler 2017).

Power consumption in recompression evaporation depends on the increase in pressure that is necessary to achieve the needed temperature for condensation. The condensation temperature depends on the BPR of the solution to be condensed. Thereby, recompression evaporation is typically economically justified for solutions with a low BPR, such as brine solutions, and not for solutions with a high BPR, such as caustic solutions. For brine solutions, a compression ratio of about 2 is adequate, while for caustic solutions, the compression ratio should be at least 4 (O'Brien et al. 2005). This means that single-stage centrifugal compressors are adequate for brine evaporation but for caustic evaporation, more sophisticated compressors would be needed.

The caustic solution from diaphragm cells has a lower BPR than the caustic soda from membrane cells (O'Brien 2005). In an analysis conducted for a Brazilian chlor-alkali plant, adopting an MVR system with two cooling stages would decrease steam consumption by 80% while increasing electricity use by 14.3 MW (Mady et al. 2015).

Properly heat and insulate caustic soda storage tanks

Caustic soda storage tanks are heated when the ambient temperature falls below 65°F (18°C). This is because the 50% caustic soda solution begins to freeze (crystallize) at 54°F (12°C), which can block the containers and the pipelines and result in product losses. The freezing point depends on the concentration. For example, it is 41°F (5°C) for 32 wt.% NaOH and 65°F (12°C) for 50 wt.% NaOH (Brinkmann 2014).

Storage tanks can be heated with steam coils or with an electrical heating tape (PETRODMO 2004). The most common heating methods are with an external heat exchanger and a caustic recirculating pump, and with internal steam heating coils (OxyChem 2022). Using an external heat exchanger and caustic recirculation loop offers several advantages: i) easier maintenance, as the storage tank does need to be drained for inspection and repairs, and ii) improved heating, as the “hot spots” commonly found in internal steam heating systems are eliminated. When heating with internal coils, nickel or nickel alloy bayonet heating coils should be used instead of carbon and stainless steel coils due to the corrosion issues arising with steel (Olin 2022).

To maintain the right solution temperature (85°F to 100°F [29°C to 38°C]) a temperature controller should be installed. When steam coils are used for heating, placing the thermocouple at the coil level avoids wrong measurements when the tank is nearly empty and thereby overheating the caustic solution (Olin 2022).

The storage tanks should also be insulated to minimize energy losses. The insulation must be well protected with jacketing to keep it dry and minimize external corrosion of the metallic surface of the storage tank. The use of aluminum jacketing materials should also be avoided as they can be easily damaged if exposed to caustic soda. If the storage tanks are only heated with electric heat trace cabling or pads, then additional insulation might be needed to minimize the heat losses (Olin 2022).

Properly heat and insulate piping

Even if the ambient temperature drops below 70°F (21°C) for a short time, caustic soda piping must be insulated and heated. The preferred heated method is with self-regulating heating cables. In the case of intermittent flow pipes, heating with steam tracing should be avoided because the caustic soda temperature can quickly exceed 140°F (60°C), leading to high corrosion rates. For steam heating continuous flow pipes, insulators should be used to separate the steam coil from the pipe to avoid localized heating and corrosion (Olin 2022).

To minimize heat losses, piping must be properly insulated with caustic-soda-resistant materials, and the insulation should be enclosed with sheathing to minimize corrosion (Olin 2022).

Hydrogen processing

Combust H_2 for heat generation

Hydrogen has a gross heating value of 323.6 Btu/cf (EIA 2023). However, the fact that it leaves the electrolytic cell as a wet gas lowers its heating value (O’Brien et al. 2005). An energy-efficient arrangement would be to first cool the H_2 to condense some of the water, recover the heat in a heat exchanger to heat the brine (see Recover waste heat from electrolysis products in Chapter 12: Brine Preparation), and then combust it in a burner.

The H_2 gas exiting the diaphragm cells has 70% water content. By cooling the gas, the temperature drops to 104°F (40°C) with about 90% of the cooling load condensing the water. The H_2 gas from membrane cells has a much lower water content, about 30% to 35%, and only about a third as much heat needs to be removed for the gas to be cooled to 104°F (40°C).

In general, it is more attractive to use burners that can use both H_2 and conventional fuels and not burners that operate only with H_2 (O’Brien et al. 2005).

CASE STUDY

In 2014, a chlor-alkali plant in Hallabat Industrial Park, in Jordan (Middle East) installed a hydrogen boiler to reuse the hydrogen generated by the electrolytic cell. The plant produces caustic soda, liquified chlorine, hydrochloric acid, and sodium hypochlorite. The annual chlorine capacity is 21,000 tons. Annually the plant produces 578 tons of H_2, of which 271 tons are used to make HCl, 58 tons are used for controlling pressure differences, and 249 tons are released to the atmosphere.

Originally, the steam consumption amounted to 24,799 tons of steam per year, which was generated by burning diesel oil. To utilize the vented H_2, a H_2 boiler was installed. On-site H_2 utilization generated about 34% of the steam needed at full capacity. The investment in the H_2 boiler was about $420,000. The payback time was a little less than a year.

Source: Khasawneh et al. (2019). Utilization of hydrogen as clean energy resource in chlor-alkali process. Energy Exploration & Exploitation 2019 Vol. 39 Pages 1053–1072. https://journals.sagepub.com/doi/10.1177/0144598719839767

Use H_2 in fuel cells to generate electricity and heat

Using the H_2 cogenerated in the electrolysis cell to generate electricity can substantially reduce the power costs in chlor-alkali plants. Membrane electrolysis consumes on average 2,000-2,400 kWh/ton Cl_2 (Schmittinger et al. 2011). For every ton of Cl_2, 0.028 tons of high-quality H_2 are co-produced. Electrochemically converting the H_2 could potentially generate 450 kWh per ton Cl_2 (Verhage et al. 2013). That is approximately 13% of the plant's electricity demand. In addition, indirect CO_2 emissions from electricity generation or direct emissions from onsite electricity generation are also reduced.

Plant demonstrations and simulations have shown that fuel cells can be well coupled with chlor-alkali plants and provide about 20% of the electrical and about 10% of the thermal energy needs, (Guandalini et al. 2017; Li et al. 2021). The heat recovered from the fuel cell stacks can be used for low-temperature preheating. Also, by coupling the fuel cell with the chlor-alkali electrolyzer, the DC power from the fuel cells can be directly used to lower DC power consumption at the electrolyzer, avoiding AC/DC inverter electrical losses (European Commission 2019). In this configuration a DC/DC converter and a control system would need to be installed.

If oxygen depolarized cathodes (ODCs) are used (see Chapter 13: Electrolysis, Convert to oxygen depolarized cathodes (ODCs)), no H_2 is cogenerated.

CASE STUDY

In 2007, a pilot 72 kW proton exchange membrane (PEM) power plant was connected to the AkzoNobel chlor-alkali plant in Delfzijl, the Netherlands. The power plant consisted of 12 fuel cell stacks, gas treatment equipment, cooling to stabilize the stack temperature, and a power conversion system. Figure 19 shows the fuel cell system.

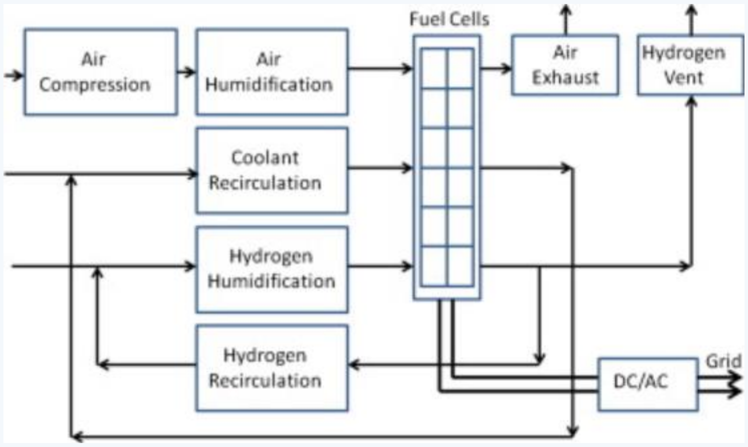


Figure 19: The fuel cell system at Delfzijl chlor-alkali plant (Verhage et al. 2013)

From 2007 to October 2012, the fuel cell operated for 30,000 hours and generated 1,400 MWh of electricity. Several reasons caused interruptions: no H_2 availability and intended and unintended fuel cell stops. Several membrane electrode assemblies (MEAs) were tested. The best MEAs allowed a 17,000-hour stack operation with an average voltage decay of 2.5µV/hour. The decay was mainly due to impurities in the anode.

Source: Verhage et al. (2013). 30,000 h operation of a 70 kW stationary PEM fuel cell system using hydrogen from a chlorine factory. https://doi.org/10.1016/j.ijhydene.2013.01.152

CASE STUDY

In 2016, a demonstration project was launched at the Ynnovate Sanzheng Fin Chemicals Co. Ltd, chlor-alkaline plant in Yingkou, China. The world's first 2 MW PEM cell was constructed and integrated into a chlor-alkali plant.

Figure 20 shows the layout of the plant. Pure H_2 leaving the electrolytic cell is humidified and fed along with humidified compressed air to the fuel cell stacks. The exhaust air is cooled down (HX4) to recover demineralized for use in the humidifiers. In a closed water loop, water is used to cool the fuel cell modules and the heat is then removed by two heat exchangers (HX2 and HX3). The first heat exchanger recovers heat that can be used on-site (e.g., for brine preheating) and the other heat exchanger is used for controlling the temperature. Lastly, a heat exchanger (HX1) provides heat for water evaporation in the hydrogen humidifier unit.

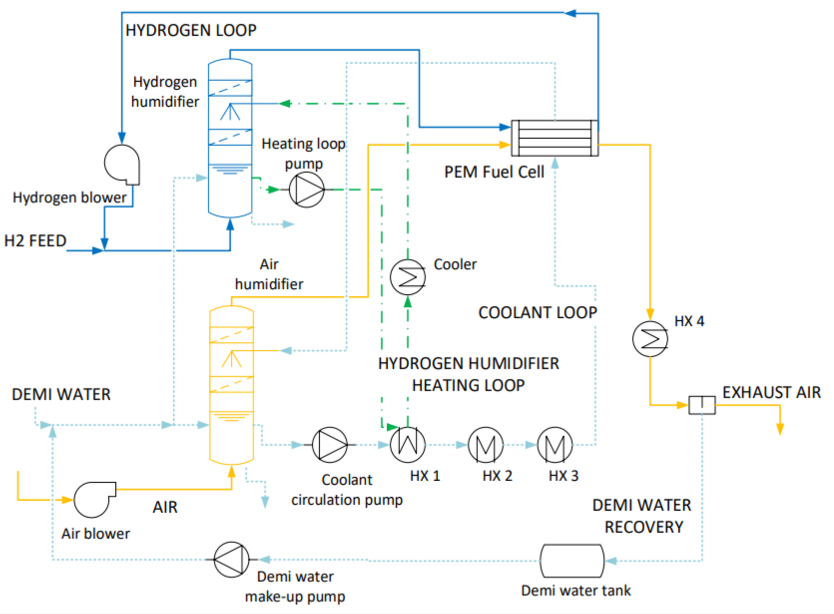


Figure 20: Layout of the PEM fuel cell system (Guandalini et al. 2017)

The project demonstrated a 20% decrease in electricity consumption while the investment required was $2,600/kWe (€3,000/kWe in 2017). The power consumption of main auxiliary equipment, mainly the AC/DC inverter and the hydrogen and air blowers was about 100 kW. To reduce the decay of the cell stacks, the hydrogen and air streams needed to be monitored, and an additional hydrogen scrubber was added.

Although there was not a full heat integration with the chlor-alkali process, the potential for heat recovery from the fuel cells was about 700 kW. Also, the electrical losses in the inverter could have been avoided if there was a direct connection with the chlor-alkali electrolyzers. In this case, a DC/DC converter and a control system should be added. In addition, the plant produces demineralized water, about 534 kg/h.

Source: European Commission. (2019). Demonstration of a combined heat and power 2MWe PEM fuel cell generator and integration into existing chlorine production plant. https://cordis.europa.eu/docs/results/621/621256/final1-final-publishable-summary-v6.pdf

Chapter 15: Decarbonizing Your Energy Use

In this chapter:	
Manage energy efficiently	Change your fuel mix
Purchase electricity from renewable sources	Self-generate renewable energy
Electrify processes	Use carbon capture, utilization, and storage

Energy usage and CO_2 emissions are inextricably linked. Combusting carbon-based fuel, such as coal, diesel, or natural gas, and using electricity results in CO_2 being emitted to the atmosphere. As the impacts of climate change are becoming more and more visible, it is important to reduce GHG emissions. A company's energy-related GHG emissions are generally categorized as *scope 1*, *scope 2*, or *scope 3* emissions. Scope 1 energy-related emissions are all direct emissions from on-site fuel use. Scope 2 emissions are released during the generation of purchased energy (e.g., electricity, steam, and heat). Scope 3 emissions are indirect emissions that occur in the value chain of the organization, either upstream or downstream of its operations. For example, the emissions from producing materials used as inputs to a company's production process or emissions associated with the use of the product made by a company are scope 3. In general, a company has complete control over its scope 1 emissions, while it can exercise influence over scope 2 and 3 emissions.

Another increasingly common term in emission reporting is a product's "embodied carbon." A product's embodied carbon can be considered the sum of an organization's scope 1, 2, and 3 GHG emissions normalized by a unit of production. More specifically, embodied carbon consists of the GHG emissions released during the extraction, manufacture, fabrication, maintenance, and disposal of a product (or service).

In some manufacturing industries, scope 3 emissions are greater than the sum of the company's scope 1 and 2 emissions. Reducing GHG emissions throughout the life cycle of a product requires a variety of strategies and approaches. However, reducing GHG emissions from a company's owned operations represents an important set of actions that can be taken now to reduce climate-related risks.

Chlor-alkali plants are electricity intensive. For this industrial sector, indirect emissions (scope 2) represent the majority of emissions if electricity is purchased from utility companies. Chlor-alkali plants with combined heat and power generation units, have larger direct (scope 1) than indirect emissions (scope 2).

In 2020, the U.S. chlor-alkali industry is estimated to have consumed a total of 130 TBtu, of which 94 TBtu was electricity and 36 TBtu was fuel (see Appendix B: Energy Consumption). Due to a lack of data, the fuel use does not take into account the fuel consumption for electricity generation. The industry's total CO_2 emissions, using the average emission factors for natural gas and the U.S. average emission factor for electricity generation, are estimated at 13.9 Mtons; 2.1 Mtons were from burning natural gas and 11.8 from using grid electricity. Accounting for cogeneration would have resulted in lower total CO_2 emissions. Due to the limited data on on-site electricity generation, it is difficult to calculate the industry's direct and indirect emissions. For more information on energy use and CO_2 emissions, see Appendix B: Energy Consumption.

Decarbonization Checklist

Electricity and fossil fuels, primarily natural gas, are used throughout chlor-alkali plants. To decarbonize the chlor-alkali industry, a variety of measures need to be adopted. These are mostly measures that deal with decarbonizing steam and electricity generation.

The first step for decarbonizing any industry is to maximize energy efficiency. Energy efficiency is normally low cost, saves money that can be reinvested in other decarbonization and process improvement technologies, and is readily available for most industries. The previous sections of this *Energy Guide* provide information on energy efficiency opportunities for cross-cutting measures (chapters 4 to 11) and for the four main chlor-alkali manufacturing process (chapters 12 to 14). Note that this guide emphasizes energy management as a way to reduce your carbon footprint. However, increased material efficiency may also reduce your scope 1, 2 and 3 emissions, as it reduces the energy needed to manufacture material or products (those that are off-spec) that would otherwise become waste. Next to reducing energy use and your carbon footprint, it will also reduce waste management costs, and may have other favorable economic benefits.

The checklist[11] below can be used to prompt conversations about finding ways to decarbonize energy consumption.

Decarbonization Checklist	✓
Are fuel and electricity managed efficiently, and are reduction opportunities identified and adopted?	
Can peak power be reduced through demand response?	
Is the purchased power generated from renewable sources?	
Can fossil fuels be replaced with low-carbon or renewable fuels?	
Is the power generated on-site produced from renewable sources?	
Can processes be electrified?	
Can carbon capture, utilization, and storage be adopted?	

Decarbonization Practices

Manage energy efficiently

Given the correlation between energy use and emissions, lowering energy use can reduce both direct and indirect emissions. For many manufacturing facilities, direct emissions (scope 1) from on-site fuel use represent the largest source of CO_2 emissions, particularly if manufacturing processes require high temperatures and have large fuel demands. For the

---

[11] ENERGY STAR offers a more in-depth decarbonization checklist for its industrial partners. For more information, contact energystrategy@energystar.gov.

electricity-intensive manufacturing industries, the direct emissions from fuel use (scope 1) may be less than the indirect emissions (scope 2) as there is a relatively low fuel consumption. This holds true if carbon emissions associated with the regional electrical grid are higher than the emissions of the fuels consumed on-site—if most electricity comes from renewables, then scope 1 emissions may still be higher.

Energy management plays an important role in reducing GHG emissions from manufacturing operations. In many industrial sectors, CO_2 emissions (scopes 1 and 2) associated with energy use at a manufacturing plant represent the largest source of emissions for the plant. In such a case, energy efficiency is an important decarbonization strategy.

A study supported by the EPA's ENERGY STAR program found that 86% of industrial carbon dioxide emissions could be reduced through a variety of existing measures, including greater energy efficiency, fuel switching, and process optimization. Of these energy-related emission reductions, across all industrial sectors, energy efficiency has the potential to reduce carbon dioxide emissions from manufacturing by up to 34% by 2050 (Worrell and Boyd 2022). Figure 21 shows the contribution of various decarbonization opportunities for U.S. industry. The size of contribution of the opportunities will vary for each industry.

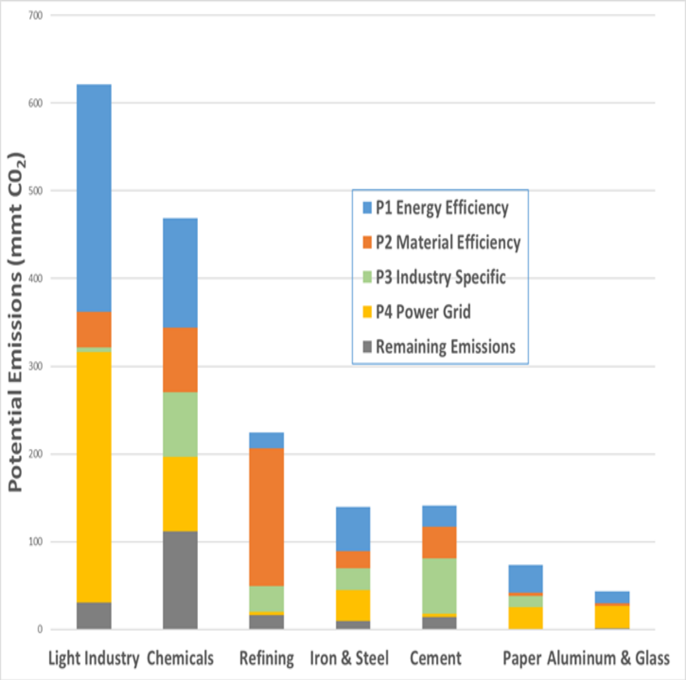


Figure 21: Breakdown of CO_2 emission reduction potentials for the main industrial sectors (Worrell and Boyd 2022)

This *Energy Guide* covers available options to better manage energy use, realize energy savings, and control GHG emissions through activities such as the following:

Operational and behavioral measures are those that are promoted through an energy management program. Chapter 3 of this guide explains how energy management practices can be incorporated in a company and how engaging employees can encourage positive behavioral changes that support energy efficiency.

Equipment upgrades involve retrofitting or replacing existing equipment with more energy-efficient technology that is commercially available and has reasonable payback periods. Chapters 4 to 11 of this *Energy Guide* address upgrades for cross-cutting equipment used in industrial facilities, such as motors, fans, compressed air, and lighting, while chapters 12 to 14 consider energy efficiency upgrades for equipment specific to the chlor-alkali industry.

Process optimization measures focus on significantly reducing the energy use of existing manufacturing processes and supporting plant utility systems. These types of measures usually require collaboration with process operators, managers, and others to identify, study, test, validate, and implement optimization measures.

Custom engineering capital projects use known technologies or approaches for improving the efficiency of plant utility systems or processes and involve more site-specific engineering work and custom designed equipment. These projects may have longer payback periods but often can deliver greater energy and carbon savings.

Process redesign identifies new manufacturing methods and technologies that use less energy or produce lower CO_2 emissions. Process redesign involves research and can have a longer time horizon for implementation. However, for many companies, redesigning how products are made will be necessary to achieve deep reductions in GHG emissions. In virtually every industry, new low-carbon processes are being developed. These are in varying stages of development and readiness.

Process redesign principles can also be applied to plant utility systems to identify lower-carbon ways to provide heat, hot water, compressed air, cooling, and other energy-related manufacturing inputs. Electrification of thermal processes or eliminating compressed air use are examples of utility process redesigns.

Change your fuel mix

Fuel switching to a lower-carbon fuel provides another option for lowering emissions. Facilities currently using carbon-intensive fuels such as coal can achieve significant reductions by switching to natural gas, which generates significantly lower CO_2 emissions. Fuel switching will often require retrofitting or replacing existing equipment and may involve significant investments. However, in some fuel switching scenarios, operating and fuel costs may be reduced.

For facilities already burning natural gas, switching to lower-carbon fuels can be challenging due to the availability and cost of alternative fuels. Potential lower-carbon fuels include:

Biogas/renewable natural gas (RNG). Biogas is gas resulting from the decomposition of organic matter under anaerobic conditions. It comes from a variety of sources, including municipal solid waste landfills, digesters at water resource recovery facilities (wastewater treatment plants), livestock farms, food production facilities, and organic waste management operations. RNG is a term used to describe biogas that has been upgraded for use in place of fossil natural gas. Natural gas produced from renewable sources is considered by some to be carbon neutral. The carbon intensity of RNG varies depending on the type of feedstock (waste) used to generate it. The Renewable Fuel Standard allows different carbon intensities for each source, while Renewable Thermal Certificates also have different carbon intensities and dollar values (MRETS 2021). In certain sectors with biomass wastes, biodigesters are installed to produce methane gas, which can be used on-site.

Landfill gas (LFG). Methane captured at landfills is considered by some to be a renewable fuel, in part because its use helps to reduce methane emissions that have a greater global warming potential than CO_2. LFG has been used as a fuel in manufacturing sites that are located near landfills with an LFG collection system (e.g., a General Motors assembly plant employs LFG collected from a local landfill). The EPA's Landfill Methane Outreach Program works cooperatively with industry stakeholders to help identify, develop, and promote the benefits of your LFG energy project.

Biomass. There is a wide range of biomass fuels, spanning from wood to agricultural byproducts. While the actual carbon content of biomass fuels may be greater than natural gas, many consider combustion emissions as carbon neutral because they do not originate from fossil fuels and the biomass was renewably grown. Various industries have biomass-based byproducts that can be used as fuel, either directly (e.g., in combustion) or indirectly through digestion or gasification (see also Biogas, above). The actual emissions from burning biomass vary greatly depending on the heterogeneity in feedstock types, sources, and production methods (EPA 2023b). The GHG protocol requires that biogenic emissions (i.e., CO_2 emissions from burning biomass) are reported separately from fossil CO_2.

Bio-ethanol. Bio-ethanol, considered a biofuel, is largely produced from corn, grain, and other natural materials. While used in the United States mainly as a fuel additive to gasoline, ethanol has not been widely used as an industrial fuel. Ethanol has powered fuel cells (direct ethanol fuel cells, or DEFC) to generate electricity. To date, most research into DEFC has been focused on motor vehicle applications.

Hydrogen (H_2). The benefit of H_2 as a fuel is that it produces no CO_2 when combusted. The use of H_2 as a fuel in manufacturing is in early stages of research, development, and deployment. The industrial H_2 market also is in its infancy, and the availability of H_2 in many parts of the United States is limited. Currently, most hydrogen produced in the United States is used for refining petroleum, treating metals, producing fertilizer, and processing foods.

H_2 can be produced in different ways and is regularly classified using a color code. The H_2 produced using renewable energy is referred to as renewable H_2 or green H_2. The H_2 produced from coal is brown H_2, and H_2 from natural gas or petroleum is grey H_2. Blue H_2 is the H_2 produced from natural gas or petroleum in combination with carbon capture and storage (CCS). Chlorine production leads to incidental production of H_2 (white H_2). The type of H_2 that is used is important because not all H_2 is considered carbon neutral. Currently, most H_2 is produced from fossil fuels, and significant CO_2 emissions are generated in that process. Further, the production of H_2 results in significant energy losses across the whole supply chain, making H_2 a relatively expensive fuel. Therefore, based on the current state of H_2 production, H_2 as a fuel should primarily be used for those processes for which no other alternative decarbonization options are available. If H_2 is used as a tool to decarbonize operations, care should be taken to procure H_2 from renewable energy sources.

Many chlor-alkali plants have modified their plant utility boiler system(s) to accept H_2 as a fuel source. To use H_2, existing equipment and burners must be modified to burn 100% or high concentrations of H_2. H_2 is also more corrosive, so pipelines and plant piping need to be designed to handle H_2. Blending H_2 with natural gas is being deployed in some places to provide lower carbon fuels, although this may lead to higher air pollutant NOx emissions. Beneficial ways of using the H_2 generated in chlor-alkali plants are discussed in Chapter 14: Product Processing.

E-fuels /synfuels. Synthetic fuels, also known as synfuels and, in the future, e-fuels, are artificial fuels produced from renewable or non-renewable sources. They have similar characteristics to conventional fuels and can be used in heating and electricity generation and in transportation.

When the synfuels are produced from renewable sources and non-fossil feedstocks, CO_2 emissions are reduced. There is a wide variety of synfuels (e.g., synthetic natural gas, gasoline, and synthetic diesel). These fuels can be produced by using electricity to convert water and CO_2 into a liquid fuel in a power-to-liquid (PtL) process. They can also be produced from natural gas or other gas feedstocks in a gas-to-liquid process (GtL). As with H_2, the production of synfuels may lead to considerable energy losses in the supply chain, making it a less attractive option, both economically and energetically.

Solar thermal. Solar thermal energy can be used to supply hot water, hot air, and steam at temperatures up to 750°F (400°C) to a variety of industries. In the U.S., most industrial process heat is needed at temperatures below 572°F (300°C) (Schoeneberger et al. 2020); thus, solar thermal energy can be used to generate heat for many types of processes. The type of solar heat generation system is strongly dependent on the geographical location and availability of direct solar irradiation. Solar thermal energy is commonly used to produce hot water, while it can also be used to produce steam (e.g., at Frito-Lay's SunChips plant in Modesto, California). Several technology variations exist. Conventional flat plate collectors (FPC) and evacuated tube collectors (ETC) can provide heat with temperatures up to 210°F (100°C). Modified FPC and ETC systems with high vacuum and concentrators can provide heat at higher temperatures, to about 390°F (200°C).

Purchase electricity from renewable sources

Part of the CO_2 emission footprint of a plant is due to emissions associated with generation of purchased electricity (scope 2 emissions). These emissions depend on the mix of power generation and energy sources by regional utilities and power generators. The EPA provides regional and state electricity grid emission factors based on the electricity generation mix in regional distribution networks through the Emissions & Generation Resource Integrated Database (eGRID) and AVoided Emissions and geneRation Tool (AVERT). Figure 22 shows the average emission factor (CO_2/kWh) from electricity generation per state (EPA 2023a).

For reporting GHG emissions, organizations should use the emission factor with the highest precision. The location-based emission factor shows the carbon intensity of the local electricity grid and is not very precise. The market-based emission factor is more precise as it shows the carbon intensity of the specific energy contract that a company has in place. If a company has purchased energy through Renewable Energy Contracts, the market-based emission factor will be lower than the local-based emission factor.

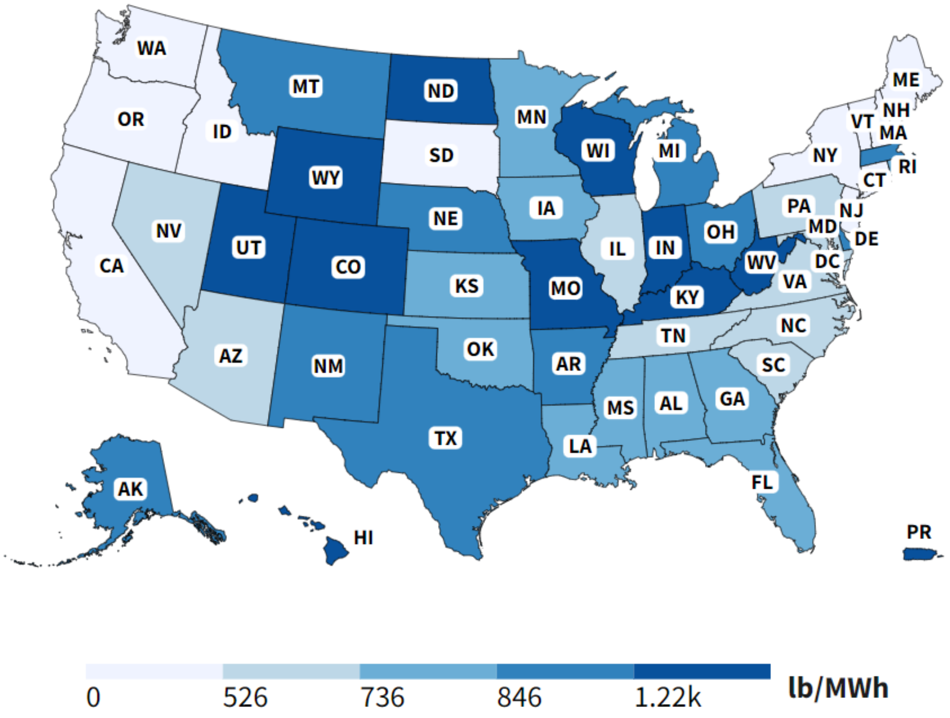


Figure 22: CO_2 total output emission rate, in lb./MWh, by state in 2021 (EPA 2023a)

The U.S. electricity grid is expected to decarbonize as older coal-fired electricity generation units are retired and more renewable sources come online. Consequently, national and regional carbon emissions and associated location-based average and residual emission factors for electricity should decline in the future. While it is difficult to predict exactly when, where, and how much grid-related emissions will decrease, recognizing that the electricity grid is expected to decarbonize in the future is important for planning decarbonization projects.

Renewable power can be procured through power purchase agreements (PPA) with dedicated renewable power suppliers. As of 2023, 29 states plus Washington D.C. authorize or allow third-party solar photovoltaic (PV) agreements (see Figure 23). The U.S. EPA Green Power Partnership offers guidance, tools, and other resources for companies interested in using renewably sourced energy.

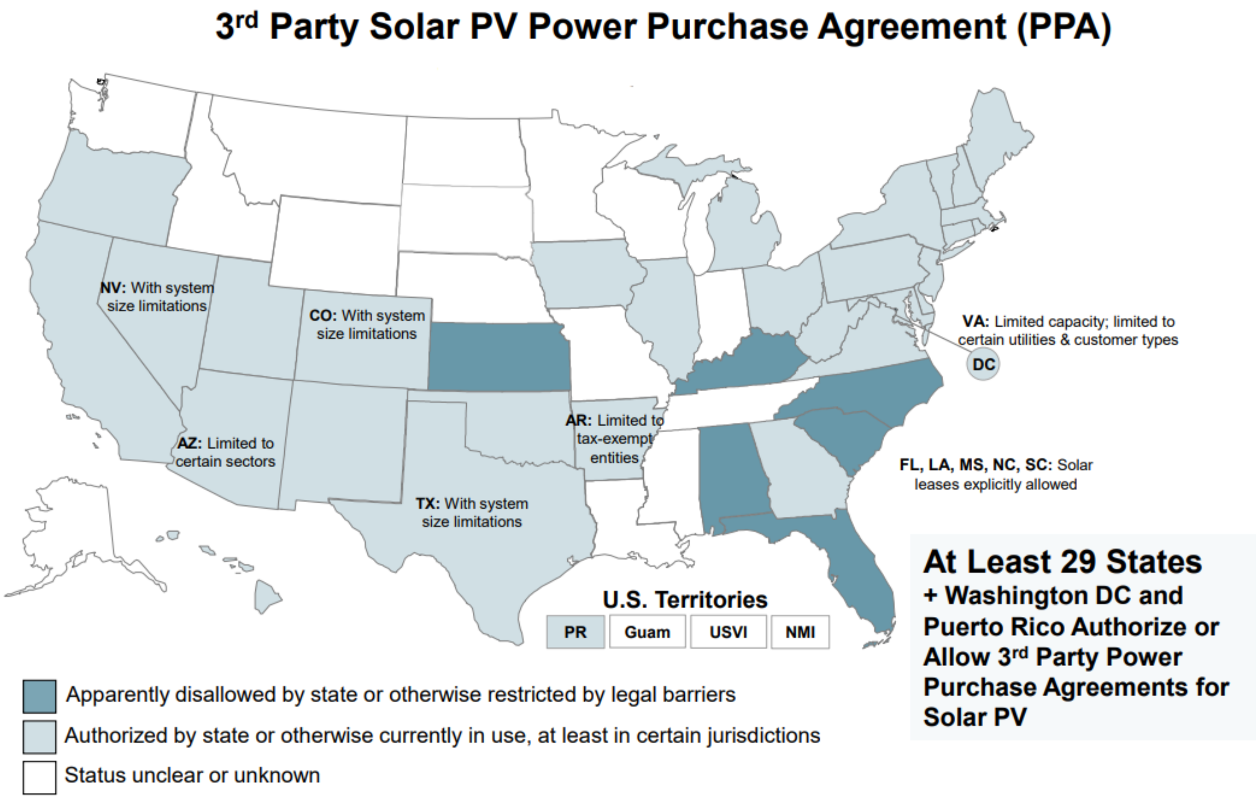


Figure 23: Third-party solar PV PPA (DSIRE 2023)

Self-generate renewable energy

On-site electricity generation from renewable sources can ensure that the energy consumed in industrial processes is sourced by environmentally efficient means (if the associated certificates are retained and not sold). On-site power generation with PVs or wind turbines is now found at many sites around the United States, ranging from PVs on warehouses or nearby brownfield sites to on-site wind turbines (e.g., California Portland's cement plant in Mojave, California).

Industrial organic waste and byproducts can be used as feedstock for bioenergy production. Organic matter in wastewater can be treated anaerobically to produce biogas, which is a sustainable energy source. Anaerobic digestion relies on microbial activity to break down organic matter in a digester to produce biogas. Biogas consists of methane (50%) and CO_2 (50%) and can be burned in boilers and gas engines as fuel. The digestor also produces a liquid effluent that can be centrifuged; the resulting biosolids can be sold as fertilizer and the liquids discharged to the sewer system.

Electrify processes

Electrification is the process of replacing technologies or processes that use fossil fuels, like internal combustion engines and gas boilers, with electrically powered equivalents, such as electric vehicles or heat pumps (IEA 2023). Heat pumps are devices that move heat from low to high temperature. Electric-driven heat pumps are a decarbonization technology suitable for supplying process heat, including low-pressure steam, to several industrial processes while improving a plant's level of heat integration and overall energy efficiency (Zhao et al. 2021).

Electrification is a special way to change a plant's fuel mix and decarbonize it, especially as electricity generation is decarbonizing rapidly. Electrification of thermal processes offers another means to reduce direct emissions from fuel use. By using electricity rather than fuel to power processes, a facility's scope 1 emissions go down. But keep in mind that scope 2 emissions will increase if electricity is powered from sources other than those that are carbon-free. To determine whether electrification helps a company reduce its overall emissions footprint, one needs to consider whether the increase in scope 2 emissions is less than the amount by which scope 1 emissions decrease. The emission factor of purchased grid electricity varies by region and even by the mix of electricity generation units used locally. Globally, fully electric plants are being seen in various industries, including Diageo's CO_2-neutral distillery in Lebanon, Kentucky, and a malting plant in the Netherlands.

Electrification can result in significant other benefits such as improved energy efficiency. For example, switching to heat pumps (or mechanical vapor compression) to provide heat will result in energy savings, while switching to electric processes may reduce on-site air pollutant emissions, leading to cost reductions and easier permitting. Globally, heat pumps have been commercially applied in virtually all industries. However, there are important engineering, power supply, and cost factors to assess when evaluating electrification options, including infrastructure requirements (e.g., expansion of transformers, sub-stations) and the availability of sufficient power capacity from the local electricity utility.

Electrification also provides a facility more leverage to implement demand response programs. Demand response programs provide utility customers the option to reduce power demand at times of high demand on the grid in return for an incentive. Options for *demand response* can be an effective way to reduce power prices and costs, if time of use pricing is more common, or if the power tariff/price is determined by your power consumption at peak hours. Depending on the processes used and the way that they are operated, it may be feasible to (partially) shut down processes at peak hours. Some electric-intensive industries already shift production to low-cost hours (e.g., batch processes such as grinding mills, electric furnaces), pre-cooling (e.g., processes in the food industry, refrigerated warehouses), or nighttime cooling of buildings by controlling the air intake during the cooler night.

Alternatively, *energy storage* may provide an option to shift part of the power demand to low-cost off-peak hours. Energy storage systems allow for the consumption of energy at a different time from the production of energy. The decoupling of energy demand from energy supply can help with the integration of higher renewable energy shares. Both electrical and thermal energy can be stored. There are several storage technology options available. It is estimated that large, behind-the-meter batteries would have a positive net present value for the chlor-alkali industry between 2019 and 2050 (Garfield et al. 2021).

Electricity typically can be stored in batteries (e.g., lithium-ion, lead acid, sodium-sulfur) or in mechanical systems such as pumped hydroelectric storage systems. Battery electricity storage enables the use of electric vehicles and supports power self-sufficiency when solar panels are in place. Thermal energy storage (TES) technologies include some simple designs, such as hot water tanks, and more advanced technologies, such as molten-salt storage, solid-state technologies, chemical looping, and composite phase change materials (CPCM). In low-temperature (< 194°F [< 90°C]) industrial processes, water tanks can be used to store heat generated from on-site solar thermal units or heat sourced from heat pumps powered by variable renewable energy. Medium- to high-temperature heat is still hard to store; new technologies, including latent systems (i.e., CPCMs) and thermochemical (e.g., salt hydration, chemical looping) storage solutions, are being developed.

When combined with the (on-site) production of *renewable power* or purchasing of renewable power, electrification offers an option for deep reductions in GHG emissions.

Use carbon capture, utilization, and storage (CCUS)

Capturing carbon emissions using a control technology installed on exhaust stacks and systems from combustion sources provides another means for reducing direct emissions, especially for those processes with CO_2-rich flue gases (such as found in the chemicals, cement, and iron and steel industries). Several types of carbon capture technologies exist, but the most common systems use an amine solvent to absorb CO_2 emissions from an exhaust stream. After the carbon has been captured, it can either be used in other processes (utilization), stored, or disposed of (sequestered) through deep well injection. Today, carbon capture and storage (CCS) is found in the refining and chemical industries where captured CO_2 is used for enhanced oil recovery (e.g., in Texas and Louisiana). CO_2 is mainly recovered from hydrogen and ammonia plants where pure CO_2 streams are available and easy to recover. It is also used by the natural gas industry in selected gas fields, as the CO_2 content of the recovered natural gas is very high. Application in other industries is still limited.

Captured CO_2 can be used. In this case, the technology is described as carbon capture and utilization (CCU). CO_2 is commonly used to make urea in the fertilizer industry, as a food ingredient (e.g., beer and soft drinks), to produce dry ice (as refrigerant), or as growth accelerants in greenhouses. In selected chemical processes, captured CO_2 can be used as a feedstock, although production volumes of these chemicals are relatively limited. Typically, the CO_2 is stored underground in depleted gas reservoirs, closed aquifers, or other locations.

CCUS systems are generally expensive to install due to high capital costs and, in the case of CCS, the need for infrastructure to transport the CO_2 to a (permitted) storage site. Therefore, facility location can greatly affect the feasibility of a carbon capture project. In North America, a few CO_2 pipelines exist that are primarily dedicated to enhanced oil recovery projects. Additionally, they can be expensive to operate due to the large energy demands of the carbon capture process. The cost effectiveness of carbon capture as a decarbonization strategy will depend on the facility, its energy and emissions profile, and the price of alternative strategies. With increased research and development (R&D) going into carbon capture systems, cost and technology options are expected to evolve over the next 10 to 20 years.

Conclusion: Why Manage Energy?

The U.S. chlor-alkali industry is energy intensive, with an annual energy expenditure of more than $1 billion. Improving energy efficiency is an important way to reduce energy costs, increase predictable earnings, and limit GHG emissions. Chlor-alkali producers should look strategically at how energy is currently used in plants, systems, and production processes and focus on the areas where the greatest savings can be generated. This guide provides many examples of cost-effective best practices to increase energy efficiency, including:

- How to create a successful energy management program that assesses and tracks energy and uses energy teams dedicated to finding and improving energy savings.
- How to assess and fix energy waste in plants, systems, and production processes, as well as at the organizational level.
- How to assess a company and its plants in relation to the current state of energy use in the chlor-alkali industry.

The most effective way to reduce energy costs is to cultivate a culture of energy efficiency. As explained in Chapter 3, establishing an energy management program creates a culture of energy efficiency, while assessing and tracking energy improves savings. When the entire energy team, plant, and company are engaged in energy management, additional cost-saving opportunities can be identified and create a process for continuous energy improvement within the organization.

The EPA's ENERGY STAR program offers tools and resources to help companies develop and continuously improve their energy management programs. These tools and resources include communication materials, assessment tools, goal setting and recognition tools, and guides to help benchmark plant energy performance and energy management practices. Companies also can become ENERGY STAR partners and receive additional benefits. You may access these tools and resources at www.energystar.gov/industry. If your company has questions or needs assistance with building a corporate energy program, please contact energystrategy@energystar.gov.

Despite what efficiency measures you may have implemented in the past, there is always room for additional cost-effective energy efficiency improvements that will pay your company back tenfold and grow your bottom line!

Acknowledgments

This work was supported by the Climate Protection Partnerships Division, Office of Air and Radiation, U.S. Environmental Protection Agency, under U.S. GSA Contract No. GS-00F-010CA, BPA 47QFDA21A0006BPA (ICF), CLIN 4 (Elizabeth Dutrow, EPA; Joshua S. Smith, ICF).

We would like to thank Robyn Brooks, Frank Reiner, and Daniel Stein (Chlorine Institute), Robert Craig and Jim Sims (INEOS), Robert Bruce Lung (Lindahl-Reed), Senthil Sundaramoorthy (Oak Ridge National Laboratory), Thomas Pagliuco (TAPco Enterprises), and Alexis Cain (U.S. Environmental Protection Agency) for their constructive support and review.

Despite all efforts, any remaining errors are the responsibility of the authors. The views expressed in this guide do not necessarily reflect those of the U.S. Environmental Protection Agency, or the U.S. Government.

Appendix A: The Chlor-Alkali Industry

The "alkaline and chlorine" industry is widely referred to as the "chlor-alkali" industry, North American Industry Classification System (NAICS) 325181 (Standard Industrial Classification (SIC) code 2812). This category includes establishments primarily engaged in the production of chlorine, sodium hydroxide (i.e., caustic soda), and other products using the electrolysis process. The primary products of the chlor-alkali industry are chlorine and sodium hydroxide. Establishments engaged in mining and beneficiating alkalis, preparing chlorine, and manufacturing hypochlorites (i.e., sodium/calcium hypochlorite) are not included.

Because chlorine and caustic soda are produced together and in fixed ratios, the production data have similar trends (see Figure 24). For every ton of chlorine produced, 1.13 tons of caustic soda is produced, together with 0.028 tons of hydrogen (O'Brien et al. 2005). Figure 24 shows the U.S. production of these two main products between 1981 and 2020 (The Chlorine Institute 2022). Chlorine and caustic soda production rose steadily during the 1990s. After 2000, chlorine production faced a steady decline until 2013. In 2020, the U.S. chlorine production reached 11.05 million tons, and the production of caustic soda was at 11.72 million tons.

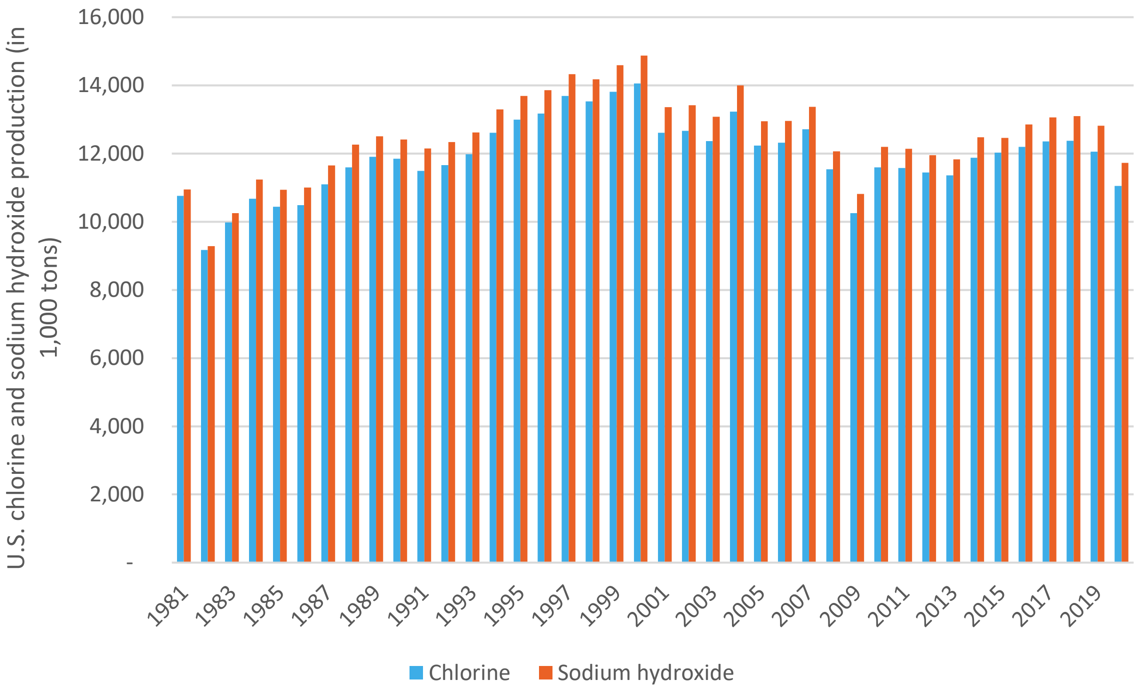


Figure 24: U.S. chlorine and caustic soda production between 1981 and 2020 (The Chlorine Institute 2022)

In the past decades, the chlorine industry faced several environmental pressures. Regulations contributed to the closure of mercury plants, and the industry switched from the mercury and asbestos-based processes to the more efficient and environmentally friendly membrane process. In addition, chlorine use in pulp and paper bleaching was reduced, while the use of certain other chlorinated products was restricted (ATSDR 2010). On the other hand, the chlorine market profited from the growing demand for other products, especially polyvinyl chloride (PVC). Almost all the chlorine produced is consumed as an intermediate product in many chemical processes. Chlorine is used to make a variety of polymers, such as PVC, polyurethanes, and polycarbonate. It is also used to produce bleach and used in cleaning agents and as a disinfectant for water. In 2006, most chlorine was used in the manufacture of organic compounds (41%), followed by the production of PVC polymers (36%), the manufacture of inorganic chemicals (15%), and water treatment (4%) (ATSDR 2010). Much of the caustic soda produced is consumed by the same industries that use chlorine, although caustic soda is consumed by a larger variety of industries. Caustic soda is used in the organic and inorganic chemical industries; in the production of alumina, soaps, and detergents; in textiles; and in water treatment (O'Brien et al. 2005).

In the United States, 99% of chlorine production takes place in electrolytic cells (The Chlorine Institute 2022). There are three main types of electrolytic cells used for commercial manufacturing (Schmittinger et al. 2011):

- Mercury cells.
- Diaphragm cells.
- Ion exchange membrane cells.

Each cell uses a different method to produce chlorine at the side of the anode that is separate from the production of caustic soda and hydrogen at the side of the cathode. Mercury cell technology, although widely used in the past, is being phased out since the Minamata Convention entered into force: UNEP Global Mercury Partnership: Chlor-alkali sector - World Chlorine Council. Only a few plants currently remain in operation. Most mercury plants will cease operating in 2025, while two plants, both outside the U.S., have a 5-year extension to 2030. In the U.S. there is only one mercury plant.

The main raw material needed in chlor-alkali plants is sodium chloride (i.e., salt). There are three main sources of salt: wells where liquid salt (i.e., brine) can be extracted; mines where rock salt can be excavated; and fields where solar-evaporated salt, mostly from seawater, can be collected. Inexpensive brine from wells can be used in diaphragm process plants, while the more electricity-intensive mercury process plants require rock salt for efficient utilization. Mercury cells can also use brine, but the brine price needs to be sufficiently low to justify this choice (Yarime 2009).

Figure 25 shows the shares of the three cell technologies in the United States and Western Europe. The industrial use of mercury and diaphragm cells for the manufacture of chlorine and caustic soda started almost simultaneously at the end of the 19th century. At first, both technologies were used in both regions, but later U.S. companies developed the diaphragm process, and Western European companies developed the mercury process. In 1972, Western Europe based its chlorine production on the mercury process (86%), and the United States based its production on the diaphragm process (72%). According to Yarime (2009), several reasons contributed to the predominance of one process or the other, with main ones being the availability of mercury for use in mercury cells and asbestos for use in the diaphragm cells, as well as the source of salt.

In Europe, large mercury reserves were available in Italy and Spain, while the United States imported asbestos from Canada, the largest world asbestos producer. In the past, most salt in Europe came from salt mines, which could explain why the mercury process became prevalent in these regions (Yarime 2009). In the United States, brine wells primarily supplied the salt that can be efficiently processed in diaphragm cells.

In the past decades, the use of mercury cell technology has been declining worldwide due to the conversion to mercury-free processes and plant closures of outdated mercury-based plants. In 1993, in the United States, there were 13 plants using the mercury process, while by the end of 2020 only one remained (EPA 2021). In 2020, 49.7% of chlorine production in the United States took place in diaphragm cells, 48.6% took place in membrane cells, and 0.5% took place in mercury cells (The Chlorine Institute 2022). As can be seen in Figure 26, during the past few decades, the U.S. chlor-alkali industry has been replacing diaphragm cells with more energy-efficient membrane cells.

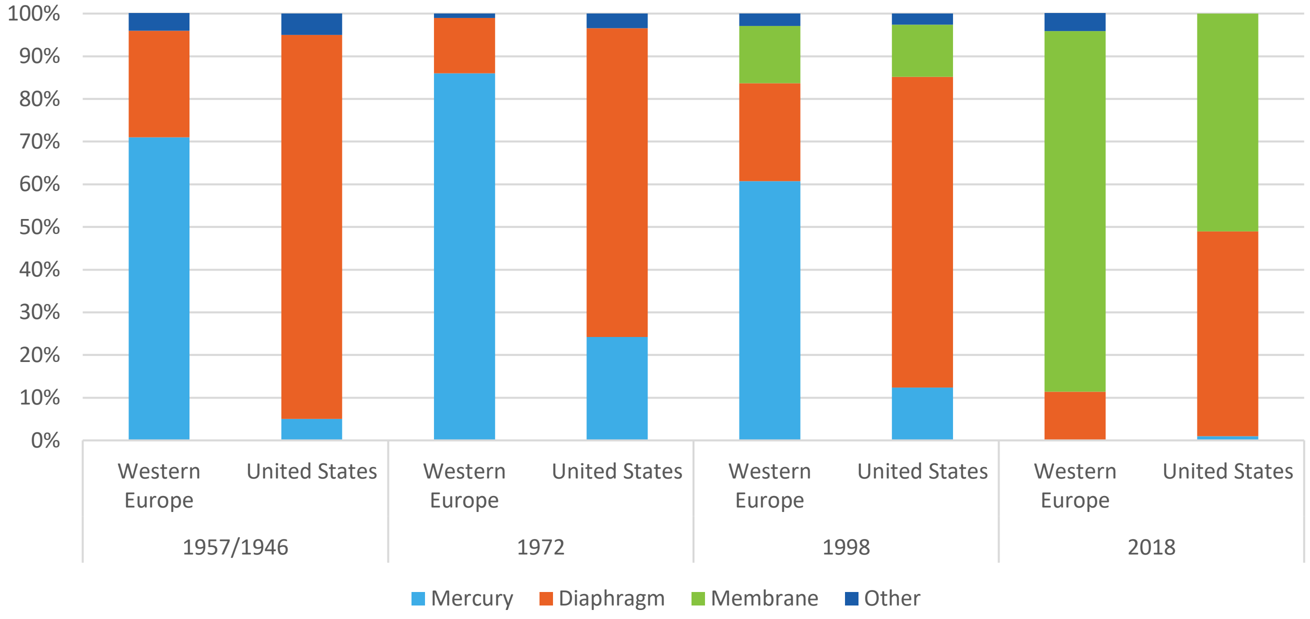


Figure 25: Shares of mercury, membrane and diaphragm processes in Western Europe and the United States in 1946/1957, 1972, 1998, and 2018 (The Chlorine Institute 2022; Vallette et al. 2018; Yarime 2009)

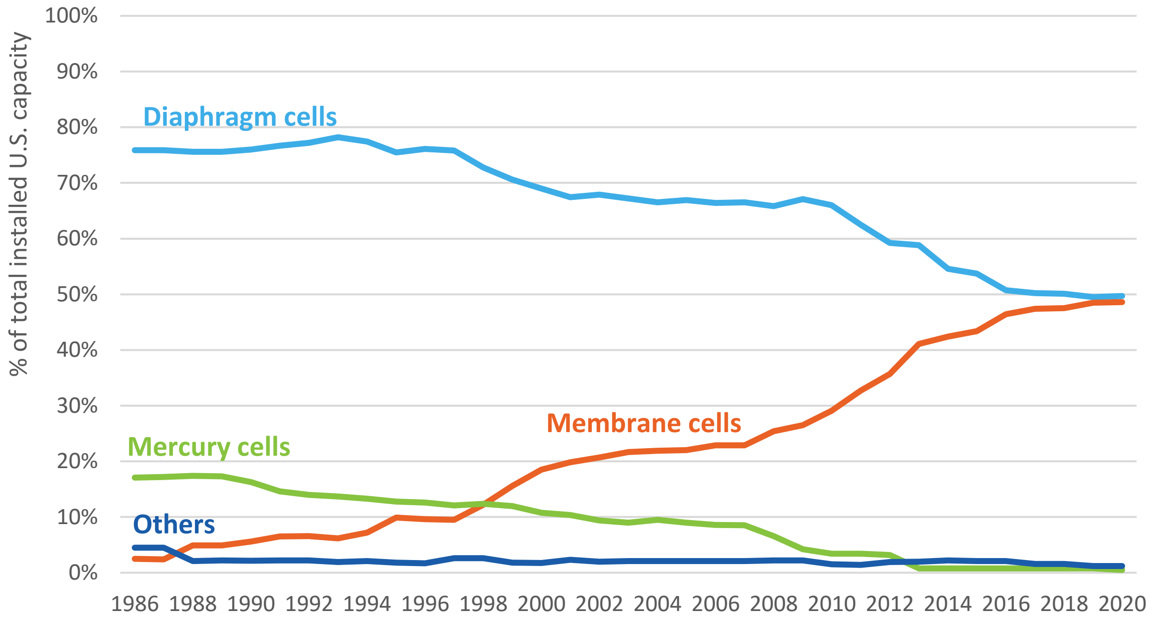


Figure 26: Use of the different electrolysis cell technologies in the U.S. chlor-alkali plants through the years (The Chlorine Institute 2022)

Table 22 lists the U.S. chlor-alkali plants along with information on production capacities and the type of cell technology used. In 2018, only INEOS KOH's (formerly ASHTA Chemicals, Inc.) Ashtabula, Ohio, plant and Westlake's Natrium, West Virginia, plant used the mercury process. In 2020, the INEOS KOH-Ashtabula, Ohio, plant ceased operation of mercury cells, which were replaced with membrane cells with an annual plant capacity of 100kt (INEOS 2022; EPA 2021). Table 27 in Appendix G: Chlor-Alkali Manufacturing Facilities in the United States lists the major U.S. chlor-alkali plants, the year of construction, their capacities, the electrolysis technologies, and the main technology conversions.

Table 22: Estimated[1] chlorine capacities per cell technology in the U.S. chlor-alkaline plants (unit: short tons) (The Chlorine Institute 2022; Vallette et al. 2018)

		Mercury	Membrane	Asbestos diaphragm	Synthetic diaphragm	Total
Occidental Petroleum	OxyVinyls – Battleground (La Porte)	-	-	590	-	590
	OxyChem – Ingleside	-	-	630	-	630
	OxyChem – Geismar	-	240	-	240	480
	OxyChem – Convent	-	-	390	-	390
	OxyChem – Taft	-	240	480	-	720

		Mercury	Membrane	Asbestos diaphragm	Synthetic diaphragm	Total
	OxyChem – Wichita	-	90	180	-	270
	OxyChem – New Johnsonville	-	180	-	-	180
	INEOS KOH – Ashtabula	-	70	-	-	70
	Covestro – Baytown	-	400	-	-	400
	Formosa Plastics – Point Comfort	-	1,000	-	-	1,000
Olin	Olin – Charleston	-	220	-	-	220
	Olin – McIntosh	-	350	400	-	750
	Olin – Niagara Fall	-	260	-	-	260
	Olin – Freeport	-	1,600	1,740	-	3,340
	Olin – St. Gabriel	-	270	-	-	270
	Olin (Blue Cube) – Plaquemine.	-	-	1,070	-	1,070
	Shintech Plaquemine	-	1,160	-	-	1,160
Westlake Corp.	Westlake – Plaquemine	-	-	470	-	470
	Westlake – Geismar	-	350	-	-	350
	Westlake – Lake Charles	-	1,130	-	270	1,400
	Westlake – Calvert City	-	280	-	-	280
	Westlake – Natrium	110	-	-	140	250
	K2 Pure – Pittsburg	-	N/A	-	-	N/A
SABIC	SABIC – Burkville	-	N/A	N/A	-	N/A
	SABIC – Mt. Vernon	-	N/A	-	-	N/A
	Total U.S.	**110**	**7,840**	**5,950**	**650**	**14,550**
	U.S. share	*1%*	*54%*	*41%*	*4%*	*100%*

[1] The capacity data listed in this Table must be treated with care as they represent the latest known capacity volumes at the time of writing (for more details, see Appendix G: Chlor-Alkali Manufacturing Facilities in the United States). Actual capacities may differ due to cell expansions and shutdowns.

As can be seen in Table 22 and Figure 27, the U.S. chlorine industry is highly concentrated. In 2020, three companies, Olin Corp., OxyChem, and Westlake Corp., owned more than 80% of the national production capacity (Vallette et al. 2018). The biggest companies rely heavily on the diaphragm process, with 10 plants out of the 25 using asbestos diaphragms, including the two largest plants in Freeport and Plaquemine.

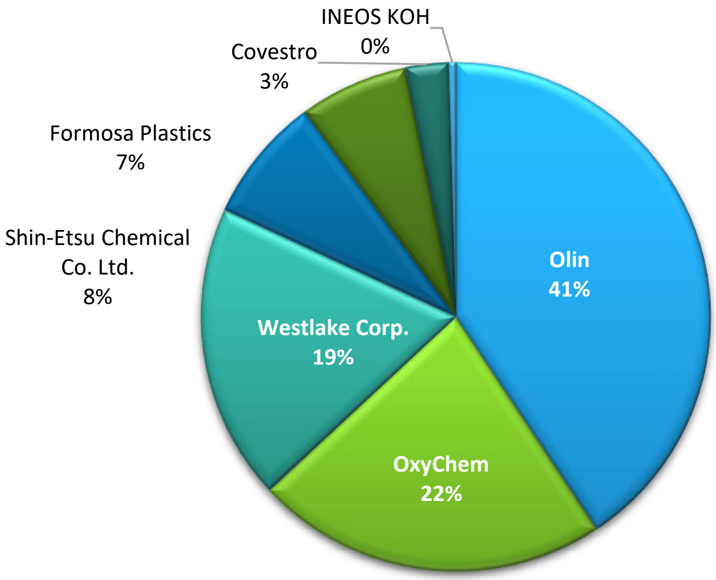


Figure 27: Estimated brand production capacity shares for chlorine production in the United States (Vallette et al. 2018)

Note: Due to the lack of data, SABIC and K2 Pure are not included in the pie chart.

The diaphragm cells use asbestos. Since 2017, chlorine plants are the last remaining consumers of asbestos in the United States (see Figure 28; USGS various years) where plants from the three largest companies, OxyChem, Olin Corp., and Westlake Corp., still consume asbestos. A recently issued EPA final rule will require industry to phase out asbestos diaphragm technology over the next several years (89 FR 21970). Asbestos mining stopped in the United States in 2002 and in Canada in 2011. Since 2011, the U.S. alkali industry relied on asbestos imports from Brazil. Currently, Brazil allows mining for export only. If Brazil forces an end to asbestos mining, another asbestos supplier will be needed, unless the industry switches to the use of asbestos-free diaphragm or membrane cells.

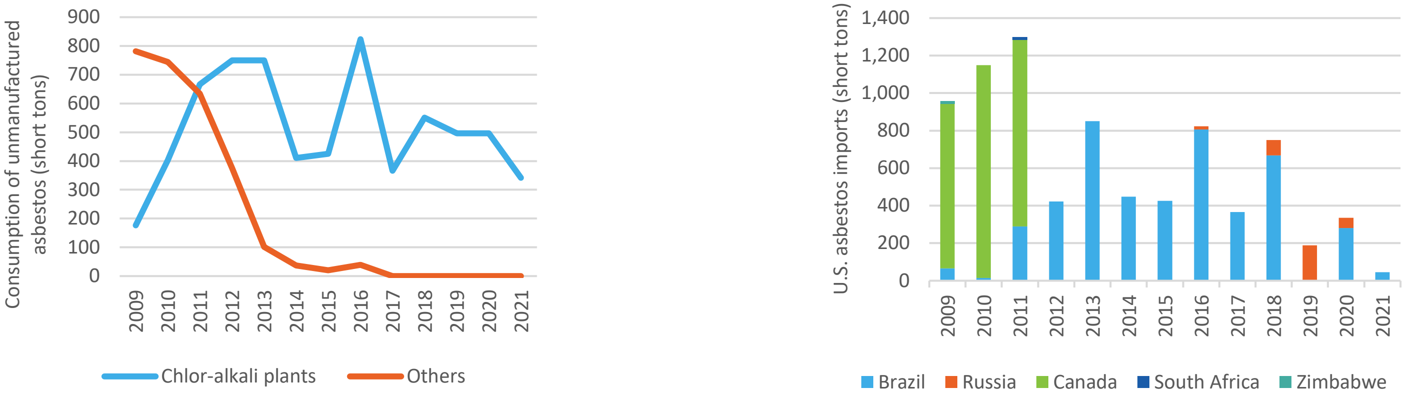


Figure 28: U.S. consumption of unmanufactured asbestos per industrial sector (left) and U.S. unmanufactured asbestos imports per country between 2009 and 2021 (USGS, various years)

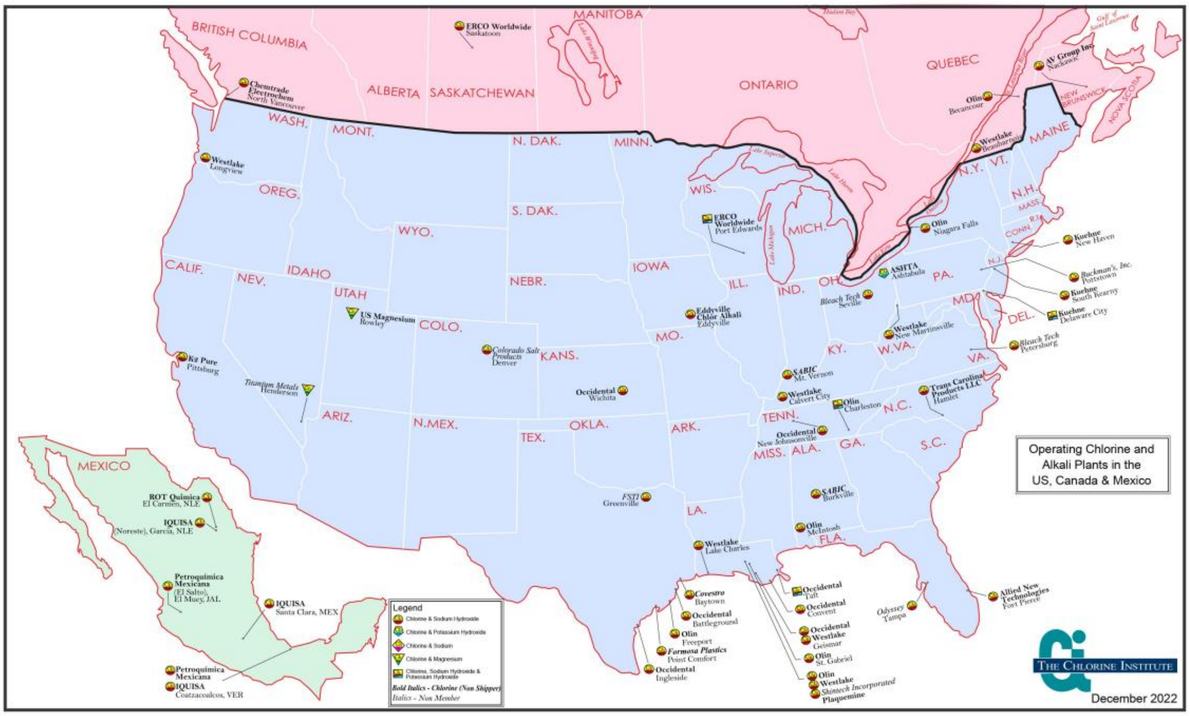


Figure 29: Location of chlorine manufacturing plants in the United States in 2020 (The Chlorine Institute 2022)

Besides salt type, asbestos is the other raw material that could have affected the geography of the U.S. chlor-alkali industry (see Figure 29), with asbestos mines situated at the northern part of the U.S. and Quebec (Stringer and Johnston 2001). Other very important parameters are the electricity prices, freight transportation considerations, and the proximity to the chlorine markets.

Process Description

This section of the *Energy Guide* describes the main processes used in the manufacture of chlorine (Cl_2) and alkali co-products (i.e., caustic soda [NaOH] and hydrogen [H_2]). The information listed below draws heavily from Ullman's Encyclopedia of Industrial Chemistry (Schmittinger et al. 2011). Any additional information is cited accordingly.

In the chlor-alkali process, brine (i.e., salty water) is electrolyzed to produce chlorine and the byproducts caustic soda and hydrogen. After chlorine is produced, it is purified and, if needed, liquified, while caustic soda and hydrogen are also processed to meet market standards.

There are three main types of electrolytic cells used: diaphragm cells, membrane cells, and mercury cells. The cell technologies differ with regard to the anode reactions and the way the different reaction products are kept separate (Schmittinger et al. 2011). The type of cell technology used dictates the upstream and downstream processes, as each cell technology has different brine requirements and generates products with different qualities.

The different manufacturing steps can be aggregated into three main processes:

1. *Brine preparation*, where the brine solution is prepared (i.e., mixed, purified, heated) so as to meet the cell requirements.
2. *Electrolysis,* where the brine is electrolyzed to produce Cl_2, NaOH, and H_2.
3. *Product processing*, where Cl_2, NaOH, and H_2 are further processed, (e.g., concentrated, cooled, compressed, liquefied) to meet market standards or other process standards.

The following paragraphs explain in more detail the three different processes. Figure 30 shows the main process steps per cell technology.

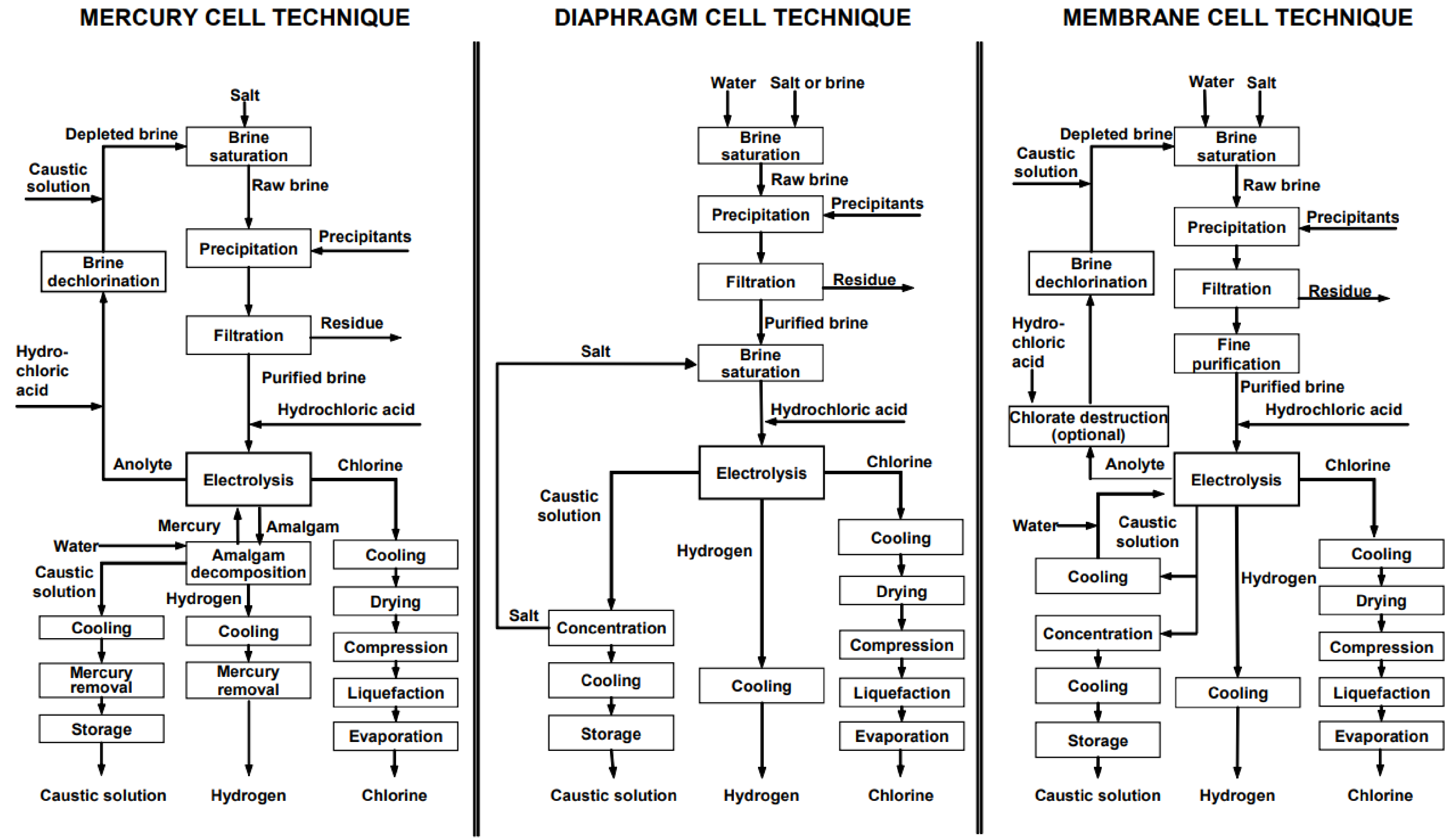


Figure 30: Main processes used in Cl_2 manufacturing in mercury cell plants, diaphragm cell plants, and membrane cell plants (Brinkmann et al. 2014)

Brine preparation

Brine is water with a high concentration of sodium chloride (NaCl), or salt. The raw material mostly used to make brine is solid salt. There are three sources of solid salt: rock salt mined from underground mines, solar salt made from the solar evaporation of sea water or brine, and vacuum evaporated salt made from purifying and evaporating mined saltwater solutions. In the United States, the type of salt most commonly used is rock salt (Schmittinger et al. 2011).

Brine saturation and resaturation

To make the brine, the dry salt is first diluted with water and/or with depleted brine from the electrolysis process (mercury and membrane cells). Some plants, however, have no brine recirculation (i.e., once-through process). In this case, the salt is simply mixed with water (Brinkmann et al. 2014). For use in diaphragm cells, solution-mined brine is mostly used. These plants have no brine recirculation, but the salt is usually recovered later in the process and maybe recycled back into the brine (Brinkmann et al. 2014). Before its use, depleted brine needs to be dechlorinated (see below, Brine dechlorination).

Older chlorine plants use open vessels or open pits to store salt as brine resaturators. Here, the depleted brine is simply sprayed onto the salt. In newer chlorine plants, the resaturators are closed vessels, where the depleted brine is fed at the base of the resaturator, and the saturated brine is removed from the top. The main advantage of closed vessel resaturators is that environmental impacts from salt sprayers and mist is avoided.

Brine purification

Depending on the source, salt composition can vary. Table 23 shows some typical compositions for rock salt and sea salt. In general, sea salt is purer than rock salt; however, sea salt is more prone to caking and mechanical degradation (Brinkmann et al. 2014). Rock salt has a higher calcium (Ca) magnesium (Mg) ratio than sea salt. A higher ratio results in improved precipitation of magnesium hydroxide.

Table 23: Typical composition of salt from various sources for use in the chlor-alkali plants (Brinkmann et al. 2014)

	Rock salt	Washed solar salt	Vacuum salt
NaCl	93-99%	99%	99.95%
SO_4^{2-}(sulfate anions)	0.2-1%	0.2%	0.04%
Ca^{2+}	0.05-0.4%	0.04%	0.001%
Mg^{2+}	0.01-0.1%	0.01%	0.0001%

The salt used by many chlor-alkali plants has already undergone some purification. For example, sea salts are usually washed to remove impurities, and vacuum salts are recrystallized from brine after the brine has been chemically treated to remove impurities. Vacuum salts contain lower impurities (99.95% NaCl).

NaCl concentrations in the saturated brine reach values of 310-315 g/l (Schmittinger et al. 2011). Ideally, the purified brine should contain cCa < 2 mg/L, cMg < 1 mg/L, and cSO_4 < 5 g/L. To achieve this, brine needs to be purified. For mercury and diaphragm cells, brine purification consists of two steps: precipitation and filtration (primary purification). For use in membrane cells, a third fine purification step is needed (secondary purification).

Primary purification

In mercury cells, Mg, and to a lesser extent Ca, can create dangerous conditions during operation, while in membrane cells, Ca and Mg ions harm the membrane. In the primary purification stage, Ca is precipitated as calcium carbonate ($CaCO_3$) with the use of sodium carbonate (Na_2CO_3—also known as soda ash). Mg is precipitated as magnesium hydroxide ($Mg(OH)_2$) with the use of sodium hydroxide (NaOH—also known as caustic soda). In this stage, metals present in the brine may also precipitate as hydroxide (Brinkmann et al. 2014).

To remove the sulfate anions, calcium chloride ($CaCl_2$) or barium salts ($BaCO_3$ or $BaCl_2$) can be used to precipitate as calcium sulfate ($CaSO_4$) or barium sulfate ($BaSO_4$) (Brinkmann et al. 2014). The barium sulfate precipitation can take place at the same time as calcium carbonate and magnesium hydroxide precipitation, while the precipitation of calcium sulfate cannot. When calcium chloride is used, a separate vessel is required (Brinkmann et al. 2014).

The use of barium salts is expensive. Other ways to reduce the sulfate content include purging part of the brine, cooling the brine and crystallizing $Na_2SO_4 \cdot 10\ H_2O$, precipitating the double salt, using an ion exchange process, and employing membrane nanofiltration. Barium salts, in general, are avoided in the case of membrane cells to protect the membrane from potential precipitation (Brinkmann et al. 2014).

After stirring the brine for about 1-2 hours, the precipitated impurities are removed, either by filtration alone or by sedimentation followed by filtration. Sedimentation takes place in large circular settling tanks where the slurry is removed by raking equipment. The filter mediums used to further remove the impurities are a sand filter, a pressure leaf filter with chlorine resistant cloths, or candle filters. The filter cake is made of 60% to 80% solids. The barium salts may be recovered by treating with sodium carbonate under pressure.

After primary purification, the brine should contain $Ca^{2+} < 2$ mg/L, $Mg^{2+} < 1$mg/L, and $SO_4^{2+} < 5$mg/L. When diaphragm cells are used, sulfate removal is not necessary as sulfate ions can be removed during the concentration process in the form of Na_2SO_4. When the raw material is vacuum salt, only a part of the brine might need to undergo primary purification, while there are some plants that skip the entire primary brine purification process (Brinkmann et al. 2014).

Finally, the brine needs to undergo acidification prior to entering the mercury or diaphragm cells. This is to increase the life of the titanium anode coating, produce a purer chlorine with higher yield, and limit the hypochlorite and chlorate formation. Acidification with hydrochloric acid increases the pH to more than 6.

Secondary purification

For use in membrane cells the brine must be further purified to avoid damaging the membrane. The impurity content should be ideally about $Ca^{2+} < 0.02$ppm, $Mg^{2+} < 0.02$ppm. This is achieved with a second purification step.

The second purification step consists of polishing filtration and brine softening in an ion exchange unit.

This filtration system uses candle type, plate frame, or pressure leaf filters, while there are cases where no polishing filter is needed (Brinkmann et al. 2014).

The ion exchange unit can decrease magnesium and calcium concentrations to less than 20 µg/L (Brinkmann et al. 2014). The specifications of impurity levels depend on whether the operation takes place at a low or at a high current density, with the more stringent specifications at higher-current densities. In addition, the specifications also depend on impurity interactions. The resins used in the ion exchange unit are periodically regenerated with hydrochloric acid of high purity and sodium hydroxide solutions.

As in the case of use in mercury and diaphragm cells, the brine heading to the membrane cells needs to undergo acidification (Brinkmann et al. 2014). Acidifying the brine with hydrochloric acid extends the lifetime of the anode coating and limits the formation of oxygen, hypochlorite, and chlorate. Over-acidification should be avoided, as it can affect the membrane selectivity and result in damage to the membranes.

Brine dechlorination

In mercury and membrane chlor-alkali plants, the depleted brine exiting the electrolysis cells is dechlorinated before used for brine resaturation.

In the case of mercury cells, the depleted brine can be only partially dechlorinated. This is because active chlorine in depleted brine keeps mercury in its oxidized form, avoiding the presence of mercury in the sludge produced from brine purification. For use in a membrane cell, full dechlorination is needed because the presence of chlorine will harm the resins used in secondary purification.

In general, depleted brine with a 0.4-1 g/L chlorine content is acidified to pH 2-2.5 and sent to an air-blown packed column or sprayed into a vacuum system of 50-60 kPa to extract the chlorine to reach a residual concentration of 10-30 mg/L.

For this purpose, the brine containing 0.4-1 g/L of dissolved chlorine is typically acidified to pH 2-2.5 and passed down an air-blown packed column or sprayed into a vacuum system of 50-60 kPa (Schmittinger et al. 2011). This reduces the chlorine concentration to about 10-30 mg/L. The collected chlorine gas is fed into the chlorine stream. The water that evaporates from the dechlorinated brine is condensed in a cooler. The condensate can return back to the brine circulation system or be chemically dechlorinated.

Complete dechlorination can be achieved by passing the brine through an activated carbon bed, by catalytic reduction, or by using chemical reducing agents such as sulphite (Brinkmann et al. 2014). The chlorine concentration levels were reported to decrease to < 0.5 mg/L or below the detection limit.

Electrolysis

In the electrolysis process, a direct current is used to electrolytically decompose the brine in an electrolytic cell. Along with the chlorine generated, caustic soda—and to a much smaller quantity, hydrogen—are produced. For every ton of Cl_2 produced, 1.07-1.13 tons of caustic soda and about 0.028 tons of H_2 are also produced (O'Brien et al. 2005). This product combination is often referred to as an "electrochemical unit" or ECU.

The overall reaction of the chlor-alkali process is:

$$2NaCl + 2H_2O \rightarrow Cl_2 + 2NaOH + H_2$$

At the anode, chloride ions are oxidized, and chlorine is formed. In all three cell types, the anode reaction is the same:

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

The cathode reaction, however, differs between cells.

In mercury cells the reaction taking place is:

$$Na^+ + e^- + Hg_x \rightarrow Na - Hg_x$$

followed by a decomposition reaction taking place in a separate reactor:

$$2NaHg_x + 2H_2O \rightarrow 2NaOH + H_2(g) + 2Hg_x$$

The cathode reaction for diaphragm and membrane cells is the same:

$$2Na^+ + 2e^- + 2H_2O \rightarrow 2NaOH + H_2$$

There are several side reactions that take place during chlor-alkali electrolysis, so cell efficiency can never be 100%. At the anode, for example, water is oxidized to oxygen and hypochlorous acid to chlorate. To repress the side reactions, the pH is lowered.

The electrolytic cells differ in the way the various electrolysis products are prevented from mixing. The following paragraphs explain how the different cells work.

Mercury cells

In mercury cells, the chlorine is formed inside the cell, but the hydrogen and sodium hydroxide are formed in a separate reactor called the “decomposer” or “denuder” (see Figure 31).

In the electrolytic cell, electric current decomposes the brine, liberating chlorine gas (Cl_2) at the anode and metallic sodium (Na) at the cathode. The chlorine gas accumulates above the anode and is discharged. The sodium produced at the cathode immediately dissolves in mercury to form a liquid amalgam ($NaHg_x$), which also serves as the cathode. The amalgam then flows to the decomposer where it reacts with water in the presence of a graphite catalyst to form sodium hydroxide and hydrogen gas. The decomposer actually is a short-circuited electrical cell with the amalgam now serving as the anode and the graphite as the cathode.

The sodium-free mercury is recycled back to the cell. The depleted brine is saturated with chlorine, and only partially de-chlorinated before being returned to the resaturators used for brine preparation. The sodium hydroxide and hydrogen are transferred to downstream processes for purification.

About 2,971 kWh (AC) are needed to produce one ton of chlorine. The total energy requirements should also include the transformer and rectifier losses, about 27-36 kWh/ton Cl_2 (30-40 kWh/tonne Cl_2), and the energy needs in ancillary equipment, another 109-145 kWh/ton Cl_2 (120-160 kWh/tonne Cl_2) (Schmittinger et al. 2011).

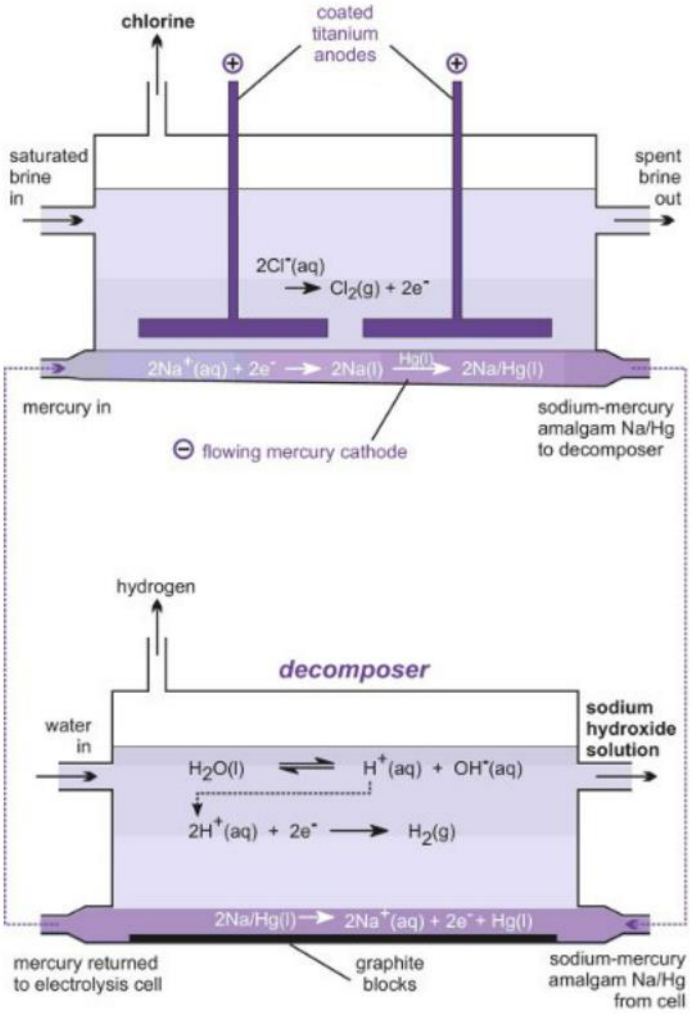


Figure 31: The mercury cell and the decomposer (EU-MERCI 2018)

Mercury cells operate at 21-22 wt.% salt concentration in the depleted brine leaving the cell. This means that 15% to 16% of the salt contained in the brine is decomposed in a single pass. Higher salt decomposition would decrease electrical efficiency due to the lower brine loss conductivity. Chlor-alkali plants with no brine recycling (i.e., once-through plants) decompose about 40% of the salt (Brinkmann et al. 2014). The main advantages of mercury cells are the high purity of chlorine (almost oxygen-free) and the 50 wt.% caustic soda solution. Main disadvantages are the high electricity consumption due to the operation in high voltages (3-5V) and high current densities (7-10 kA/m^2), the high brine purity requirements, and the release of mercury.

Diaphragm cells

In diaphragm cells, as is the case in membrane cells, all reactions take place in the electrolytic cell (see Figure 32). Here, a diaphragm is used to separate the chlorine generated at the anode and the hydrogen and sodium hydroxide generated at the cathode. The diaphragm is used to isolate the different products. Without the use of the diaphragm, the chlorine and hydrogen would automatically ignite and the chlorine would react to form sodium hypochlorite ($NaClO$) and then sodium chlorate ($NaClO_3$) (Brinkmann et al. 2014).

The brine enters at the anode and percolates through the diaphragm to the cathode. The rate of percolation is carefully controlled to maintain a balance between a low rate, desired for high sodium hydroxide formation at the cathode, and a high rate, needed to limit back-migration of hydroxyl ions from the catholyte (caustic rich effluent) to the anolyte (feed brine), which reduces the current efficiency.

The saturated brine feed (25 wt.% NaCl) is decomposed to approximately 13 wt.% NaCl (Brinkmann et al. 2014). Due to the electric current, the electrolyte temperature rises to 176°F to 210°F (80°C to 99°C). The main advantages of diaphragm cells are that the brine feed quality can be low and that the electrical energy is also low (cell voltage 3-4V; current density 0.5-3 kA/m^2). Main disadvantages concern the lower quality of caustic soda and chlorine produced, high steam needs for caustic soda concentration, and the use of asbestos.

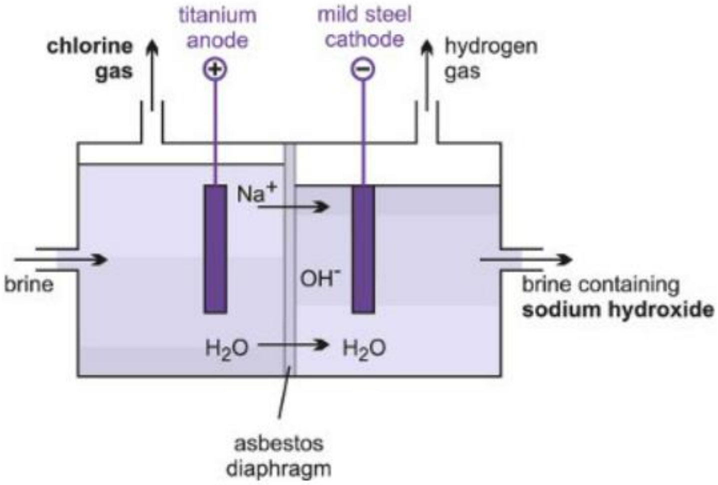


Figure 32: The diaphragm cell (EU-MERCI 2018)

Membrane cells

Membrane cells were introduced in the 1970s and represent the latest of the three technologies. In membrane cells, the anode and cathode are separated by an ion-conducting membrane (Figure 33). The brine solution enters the anode compartment where chloride ions are oxidized to form chlorine gas. The sodium ions, along with water, move through the membrane to the cathode compartment (about 3.5-4.5 moles of water per mole of sodium). At the cathode, water is electrolyzed to release hydrogen and hydroxide ions. The hydroxide ions then combine with the sodium to form caustic soda, which is continuously removed from the cathode compartment.

The membrane keeps the chloride ions from travelling to the anode but not entirely. Therefore, caustic soda can contain small quantities of sodium chloride. Hydroxide is also largely prevented from travelling to the anode compartment. Nevertheless, the little hydroxide reaching the anode results in the formation of oxygen, hypochlorite, and chlorate, reducing current efficiency (Brinkmann et al. 2014).

Brine decomposition in membrane cells is 2 to 3 times greater than in mercury cells. This means that the brine preparation system can be much smaller, which results in lower recycling rates and less equipment. The main advantages of membrane cells are the lower electricity consumption, the higher purity of caustic soda, and the use of nontoxic materials (i.e., mercury and asbestos). The main disadvantage is the higher number of upstream and downstream processes. Due to the greater need for high-purity brine, an extra purification step is needed, while the caustic soda produced may need to be evaporated for use in certain applications (Brinkmann et al. 2014).

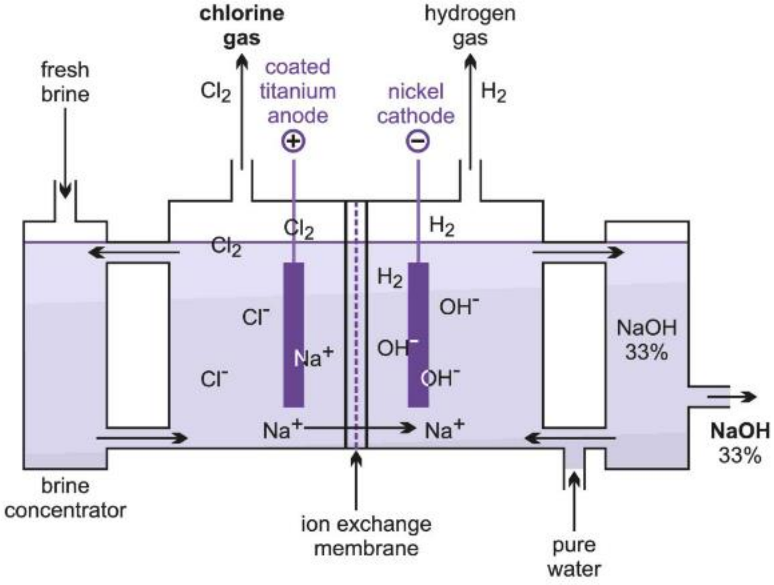


Figure 33: The membrane cell (EU-MERCI 2018)

Table 24 lists the main characteristics and advantages and disadvantages of the different cell technologies used.

Table 24: Main characteristics of electrolysis cells used in the chlor-alkali industry (Brinkmann et al. 2014; Schmittinger et al. 2011)

	Mercury	Diaphragm	Membrane
Anode	Titanium anodes coated with with oxides of ruthenium (Ru), titanium (Ti)	Titanium anodes coated with oxides of ruthenium (Ru), titanium (Ti), and tin (Sn)	Titanium anodes coated with oxides of iridium (Ir), ruthenium (Ru), or platinum (Pt)
Cathode	Mercury	Carbon steel covered with activated nickel[1]	Nickel coated with a catalyst (Ni-S, Ni-Al, and Ni-NiO)
Separator	Not present	Asbestos, polymer-asbestos, non-asbestos diaphragm	Ion-exchange membrane
Cell voltage (V)	3.15-4.80	2.90-3.60	2.35-4.00
Current density (kA/m^2)	2.2-14.5	0.8-2.7	1.0-7.0
Electricity (kWh/ton Cl_2)	2,700-4,000	2,400-2,800	2,000-2,700
Advantages	High-purity products (chlorine, caustic soda, and hydrogen), simple brine purification process	Well brine, low electricity use	Low total energy consumption, low investment, inexpensive cell operation, insensitivity to cell load variations and shutdowns, high-quality caustic soda
Disadvantages	Use of mercury, high brine purity, electricity intensive, large floorspace area, costly environmental control and operation	Use of asbestos, high steam consumption for caustic soda concentration in expensive multistage evaporators, low-purity caustic soda, low chlorine quality, cell sensitivity to pressure variations	High-purity brine, high oxygen content in chlorine, high cost in membranes

Of the three processes, the mercury process uses the most electric energy; however, no steam is required to concentrate the caustic solution. The consumption of electric energy with the diaphragm cell process is approximately 15% lower than for the mercury process, but the total energy consumption is higher because of the steam required to concentrate the caustic brine.

Chlorine processing

Inside the electrolytic cell, the chlorine is generated at atmospheric pressures and saturated with water vapor at temperatures above 176°F (80°C). The water content of the chlorine gas leaving the electrolytic cell is high, around 25%

(Jovic 2016). The gas can also contain brine mist and traces of chlorinated hydrocarbons (Schmittinger et al. 2011). Before the chlorine can be used, it needs to undergo cooling, cleaning, drying, compression, and, when needed, liquefaction.

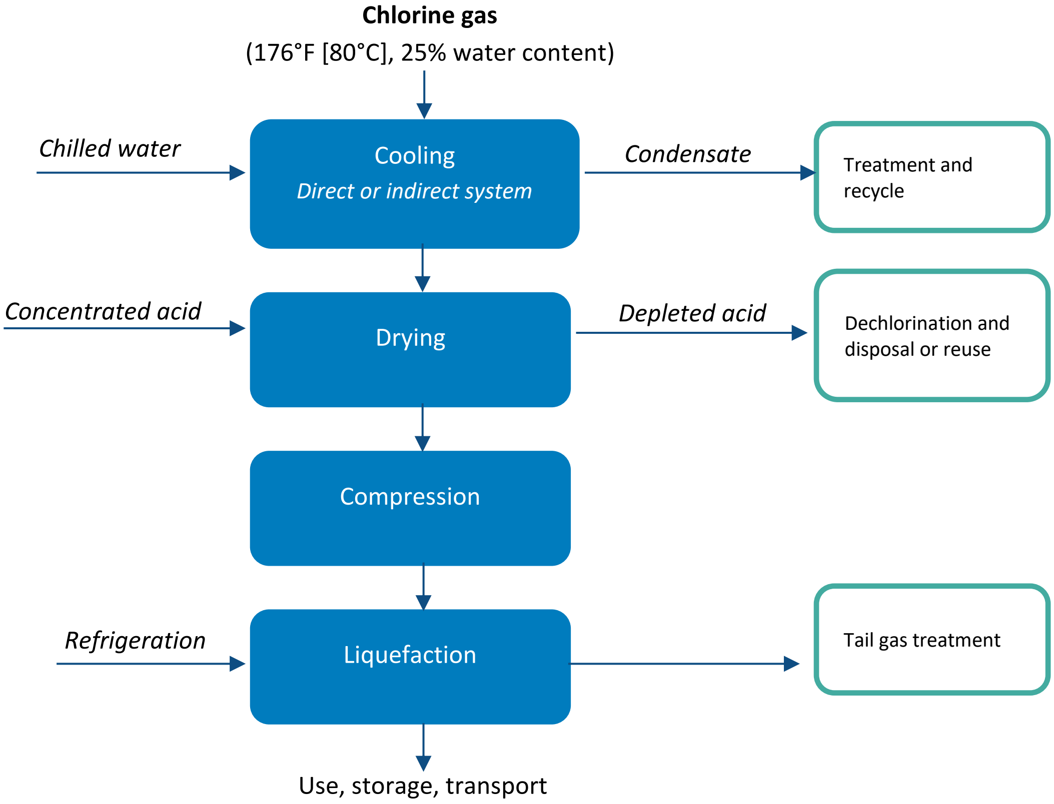


Figure 34: Main steps in chlorine processing (based on O'Brien et al. 2005)

Cooling

Cooling is carried out with chilled water, either in one stage or in two stages. When two stages are used, chilled water is used only in the second stage.

There are two main methods used for cooling: indirect and direct. In indirect cooling, the gas flows through titanium-plated heat exchangers that condense the water vapor, reducing the water content in the chlorine gas from 25% to between 1% and 2% (Jovic 2016). The condensate produced is either directly used for brine resaturation (mercury and membrane cells) or, in the case of diaphragm cells, dechlorinated by evaporation and then used for resaturation. There can be once-through, open-recirculating, and closed-loop indirect cooling systems. In direct cooling, the chlorine gas passes through packed towers where cooling water is sprayed from the top, in the opposite direction to the chlorine gas stream. Direct cooling is usually performed in closed-loop systems and has a higher thermal efficiency than indirect cooling (Brinkmann et al. 2014). However, in indirect cooling, the cooling water is not contaminated, thereby avoiding the need for wastewater dechlorination, as less chlorine is condensed and also the pressure drop is lower (Schmittinger et al. 2011).

Excessive cooling must be avoided. At temperatures below 50°F (10°C), chlorine reacts with water to form a solid material, chlorine hydrate, that can cause blockages. By maintaining a temperature above 59°F (15°C), this can be avoided.

After the chlorine gas is cooled, impurities such as brine mist and water droplets are removed by passing the chlorine gas through filters with glass wool fillings or porous quartz granules, or through an electrostatic precipitator.

Drying

To avoid corrosion in downstream equipment (stainless steel is resistant to dry chlorine) and minimize the formation of hydrates, the water content must be further reduced (Brinkmann et al. 2014).

The cooled chlorine is dried with concentrated sulfuric acid (93% to 98%) in plate, packed, or hybrid (plates on top of the packing) columns where the acid and chlorine flow counter-currently. Drying can take place in two to six stages, depending on the desired acid concentration level in the last stage. The final chlorine gas moisture content will depend on the acid concentration and the temperature on the final drying stage (Schmittinger et al. 2011). In general, the higher the number of stages, the lower the acid concentration. For a three-stage process, the acid concentration is 50-65 wt.%, while for a six-stage process, it is 30-40 wt.% (Brinkmann et al. 2014). The higher the acid dilution, the higher the corrosion rates and the higher the chlorine losses (Jovic 2016).

For the first drying stages, packed towers are normally used, while in the last stages, bubble cap plates or sieve trays are employed. The heat liberated on dilution of the acid is removed by titanium surface heat exchangers, and the weak acid is reconcentrated and reused. For many plants, selling diluted acid can be more attractive as processing acid requires higher capital costs and is a larger operation (Jovic 2016).

Finally, the dry chlorine (< 10 ppm) passes through carbon steel demisters or a packed bed to prevent the entrainment of sulfuric acid droplets.

Compression

Drying with sulfuric acid is less expensive than using chlorine with a higher water content in novel corrosion resistant compressors (Jovic 2016). All the previous steps are therefore performed to ensure that dry and clean chlorine can be used in compressors.

The type of compressors used depends on product throughput and desired pressure. Rotary compressors, such as sulfuric acid liquid ring compressors and screw compressors, can be used for low throughputs of about 150 t/d and for pressures up to 170 psi (12 bar) and 230 psi (16 bar), respectively. Reciprocating compressors, such as dry ring compressors, can be used for medium throughputs of 200 t/d and for pressures up to 230 psi (16 bar). For larger throughputs, up to 1,800 t/d, centrifugal compressors, such as turbo compressors, can be used.

Compression is usually conducted in multistage compression units with coolers in between to prevent high heat buildup. The heat of compression is removed in rotary compressors by cooling the circulating liquid (cooling the chlorine gas is not necessary) in reciprocating and centrifugal compressors by heat exchangers or by injecting liquid chlorine.

Liquefaction

Not all chlorine needs to be liquified. In the EU, approximately half of the produced chlorine is used on the spot, while the rest is liquefied and transported to other consumers (Brinkmann et al. 2014). In the United States, 81% of chlorine is liquified (The Chlorine Institute 2022).

Liquefaction takes place in carbon steel heat exchangers where a refrigerant or water is used for indirect heat transfer. It can be conducted at different temperatures and pressures: at high pressure and temperature (100-230 psi, 100°F), at medium pressure and temperature (29-87 psi, (-4-14°F), at normal pressure and low temperature (15 psi, -40°F), and other combinations of pressure and temperature. For the choice of liquefaction conditions, important parameters are the purity of the chlorine gas, the desired purity of the liquid chlorine, and the desired throughput. In general, liquefaction at high pressures increases the energy needs for compression but reduces the energy needs for cooling, resulting in a more energy-efficient operation.

All hydrogen present is concentrated in the residual gas (tail gas). The liquefaction yield in single-stage installations is 90% to 95%. This is to ensure that hydrogen concentration is below the 6% explosion limit. A higher liquefaction yield of more than 99% can be achieved by adding a second liquefaction stage where the chlorine from the residual gas is also condensed. To achieve this, small volume liquefiers are typically used that are explosion protected, and inert gas is added to maintain the gas below the explosion limit. Another way to remove the hydrogen is by reaction with chlorine gas in a column, which produces hydrogen chloride. The hydrogen chloride can be removed in a hydrochloric acid unit, and the chlorine gas can be safely condensed.

Caustic soda processing

The caustic soda generated in the three types of electrolytic cells varies in concentration and composition, requiring different downstream processing. The caustic soda leaving the decomposer in mercury cells is highly concentrated (50 wt.%). Typical downstream processing, in this case, involves cooling and mercury removal. A common way to remove the mercury is by using a plate or leaf filter with a carbon pre-coat (Brinkmann et al. 2014). In some cases, the caustic soda might also be heated before filtration.

The caustic soda produced in diaphragm and membrane cells needs to be concentrated by evaporation. In the case of diaphragm cells, evaporation takes place in triple- or quadruple-effect evaporators (also known as three- to four-stage evaporators). The higher the number of evaporator effects, the lower the energy consumption and the higher the investment costs. To draw off the precipitated salt, the evaporators need to be equipped with scraper blades (Brinkmann et al. 2014). In the case of membrane cells, the caustic soda (32 wt.%) evaporation takes place in two to three stages in plate or shell-and-tube evaporators (Brinkmann et al. 2014).

To reduce energy expenses, facilities with both mercury and membrane cells may combine caustic soda processing. Also, because caustic soda solutions can freeze under low temperatures, storage tanks should be heated with steam or electrical heat sources and properly insulated. Insulation jacketing materials made of aluminum should be avoided as exposure to caustic soda can easily damage it (Olin 2022). The freezing point for 32 wt.% caustic soda is 40°F (4°C) and for 50 wt.% caustic soda is 54°F (12°C) (Brinkmann et al. 2014).

Hydrogen processing

The hydrogen leaving the electrolytic cells is highly concentrated (> 99.9 vol-%). Main downstream processing involves cooling and removal of condensed salt water and sodium hydroxide, which can be used as brine makeup or in caustic production (Brinkmann et al. 2014). For the hydrogen produced in mercury and membrane cells, cooling takes place in heat exchangers. In the case of hydrogen from mercury cells, primary cooling takes place at the electrolyzer to allow for mercury condensation in the main mercury unit.

Appendix B: Energy Consumption

Figure 35 shows the energy expenditures of the U.S. chlor-alkali industry between 2007 and 2011 (U.S. Census Bureau 2012). The latest Annual Survey of Manufactures (ASM) with specific data for the industry was produced in 2011 (in 2011, the survey stopped reporting data specific to the chlor-alkali industry for NAICS code 325181, and the data were absorbed within "Other basic inorganic chemical manufacturing" (NAICS code 32518)) (U.S. Census Bureau 2017; U.S. Census Bureau 2021). In 2011, the U.S. chlor-alkali industry spent approximately $1.1 billion on energy, with electricity and fuel expenditures being similar. In 2007 and 2008, however, the fuel costs greatly surpassed electricity costs. This was mainly the result of high natural gas prices, which peaked in 2008 at $9.70/MBtu (EIA 2022d). Currently, both natural gas and electricity prices are experiencing an increasing trend (see Figure 35, top right and bottom right).

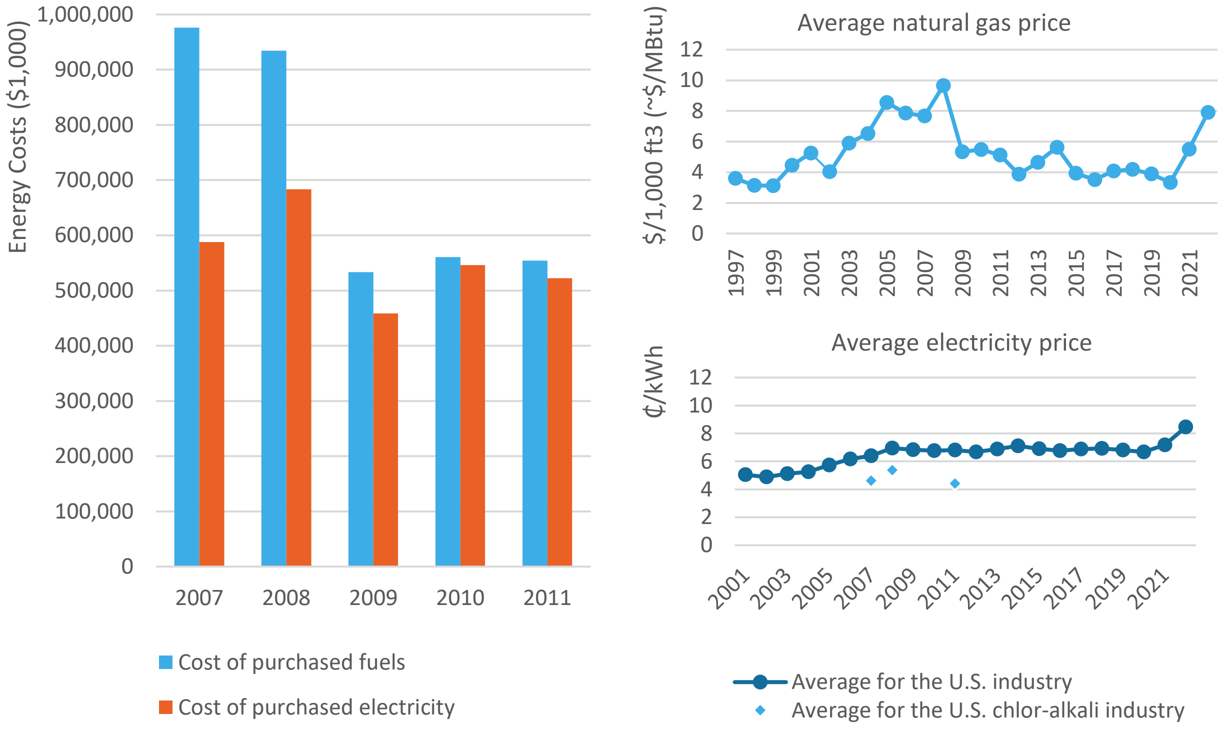


Figure 35: Energy expenditures in the U.S. chlor-alkali industry between 2007 and 2011 (left) (U.S. Census Bureau 2012), average natural gas (top right) and electricity prices (bottom right) paid by U.S. industry (EIA 2022a; EIA 2022d)

Since 2011, the average industrial natural gas price in the United States has increased annually about 4%/yr. (EIA 2022d). In addition, the U.S. average electricity prices for industrial consumers increased by 2%/yr. from 6.8¢/kWh in 2011 to 8.5¢/kWh in 2022 (EIA 2022a). The electricity prices paid by chlor-alkali manufacturers were estimated from the annual electricity consumption and annual electricity expenditures reported in the ASMs (U.S. Census Bureau 2012). They were found to be 30% to 55% lower than the average electricity prices paid by the industry in the years 2007, 2008, and 2011 (see Figure 35, bottom right).

In 2011, the U.S. chlor-alkali industry purchased 40 TBtu (12 TWh) of electricity (U.S. Census Bureau 2012). Since no data is available on the purchased fuel quantities but only on the fuel expenses, the fuel consumption was estimated by dividing the fuel expenditures by the average annual natural gas prices for industrial consumers. The assumption was made that all fuel is natural gas. It is estimated that in 2011 about 112 TBtu of fuels were consumed (Figure 36).

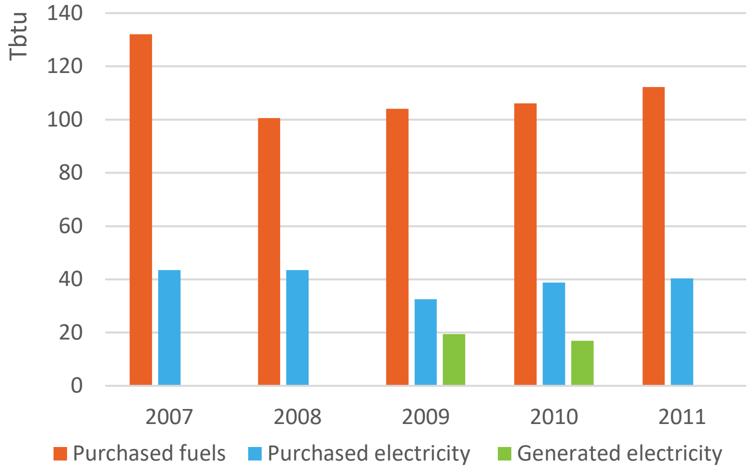


Figure 36: Electricity consumption and estimates on natural gas consumption in the U.S. chlor-alkali industry in 2011 (U.S. Census Bureau 2012)

The chlorine industry has long employed cogeneration for generating heat and electricity. A significant amount of the fuel consumed is used for electricity generation. In 2010, about 17 TBtu of electricity were generated from combined heat and power plants (CHP) located on the plant site (U.S. Census Bureau 2012).

The energy and material costs have the highest share of the overall production costs. As shown in Table 25, in 2011, the raw materials and supplies accounted for 47% and energy for about 21% of the overall production costs. With the increasing trend in energy prices that has been experienced in recent years, energy costs are expected to represent an even higher share of the overall production costs.

Table 25: Production costs in the U.S. chlor-alkali industry in 2011 (U.S. Census Bureau 2012)

	Expenditures ($1,000)	Share of total costs (%)	Share of value of shipments (%)
Raw materials and supplies	$2,317,723	47%	29%
Fuels	$554,191	11%	7%
Electricity	$522,218	10%	6%
Labor	$547,390	11%	7%
Depreciation	$308,533	6%	4%
Rental payments	$40,964	1%	1%
Other expenses	$687,819	14%	9%
Total	**$4,978,838**	**100%**	**62%**
Value of shipments	*$8,056,148*		

Chlorine is produced by passing an electric current through brine (a salty water solution) in an electrolytic cell. Chlorine manufacturing is very electricity intensive with the chlor-alkali industry representing the main electricity-consuming industry within the chemical sector. The electricity consumption ranges between 2,100-4,000 kWh/ton Cl_2 produced (Brinkmann et al. 2014), depending on the cell technology used and operating conditions. An additional 10% of electricity is used for lighting and for operating pumps, compressors, and motors. Steam is mainly used in heating the brine and the brine equipment and concentrating the caustic soda. Steam consumption also depends on the electrolytic cell technology, as it affects the caustic concentration requirements. Brine evaporation is another energy-intensive process that is only used in membrane and mercury plants that use solution-mined brine as the raw material (Brinkmann et al. 2014).

Table 26 shows estimates on the energy consumption in the U.S. chlor-alkali industry using U.S. production volumes and average energy intensities found in the literature. It is estimated that in 2020, the U.S. chlor-alkali industry consumed 130 TBtu, of which 94 TBtu was electricity and the remaining 36 TBtu fuel. Some plants use cogeneration to generate a part of the heat and electricity; however, due to the lack of data, cogeneration was not accounted for in Table 26. The electrolysis process, using diaphragm and membrane cells, accounted for most of the electricity consumption, approximately 90%. The remaining 10% of electricity was used in pumps, motors, compressors, and coolers. The fuel is consumed to generate steam to heat the brine and the brine equipment (14% of fuel use) and to concentrate caustic soda (76% of the fuel use).

The overall CO_2 emissions are estimated using the U.S. average emission factor for electricity generation and the natural gas emission factor. It is estimated that in 2020, the U.S. chlor-alkali industry released 2.1 Mtons of CO_2 from fuel combustion, while the indirect CO_2 emissions from using grid electricity amounted to 11.8 Mtons. Accounting for cogeneration would have resulted in lower CO_2 estimates. In addition, accounting for waste heat recovery to heat the brine and caustic soda concentration would have also resulted in lower emissions.

Figure 37 shows the flow and energy diagram in a Dutch membrane cell technology plant with a CHP unit and waste heat recovery (Scherpbier and Eerens 2021). The overall electricity consumption is 2,180 kWh/ton Cl_2. The membrane cells are responsible for 89% of the overall electricity use. About 12% of the electricity used is generated by an on-site CHP plant. The heat used for manufacturing 1 ton of Cl_2 is about 2.8 MBtu. The CHP plant provides 56% of the total heat requirements, while the remaining 44% comes from recovering waste heat. The heat recovered from the electrolyzers (1.5 MBtu/ton Cl_2) is used to heat the brine to 194°F (90°C) and concentrate the caustic soda. In addition, about 0.03 MBtu of heat is recovered from hydrogen cooling and another 0.1 MBtu from chlorine cooling.

Table 26: Estimated energy use and CO_2 emissions in the U.S. chlor-alkali industry in 2020

Process stage	2020 production (1,000 tons Cl_2)[1]	Average electricity intensity (kWh/ton Cl_2)	Average fuel intensity (MBtu/ton Cl_2)	Final Energy intensity (MBtu/ton Cl_2)	Final Electricity Use (TWh)	Final Electricity Use (TBtu)	Final Fuel Use (TBtu)	Final Energy Use (TBtu)	Direct CO_2 (10^6 tons)[2]	Indirect CO_2 (10^6 tons)[3]	Total CO_2 (10^6 tons)
Transformer/rectifier system[4]	11,048	31.5	-	0.1	0.3	1.2	0.0	1.2	-	0.1	0.1
Brine preparation											
heating[5]	11,048	-	0.8	0.8	-	-	8.8	8.8	0.5	0.0	0.5
ancillary equipment[6]	11,048	10.0	-	-	0.1	0.4	-	0.4	N/A	N/A	N/A
brine evaporation[7,8]	N/A	45.9	4.2	4.4	-	-	-	0.0	-	0.0	-
Brine electrolysis											
membrane cells[4]	5,369	2,200	-	7.5	11.8	40.3	0.0	40.3	-	5.1	5.1
diaphragm cells[4]	5,491	2,350	-	8.0	12.9	44.0		44.0	-	5.5	5.5
mercury cells[4]	55	2,950	-	10.1	0.2	0.6	-	0.6	-	0.1	0.1
ancillary equipment[4]	11,048	127.0	-	0.4	1.4	4.8	-	4.8	-	0.6	0.6
NaOH concentration											
membrane cells[7]	5,369	-	1.0	1.0	-	-	5.2	5.2	0.3	0.0	0.3
diaphragm cells[7]	5,491	-	4.1	4.1	-	-	22.4	22.4	1.3	0.0	1.3
mercury cells[7]	55	-	-	-	-	-	-	-	-	-	-
Hydrogen cooling/drying[5]	11,048	15.0	-	0.1	0.2	0.6	0.0	0.6	-	0.1	0.1
Chlorine compression[4,9]	8,898	28.1	-	0.1	0.3	0.9	0.0	0.9	-	0.1	0.1

Process stage	2020 production (1,000 tons Cl_2)[1]	Average electricity intensity (kWh/ton Cl_2)	Average fuel intensity (MBtu/ton Cl_2)	Final Energy intensity (MBtu/ton Cl_2)	Final Electricity Use (TWh)	Final Electricity Use (TBtu)	Final Fuel Use (TBtu)	Final Energy Use (TBtu)	Direct CO_2 (10^6 tons)[2]	Indirect CO_2 (10^6 tons)[3]	Total CO_2 (10^6 tons)
Chlorine cooling[4,9]	8,898	40.8	-	0.1	0.4	1.2	0.0	1.2	-	0.2	0.2
Total					**27.5**	**93.9**	**36.4**	**130.3**	**2.1**	**11.8**	**13.9**

"-" indicates that no energy is used or no CO_2 emissions are emitted, 0.0 indicates that some energy is used (or some emissions are emitted) but the number is very low (ranging between 0.000 and 0.049).

[1] In 2020, the U.S. chlor-alkali industry produced 11,048,000 tons of chlorine. Abou 49.7% of United States chlorine capacity uses diaphragm cells, 48.6% uses membrane cells, 0.5% uses mercury cells, and 0.9% uses other processes (The Chlorine Institute 2022).

[2] Assuming that all fuel used is natural gas. The CO_2 emission factor of natural gas is 52.91 kg CO_2/MBtu (EIA 2022b).

[3] Electricity production from cogeneration is not included due to the lack of reliable data. The average CO_2 emission factor of electricity generation in 2020 in the United States was 0.855 lb CO_2/kWh (EIA 2022c).

[4] Schmittinger et al. 2011

[5] Brinkmann et al. 2014; Scherpbier and Eerens 2021

[6] Scherpbier and Eerens 2021

[7] Brinkmann et al. 2014

[8] Brine evaporation is needed in membrane and mercury cell technology plants that use solution-mined brine as the raw material. To reduce the water content, an evaporation step is typically needed. It is not known if any U.S. plants use brine evaporation.

[9] In 2020, about 81% of U.S. chlorine production underwent liquefaction (The Chlorine Institute 2022).

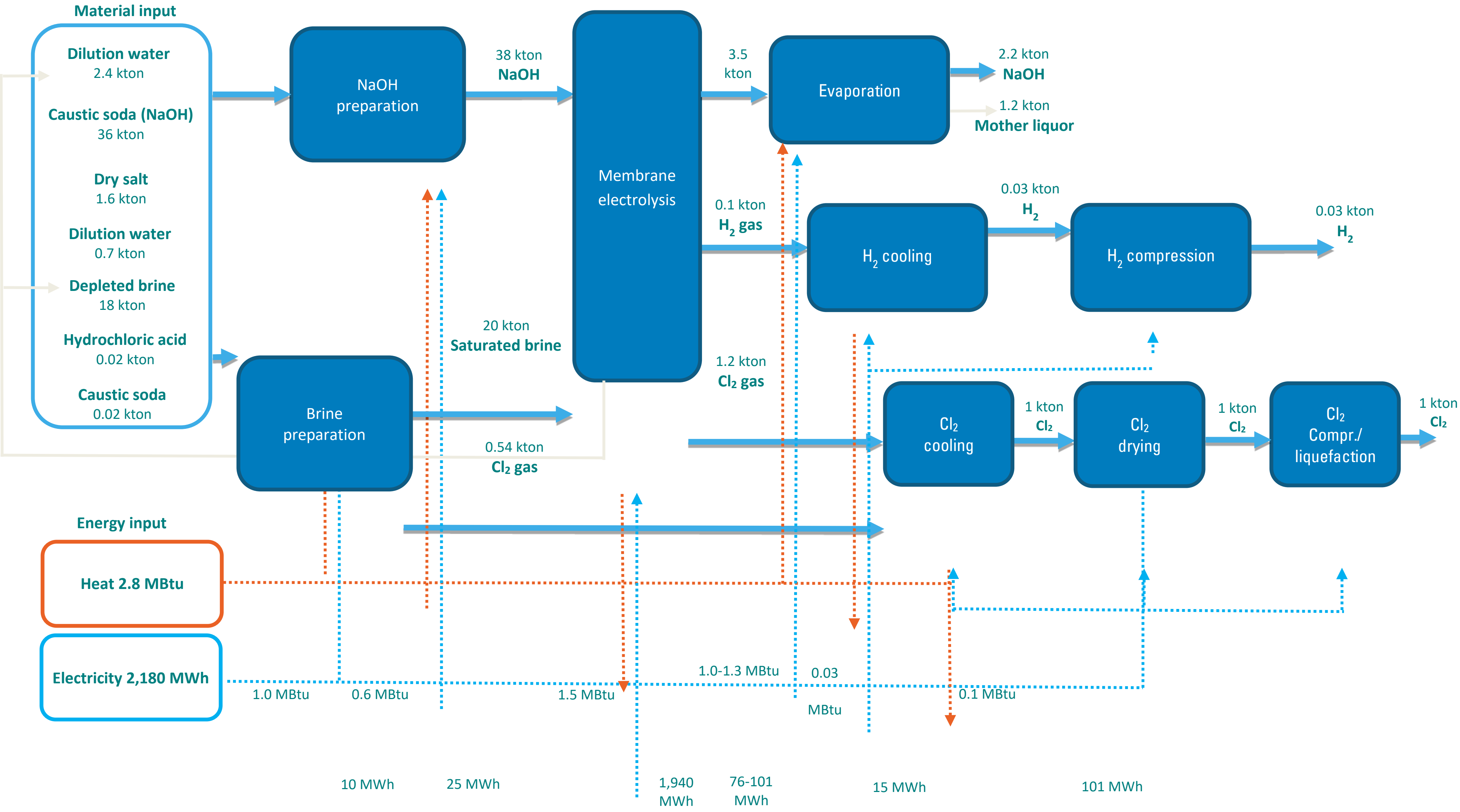


Figure 37: Chlor-alkali production process in Dutch membrane cell plant (adjusted from Scherpbier and Eerens 2021)

Appendix C: Standards for NEMA Motors

The Consortium for Energy Efficiency (CEE) has described the evolution of standards for energy-efficient motors in the United States, which is helpful for understanding “efficient” motor nomenclature (CEE 2011):

- NEMA Energy Efficient (NEMA EE) was developed in the mid-1980s to define the term “energy efficient” in the marketplace for motors. NEMA Standards Publication No. MG-1-2011, Table 12-11 defines efficiency levels for a range of different motors (NEMA 2012).
- The Energy Policy Act of 1992 (EPAct) required that many commonly used motors comply with NEMA “energy efficient” ratings if offered for sale in the United States.
- In 2010, the 2007 Energy Independence and Security Act (EISA) updated the minimum efficiency levels previously required by EPAct. The updated minimum efficiency levels for a 1-200 hp general purpose motor should be equivalent to NEMA MG-1-2011, Table 12-12. The efficiency levels listed in Table 12-12 have about 0.8% to 4% higher efficiency than the levels in Table 12-11. These minimum efficiency levels are generally referred to as “EISA levels” and are equal to the NEMA Premium efficiency levels.
- In 2010, minimum efficiency levels for previously unregulated motor types (e.g., 201-500 hp, and Subtype II) were also established. Motors in the Subtype II category include 1-200 hp: U-frame, design C, footless, 8-pole and motors with a voltage of 600 volts. The efficiency levels of manufactured or imported 201-500 hp and Subtype II motors cannot be below the efficiency levels listed in NEMA MG-1-2011, Table 12-11.
- In 1996, the CEE Premium Efficiency Criteria specification was designed to promote motors with higher efficiency levels than EPAct required, for the same classes of motors covered by EPACT. The CEE efficiency levels specified were generally two NEMA efficiency bands (Table 12-10, NEMA MG-1-2011) above those required by EPAct.
- A few years later, in 2001, CEE and NEMA aligned their specifications for the 1-200 hp motors (efficiency levels in NEMA MG-1-2011, Table 12-12). Since the CEE specifications became equivalent to the minimum federal efficiency requirements, they also became redundant. CEE has since developed the CEE Premium Efficiency Motors List that identifies the motors (1-200 hp) available with efficiency levels higher than the EISA efficiency levels.

For the 201-500 hp and Subtype II motors, the EISA federal minimum levels (equal to NEMA MG-1-2011, Table 12-11) are lower than the NEMA Premium levels. To provide performance information on large motors, the CEE created a Guidance Specification for 250-500 hp General Purpose Motors.

Appendix D: Energy Management Program Assessment Matrix

Energy Management Program Assessment Matrix

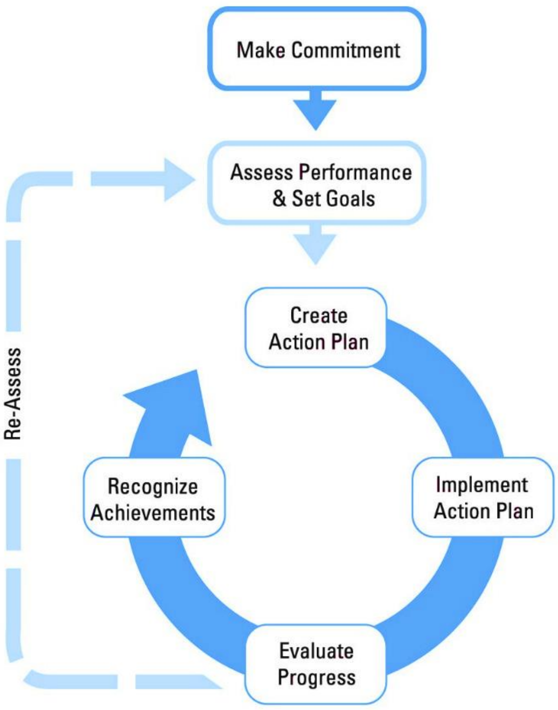
Introduction

The EPA has developed guidelines for establishing and conducting an effective energy management program based on the successful practices of ENERGY STAR partners.

These guidelines, illustrated in the graphic, are structured on seven fundamental management elements that encompass specific activities.

This assessment matrix is designed to help organizations and energy managers compare their energy management practices to those outlined in the Guidelines. The full Guidelines can be viewed on the ENERGY STAR website at www.energystar.gov/guidelines.

ENERGY STAR Guidelines for Energy Management



How To Use the Assessment Matrix

The matrix outlines the key activities identified in the ENERGY STAR Guidelines for Energy Management and three levels of implementation:

- No evidence.
- Most elements.
- Fully implemented.
- Print the assessment matrix.
- Compare your program to the Guidelines by identifying the degree of implementation that most closely matches your organization's program.
- Use a highlighter to fill in the cell that best characterizes the level of implementation of your program. You will now have a visual comparison of your program with the elements of the ENERGY STAR Guidelines for Energy Management.
- Identify the steps needed to fully implement the energy management elements and make some notes about next steps in the margin.

ENERGY STAR® Energy Management Matrix

	Little or no evidence	Some elements	Fully implemented
Make Commitment to Continuous Improvement			
Energy Director	No central or organizational resource Decentralized management	Central or organizational resource not empowered	Empowered central or organizational leader with senior management support
Energy Team	No company energy network	Informal organization	Active cross-functional team guiding energy program
Energy Policy	No formal policy	Referenced in environmental or other policies	Formal stand-alone EE policy endorsed by senior mgmt.
Assess Performance and Opportunities			
Gather and Track Data	Little metering/no tracking	Local or partial metering/tracking/reporting	All facilities report for central consolidation/analysis
Normalize	Not addressed	Some unit measures or weather adjustments	All meaningful adjustments for organizational analysis
Establish baselines	No baselines	Various facility-established	Standardized organizational base year and metric established
Benchmark	Not addressed or only same site historical comparisons	Some internal comparisons among company sites	Regular internal & external comparisons & analyses
Analyze	Not addressed	Some attempt to identify and correct spikes	Profiles identifying trends, peaks, valleys & causes
Technical assessments and audits	Not conducted	Internal facility reviews	Reviews by multi-functional team of professionals
Set Performance Goals			
Determine scope	No quantifiable goals	Short term facility goals or nominal corporate goals	Short & long term facility and corporate goals
Estimate potential for improvement	No process in place	Specific projects based on limited vendor projections	Facility & organization defined based on experience

ENERGY STAR® Energy Management Matrix

Establish goals	Not addressed	Loosely defined or sporadically applied	Specific & quantifiable at various organizational levels
Create Action Plan			
Define technical steps and targets	Not addressed	Facility-level consideration as opportunities occur	Detailed multi-level targets with timelines to close gaps
Determine roles and resources	Not addressed or done on ad hoc basis	Informal interested person competes for funding	Internal/external roles defined & funding identified
Implement Action Plan			
Create a communication plan	Not addressed	Tools targeted for some groups used occasionally	All stakeholders are addressed on regular basis
Raise awareness	No promotion of energy efficiency	Periodic references to energy initiatives	All levels of organization support energy goals
Build capacity	Indirect training only	Some training for key individuals	Broad training/certification in technology & best practices
Motivate	No or occasional contact with energy users and staff	Threats for non-performance or periodic reminders	Recognition, financial & performance incentives
Track and monitor	No system for monitoring progress	Annual reviews by facilities	Regular reviews & updates of centralized system
Evaluate Progress			
Measure results	No reviews	Historical comparisons	Compare usage & costs vs. goals, plans, competitors
Review action plan	No reviews	Informal check on progress	Revise plan based on results, feedback & business factors
Recognize Achievements			
Provide internal recognition	Not addressed	Identify successful projects	Acknowledge contributions of individuals, teams, facilities
Get external recognition	Not sought	Incidental or vendor acknowledgement	Government/third party highlighting achievements

Interpreting Your Results

Comparing your program to the level of implementation identified in the Matrix should help you identify the strengths and weaknesses of your program.

The EPA has observed that organizations fully implementing the practices outlined in the Guidelines achieved the greatest results. Organizations are encouraged to implement the Guidelines as fully as possible.

By highlighting the cells of the matrix, you now can easily tell how well balanced your energy program is across the management elements of the Guidelines. Use this illustration of your energy management program for discussion with staff and management.

Use the Resources and Help section below to develop a plan of action for improving your energy management practices.

Resources and Help

ENERGY STAR offers a variety of tools and resources to help organizations strengthen their energy management programs.

Here are some next steps you can take with ENERGY STAR:

1. Read the Guidelines sections for the areas of your program that are not fully implemented.
2. Review ENERGY STAR Tools and Resources.
3. Find more sector-specific energy management information at www.energystar.gov/industry.
4. Become an ENERGY STAR Partner, if your company is not already, to take advantage of additional resources.

Appendix E: Teaming Up to Save Energy Checklist

The following checklist can be used as a handy reference to key tasks for establishing and sustaining an effective energy team. For more detailed information on energy teams, consult the EPA's Teaming Up to Save Energy guide (EPA 2006), which is available at www.energystar.gov/energyteam.

Organizing Your Energy Team		✓
Energy Director	Able to work with all staff levels from maintenance to engineers to financial officers. Senior-level person is empowered by top management support.	
Senior Management	Energy director reports to senior executive or to a senior management council. Senior champion or council provides guidance and support.	
Energy Team	Members from business units, operations/engineering, facilities, and regions. Energy networks formed. Support services (PR, IT, HR).	
Facility Involvement	Facility managers, electrical personnel. Two-way information flow on goals and opportunities. Facility-based energy teams with a technical person as the site champion.	
Partner Involvement	Consultants, vendors, customers, and joint venture partners. Energy savings passed on through lower prices.	
Energy Team's Structure	Separate division and/or centralized leadership. Integrated into the organization's structure and networks established.	
Resources and Responsibilities	Energy projects incorporated into normal budget cycle as a line item. Energy director is empowered to make decisions on projects affecting energy use. Energy team members have dedicated time for the energy program.	
Starting Your Energy Program		✓
Management Briefing	Senior management briefed on benefits, proposed approach, and potential energy team members.	
Planning	Energy team met initially to prepare for the official launch.	
Strategy	Success showcased at the official launch.	
Program Launch	Organizational kickoff announced energy network, introduced energy director, unveiled energy policy, and showcased real-world proof.	
Energy Team Plans	Work plans, responsibilities, and annual action plan established.	
Facility Engagement	Facility audits and reports conducted. Energy efficiency opportunities identified.	

Building Capacity		✓
Tracking and Monitoring	Systems established for tracking energy performance and best practices implementation.	
Transferring Knowledge	Events for informal knowledge transfer, such as energy summits and energy fairs, are implemented.	
Raising Awareness	Awareness of energy efficiency created through posters, intranet, surveys, and competitions.	
Formal Training	Participants identified, needs determined, and training held. Involvement in ENERGY STAR Web conferences and meetings encouraged. Professional development objectives for key team members.	
Outsourcing	Use of outside help has been evaluated and policies established.	
Cross-Company Networking	Outside company successes sought and internal successes shared. Information exchanged to learn from the experiences of others.	
Sustaining The Team		✓
Effective Communications	Awareness of energy efficiency created throughout the company. Energy performance information is published in company reports and communications.	
Recognition and Rewards	Internal awards created and implemented. Senior management is involved in providing recognition.	
External Recognition	Credibility for your organization’s energy program achieved. Awards from other organizations have added to your company’s competitive advantage.	
Maintaining Momentum		✓
Succession	Built-in plan for continuity established. Energy efficiency integrated into your organizational culture.	
Measures of Success	Sustainability of program and personnel achieved. Continuous improvement of your organization’s energy performance is attained.	

Appendix F: Support Programs for Industrial Energy Efficiency Improvement

This appendix provides a list of energy efficiency support available to industry. A brief description of the program or tool is given, as well as information on its target audience and the URL for the program. Included are federal and state programs. Use the URL to obtain more information from each of these sources. An attempt was made to provide as complete a list as possible; however, information in this listing may change with the passage of time.

Tools for Self-Assessment

Implementation Guidance Toolkit

The Implementation Guidance Toolkit offers fundamental guidelines and processes to get started on implementing energy efficiency projects. The toolkit provides corporate energy managers with the necessary tools to plan projects, track progress, and communicate their accomplishments once their projects have been completed.

URL: https://betterbuildingssolutioncenter.energy.gov/better-plants/implementation-guidance-toolkit

MEASUR

The MEASUR suite can be used to improve the plant's energy efficiency and identify opportunities for energy savings. It includes a set of key software platforms with more than 80 calculators developed by the Industrial Efficiency and Decarbonization Office (IEDO). The software platforms are major updates of the older system assessment tools. They are more user-friendly, aligned with DOE cybersecurity protocols, and able to work with newer operating systems. MEASUR is free to use and accessible in an open-source environment. Because all assessment tools and the calculators are in one common environment, MEASUR allows for a higher degree of interoperability. Tools include:

- Pumping System Assessments (PSAT).
- Process Heating Assessment and Survey Tool (PHAST).
- Fan System Assessment Tool (FSAT).
- Steam System Assessment (such as SSAT/SSMT).
- Compressed Air Systems (AirMaster+).
- Energy Treasure Hunt Module.

URL: https://www.energy.gov/eere/iedo/measur

Plant Energy Profiler/Integrated Tool Suite

The Plant Energy Profiler, or ePEP (formerly called Quick PEP), is an online software tool provided by the U.S. Department of Energy to help industrial plant managers in the United States identify how energy is being purchased and consumed at their plant and also identify potential energy and cost savings. ePEP is designed so that the user can complete a plant profile in about an hour. The ePEP online tutorial explains what plant information is needed to complete an ePEP case.

Target Group: Any industrial plant

Format: Online software tool

Contact: U.S. Department of Energy

URL: https://www.energy.gov/eere/iedo/iedo-software-tools

ENERGY STAR Portfolio Manager

The Portfolio Manager is an online software tool that helps to assess the energy performance of buildings by providing a 1 to 100 ranking of a building's energy performance relative to the national building market. Measured energy consumption forms the basis of the ranking of performance.

Target Group: Any building user or owner

Format: Online software tool

Contact: U.S. Environmental Protection Agency

URL: www.energystar.gov/buildings/benchmark

ENERGY STAR Energy Tracking Tool

The tool provides manufacturers with a simple means for tracking their energy performance over time and progress toward goals. This Microsoft Excel-based tool enables users to define custom energy intensity metrics and select from a variety of reports.

Target Group: Any manufacturing plant user or owner

Format: Microsoft Excel-based tool

Contact: U.S. Environmental Protection Agency

URL: www.energystar.gov/ett

Assessment and Technical Assistance

Industrial Training & Assessment Centers

Small- to medium-sized manufacturing facilities can obtain a free energy and waste assessment. The audit is performed by a team of engineering faculty and students from 30 participating universities in the United States and assesses the plant's performance and recommends ways to improve efficiency.

Target Group: Small- to medium-sized manufacturing facilities with gross annual sales below $75 million and fewer than 500 employees at the plant site

Format: A team of engineering faculty and students visits the plant and prepares a written report with energy efficiency, waste reduction, and productivity recommendations.

Contact: U.S. Department of Energy

URL: https://www.energy.gov/mesc/industrial-assessment-centers-iacs

Manufacturing Extension Partnership (MEP)

MEP is a nationwide network of not-for-profit centers in more than 400 locations providing small- and medium-sized manufacturers with technical assistance. A center provides expertise and services tailored to the plant, including a focus on clean production and energy-efficient technology.

Target Group: Small- and medium-sized plants

Format: Direct contact with the local MEP Office

Contact: National Institute of Standards and Technology, 301-975-5020

URL: www.nist.gov/mep/

Small Business Development Center (SBDC)

The U.S. Small Business Administration administers the SBDC Program to provide management assistance to small businesses through 58 local centers. The SBDC Program provides counseling, training, and technical assistance in the areas of financial, marketing, production, organization, engineering, and technical problems and feasibility studies if a small business cannot afford consultants.

Target Group: Small businesses

Format: Direct contact with the local SBDC

Contact: Small Business Administration, 800-8-ASK-SBA

URL: www.sba.gov/sbdc/

ENERGY STAR—Selection and Procurement of Energy-Efficient Products for Business

ENERGY STAR identifies and labels energy-efficient office equipment. Look for products that have earned the ENERGY STAR. They meet the strict energy efficiency guidelines set by EPA. Office equipment includes items such as computers, copiers, faxes, monitors, multifunction devices, printers, scanners, transformers, and water coolers.

Target Group: Any user of labeled equipment

Format: Website

Contact: U.S. Environmental Protection Agency

URL: https://www.energystar.gov/products/business

Federal, State, Local, and Utility Incentives and Programs

Government and utilities sponsor incentives to assist businesses in assessing or financing energy-efficient process technology or buildings. Please contact your utility and state and local governments to determine what tax benefits, funding grants, or other assistance they may be able to provide your organization.

Database of State Incentives for Renewables and Efficiency (DSIRE)

DSIRE is a comprehensive source of information on state, local, utility, and federal incentives and policies that promote renewable energy and energy efficiency. Established in 1995, DSIRE is an ongoing project of the NC Solar Center and the Interstate Renewable Energy Council funded by the U.S. Department of Energy.

Target Group: Any industry

URL: www.dsireusa.org/

Funding and Incentives Resource Hub

The Funding and Incentives Resource Hub can help energy managers discover the many rebates, funding opportunities, and other incentives, including those available through the Inflation Reduction Act and Bipartisan Infrastructure Law. Hub visitors can refine the search for funding and incentives using filters for technology (e.g., energy efficiency, water efficiency, compressed air, lighting), source (e.g., EPA, DOE, IRA, BIL), and type (e.g., tax credit, financial assistance, technical assistance).

Target Group: Commercial, data center, education, financial services, industrial, local government, multifamily, residential, state government, utility

URL: https://betterbuildingssolutioncenter.energy.gov/funding-incentives-hub

Inflation Reduction Act (IRA) and Bipartisan Infrastructure Law (BIL, FKA Infrastructure Investment, and Jobs Act or IIJA)

The Inflation Reduction Act of 2022 is a significant climate law, offering funding, programs, and incentives to accelerate the transition to a clean energy economy and drive the deployment of new clean electricity resources.

Target Group: Homes, commercial buildings, transportation, and industry

URL: https://www.epa.gov/invest/epa-funding-announcements-bipartisan-infrastructure-law-and-inflation-reduction-act

Industrial Research and Assessment Center

The Industrial Research and Assessment Center’s Implementation Grant Program has helped small and medium-sized manufacturers (SMMs) implement the recommendations made in Industrial Assessment Center (IAC) or Onsite Energy CHP-TAP assessments since 2018. Recommendations made in assessments that DOE has deemed equivalent may also be eligible. Eligible SMMs can (i) improve energy efficiency, material efficiency, cybersecurity, or productivity or (ii) reduce waste production, GHG emissions, or non-GHG pollution.

Target Group: Small- to medium-sized manufacturing facilities

Contact: U.S. Department of Energy

URL: https://www.energy.gov/mesc/industrial-research-and-assessment-cent°er-implementation-grants

Appendix G: Chlor-Alkali Manufacturing Facilities in the United States

Table 27: U.S. chlor-alkali plant estimated capacities in tonnes (The Chlorine Institute 2022; Vallette et al. 2018)

#	Owner	Plant name	Location	Cell Technology	Start Year	Chlorine capacity[1]	Conversions
1	INEOS KOH	ASHTA – Ashtabula	Ashtabula, Ohio	Membrane *(INEOS BICHLOR Membrane '21)*	1963	60,000 (in 2021)	Converted from mercury to membrane in 2021
2	Covestro	Covestro – Baytown	Baytown, Texas	Membrane *(BiTAC Membrane)*	1972	363,000 (in 2006)	
3	Formosa Plastics Corporation	Formosa Plastics – Point Comfort	Point Comfort, Texas	Membrane	1983	910,000 (in 2017)	
4	K2 Pure Solutions	K2 Pure – Pittsburg	Pittsburg, California	Membrane *(Uhde Membrane BM 2.7)*	2011	N/A	
5	OxyChem	OxyVinyls – Battleground (La Porte)	La Porte, Texas	Asbestos diaphragm *(Oxytech MDC 29 Diaphragm)*	1974	535,000 (in 1999)	
6	OxyChem	OxyChem – Ingleside	Ingleside/Gregory/ Corpus Christi, Texas	Asbestos diaphragm *(OxyTech MDC-55 diaph. 7/98, 12/05)*	1974	570,000 (in 2011)	
7	OxyChem	OxyChem – Geismar	Geismar, Louisiana	Synthetic diaphragm & membrane *(OxyTech MDC55 Diaphragm S - 1 BITAC Bipolar Membrane '00)*	1968	438,000 (50% diaphragm, 50% membrane)	
8	OxyChem	OxyChem – Convent	Convent, Louisiana	Asbestos diaphragm *(OxyTech MDC55 Diaphragm '95)*	1981	353,000	
9	OxyChem	OxyChem – Taft	Taft, Louisiana	Asbestos diaphragm & membrane *(OxyTech H4 '75 Diaphragm S - 3 OxyTech MGC Membrane '86 OxyTech MGC Membrane '98)*	1971	650,000 (67% diaphragm, 33% membrane)	

#	Owner	Plant name	Location	Cell Technology	Start Year	Chlorine capacity[1]	Conversions
10	OxyChem	OxyChem – Wichita	Wichita, Kansas	Asbestos diaphragm & membrane *(OxyTech HC3BT, H4 '75 Diaphragm S - 1 OxyTech Membrane)*	1952	248,000 (67% diaphragm, 33% membrane)	
11	OxyChem	OxyChem – New Johnsonville	New Johnsonville, Tennessee	Membrane *(nBITAC bipolar membrane)*	2014	165,000	
12	Olin	Olin – Charleston	Charleston, Tennessee	Membrane *(INEOS BICHLOR Membrane '12)*	1962	200,000	Converted from mercury in 2011
13	Olin	Olin – McIntosh	McIntosh, Alabama	Asbestos diaphragm & membrane *(Uhde Membrane '04, '06, '07)*	1952	685,000 (53% diaphragm, 47% membrane)	All diaphragm cells to be permanently shut down by end 2022
14	Olin	Olin – Niagara Fall	Niagara Falls, New York	Membrane *(Asahi Chemical Membrane '87, '96)*	1897	240,000 (in 2016)	
15	Olin	Olin – Freeport	Freeport, Texas	Asbestos diaphragm and membrane *(Dow Diaphragm S - 1 Membrane added in '99, '14)*	1940	3,030,000 (52% diaphragm, 48% membrane)	
16	Olin	Olin – St. Gabriel	St. Gabriel, Louisiana	Membrane *(CEC nBiTAC Membrane '09)*	1970	246,000	Converted from mercury in 2009
17	Olin	Olin (Blue Cube) – Plaquemine.	Plaquemine, Louisiana	Asbestos diaphragm *(Dow Diaphragm)*	1958	971,000 (in 2016)	
18	SABIC	SABIC – Mt. Vernon	Mt. Vernon, Indiana	Membrane *(UHDE nx-BiTAC8101 Membrane '21)*	1976	N/A	
19	SABIC	SABIC – Burkville	Burkville, Alabama	Membrane and asbestos diaphragm *(OxyTech H2A diaph, Membrane '96 --- 1 Eltech Membrane '01)*	1987	N/A	

#	Owner	Plant name	Location	Cell Technology	Start Year	Chlorine capacity[1]	Conversions
20	Shin-Etsu Chemical Co. Ltd.	Shintech – Plaquemine	Plaquemine, Louisiana	Membrane *(Asahi Membrane)*	2008	1,055,000	
21	Westlake Corp.	Westlake – Plaquemine	Plaquemine, Louisiana	Asbestos diaphragm *(OxyTech H4 Diaphragm '95, '96)*	1975	426,000	
22	Westlake Corp.	Westlake – Geismar	Geismar, Louisiana	Membrane *(Chlorine Engineers Membrane)*	2013	317,000	
23	Westlake Corp.	Westlake – Lake Charles	Westlake, Louisiana	Membrane and synthetic diaphragm *(Chlorine Engineers, Membrane '07, 1 Glanor 1144 Diaphragm '77, '80 Bipolar 1161 Diaphragm '83)*	1947	1,270,000 (19% diaphragm, 81% membrane)	Converted from asbestos to synthetic in 2010
24	Westlake Corp.	Westlake – Calvert City	Calvert City, Kentucky	Membrane *(Asahi Membrane '02)*	1966	250,000	Converted from mercury in 2002
25	Westlake Corp.	Westlake – Natrium	Proctor, West Virginia	Mercury and synthetic diaphragm	1943	227,000 (44% mercury, 56% membrane)	Converted from asbestos to synthetic in 2015
26	Westlake Corp.	Westlake – Longview	Longview, Washington	Membrane *(INEOS FM-21SP, Membrane)*	2006	N/A	

---

[1] The capacity data should be handled with care as they represent latest-known capacities. Current capacities may differ due to expansions and cell closures.

Glossary

ABS	acrylonitrile butadiene styrene
AC	Alternating current
AFD	Adjustable-frequency drive
AI	Artificial Intelligence
ANN	Artificial Neural Networks
ASDs	Adjustable-speed drives
ASM	Annual Survey of Manufactures
ATSDR	Agency for Toxic Substances and Disease Registry
$BaCl_2$	Barium chloride
$BaCO_3$	Barium carbonate
$BaSO_4$	Barium sulfate
BEP	Best efficiency point
BF	Ballast factor
BMS	Building management system
BPR	Boiling point rise
Btu	British thermal unit
C	Carbon
Ca	Calcium
CAC	Compressed Air Challenge®
$CaCl_2$	Calcium chloride
$CaCO_3$	Calcium carbonate
$CaSO_4$	Calcium sulfate
cCa	Calcium concentration
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilization and storage
CEE	Consortium for Energy Efficiency
cf	cubic feet
CFL	Compact fluorescent lamp
CFM	Cubic feet per minute
CH_4	Methane

CHP	Combined heat and power
Cl_2	Chlorine
cm	Centimeter
cMg	Magnesium concentration
CO_2	Carbon dioxide
COP	Coefficient of Performance
CPCM	Composite phase change materials
CR	Copper Rotor
cSO_4	Sulfate concentration
CSP	Concentrated solar power
DC	Direct current
DEFC	Direct ethanol fuel cells
DOE	United States Department of Energy
DRDS	Daylight responsive dimming system
EASA	Electrical Apparatus Service Association
ECU	Electrochemical unit
EIA	United States Energy Information Administration (U.S. Department of Energy)
EPA	United States Environmental Protection Agency
EPAct	Energy Policy Act
ETC	Evacuated tube collectors
EU	European Union
FEMP	Federal Energy Management Program
FFTA	Fuzzy Fault tree Analysis
FPC	Flat plate collectors
ft^3	Cubic feet
GA	Generic Algorithm
GHG	Greenhouse gas
GJ	Gigajoule
gpl	Grams per liter
GtL	Gas-to-liquid
GWh	Gigawatt-hour
GWP	Global warming potential

H_2	Hydrogen
H_2O	Water
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbons
HCl	Hydrochloric acid
HFC	Hydrofluorocarbon
Hg	Mercury
HHV	High heating value
HID	High-intensity discharge
hp	Horsepower
HVAC	Heating, ventilation, and air conditioning
Hz	Hertz
IAI	Industrial Artificial Intelligence
ICT	Information and communication technology
IEA	International Energy Agency
IPLV	Integrated Part-Load Value
IR	infrared
ITAC	Industrial Training and Assessment Center
K	Kelvin
kA	Kilo ampère
kg	Kilogram
kPa	kilo Pascal
kW	Kilowatt
kWh	Kilowatt-hour
L	Liter
lb	Pound
LBNL	Lawrence Berkeley National Laboratory
LCC	Life cycle costing
LDAR	leak detection and repair
LED	Light-emitting diode
LFG	Landfill gas
Low-E	Low-emittance

Lpm	liters per minute
m^2	Square meter
m^3	Cubic meter
mbar	Millibar
MBtu	Million British thermal units
MDM	Motor Decisions Matter
MEAs	Membrane electrode assemblies
Mg	Magnesium
mg	Milligram
$Mg(OH)_2$	Magnesium hydroxide
$MgCl_2$	Magnesium chloride
MJ	Megajoule
mm	Millimeter
MPa	Million pascal (megapascal)
mV	Millivolts
MVR	Mechanical vapor recompression
MW	Million watts (megawatt)
MWe	Megawatt electric (One million watts of electric capacity)
MWh	Million watt-hour (megawatt-hour)
Na	Sodium
Na_2CO_3	Sodium carbonate, soda ash
Na_2SO_4	Sodium sulfate
Nacl	Sodium chloride
NaClO	Sodium hypochlorite
$NaClO_3$	Sodium chlorate
NAICS	North American Industry Classification System
NaOH	Sodium hydroxide, caustic soda
NEMA EE	National Electrical Manufacturers Association Energy Efficiency
NEMA	National Electrical Manufacturers Association
nm	Nanometer
NOx	Nitrogen oxides
O	Oxygen

O&M	Operations and maintenance
ODC	Oxygen depolarized cathodes
ODP	Ozon depletion potetial
OEL	Occupational exposure limit
ORC	Organic Rankine Cycle
PDP	Pressure dew point
PEM	Proton exchange membrane
pH	Potential of hydrogen
PLC	Programmable Logic Control
PM SynRM	Permanent Magnet Synchronous Reluctance
PM	Permanent Magnet
ppm	Parts per million
PPA	Power Purchase Agreement
psi	Pounds per square inch
psid	Pounds per square inch (differential)
psig	Pounds per square inch (gauge)
Pt	Platinum
PTFE	Polytetrafluoroethylene
PtL	Power-to-liquid
PVC	Polyvinyl chloride
PVs	Photovoltaics
R&D	Research and Development
RNG	Renewable natural gas
Ru	Ruthenium
SIC	Standard Industrial Classification
Sn	Tin
SO_4	Sulfate
SR	Switched reluctance
SVM	Support Vector Machine
SynRM	Synchronous reluctance
TBtu	Trillion British thermal units
TCU	Temperature control unit

TEFC	Totally enclosed, fan-cooled
TES	Thermal energy storage
Ti	Titanium
Tonne	Metric ton (1,000 kg)
TVR	Thermal vapor recompression
TWh	Trillion watthours
U.S.	United States
USGS	United States Geological Survey
UTC	Unable to collect
V	Volt
VFD	Variable-frequency drive
Vol-%	Volume percent
VSD	Variable-speed drive
W	Watt
WHP	Waste heat to power
Wt.%	Weight percent
ZrO_2	Zirconium dioxide, zirconia
µg	Microgram
µV	Microvolt

References

Abou-Ziyan, H.Z., and A.F. Alajmi. (2014). "Effect of load-sharing operation strategy on the aggregate performance of existed multiple-chiller systems." *Applied Energy*, 135, p. 329-338, https://doi.org/10.1016/j.apenergy.2014.06.065.

Akbari, H., R. Levinson, S. Konopaki, and L. Rainer. (2004). Monitoring the Energy-Use Effects of Cool Roofs on California Commercial Buildings. Lawrence Berkeley National Laboratory (LBNL). https://escholarship.org/uc/item/5j49q2kg

AkzoNobel. (2012). AkzoNobel setzt einzigartiges Eindampfsystem für Natronlauge ein. https://www.chemie.de/news/138593/akzonobel-setzt-einzigartiges-eindampfsystem-fuer-natronlauge-ein.html

Almeida A.T., F.J.T.E. Ferreira, and D. Both. (2005). Technical and economical considerations in the application of variable-speed drives with electric motor systems. IEEE Transactions on Industry Applications, vol. 41, no. 1, pp. 188-199, Jan.-Feb. 2005, http://doi.org/10.1109/TIA.2004.841022

Augustyn T. (2012). Energy efficiency and savings in pumping systems — the holistic approach. 2012 Southern African Energy Efficiency Convention (SAEEC), Johannesburg, South Africa, p. 1–7. https://ieeexplore.ieee.org/document/6408587

Barma, M.C., R. Saidur, S.M.A. Rahman, A. Allouhi, B.A. Akash, and S.M. Sait. (2017) "A review on boilers energy use, energy savings, and emissions reductions." *Renewable and Sustainable Energy Reviews*, 79, p. 970-983, https://doi.org/10.1016/j.rser.2017.05.187.

Batista, L., L. Da Costa, S. Berriah, and H. Lademann. (2013). "A Multi-Expert System for chlorine electrolyzer monitoring," *Expert Systems with Applications*, 40(8), 3128-3136, https://doi.org/10.1016/j.eswa.2012.12.094.

Bayne, C. (2011). Titan America. Personal Communication.

Becker, H., A. Vuillermoz, and F. Maréchal. (2012). "Heat pump integration in a cheese factory." *Applied Thermal Engineering*, 43, p. 118-127, https://doi.org/10.1016/j.applthermaleng.2011.11.050.

Bhadbhade, N., B.H.Y. Ong, D.G. Olsen, B. Wellig, M.K. Patel. (2024). "Assessment of CO2 abatement potential of heat pumps using pinch analysis for the Swiss chocolate industry." *Journal of Cleaner Production*, 455, https://doi.org/10.1016/j.jclepro.2024.142323.

Bhatia, A. (2020). Steam Management – Overview of Steam Traps. PDH Online Course. PDH Center. Fairfax, Virginia. https://pdhonline.com/courses/m167/m167content.pdf

Bommaraju, T.V., and T.F. O'Brien. (2015). Brine Electrolysis. *Electrochemistry Encyclopedia*. https://knowledge.electrochem.org/encycl/art-b01-brine.htm

Boyd, G., E.M. Curtis, and S. Zhang. (2021). Impact of Strategic Energy Management Practices on Energy Efficiency: Evidence from Plant-Level Data. https://www.aceee.org/sites/default/files/pdfs/ssi21/panel-3/Boyd.pdf

Brambley, M.R., P. Haves, S.C. McDonald, P. Torcellini, D. Hansen, D.R. Holmberg, and K.W. Roth. (2005). Advanced Sensors and Controls for Building Applications: Market Assessment and Potential R&D Pathways. U.S. Department of Energy, Office of Scientific and Technical Information. https://doi.org/10.2172/1217909

Brinkmann, T., G. Giner Santonja, L. Delgado Sancho, F. Schorcht, and S. Roudier. (2014). Best available techniques (BAT) reference document for the production of chlor-alkali: Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). Publications Office. https://doi.org/10.2791/13138

Browning, A., M. Sanders, and D. Weimar. (2010). Effective Water Treatment for Evaporative Condensers. International Institute of Ammonia Refrigeration (IIAC). 32nd Annual Meeting International Institute of Ammonia Refrigeration March 14–17, 2010. San Diego, California. https://web.iiar.org/membersonly/pdf/tc/T397.pdf

Buddingh, P., and S. Hagemoen. (2001). New life for old power rectifiers The Chlorine Institute, Inc. 2001 Annual Meeting, New Orleans, Louisiana, March 11-14.

Carbon Trust. (2017). Lighting Guide – Bright ideas for efficient illumination. United Kingdom. https://ctprodstorageaccountp.blob.core.windows.net/prod-drupal-files/documents/resource/public/Lighting-guide.pdf

CASTLET. (n.d.). R&D project to develop and AI process monitoring system for chlor-alkali cell process lines. CASTLET Ltd. Lincoln, United Kingdom. https://www.castletltd.com/case-studies/rd-project-to-develop-an-ai-process-monitoring-system-for-chlor-alkali-cell-process-lines-101

CEATI. (2007). Compressed Air Energy Efficiency Reference Guide. Natural Resources Canada. https://natural-resources.canada.ca/sites/nrcan/files/energy/pdf/energystar/compressed-air-ref-eng.pdf

CEE (2011). Motor Efficiency, Selection, and Management A Guidebook for Industrial Efficiency Programs. Consortium for Energy Efficiency. https://www.xcelenergy.com/staticfiles/xe/Marketing/Files/MN-Bus-CEE-Guidebook.pdf

Cella, L. (2021). Top eight ways to improve energy efficiency pumps. Pump Industry Magazine. https://www.pumpindustry.com.au/top-eight-ways-to-improve-energy-efficiency-in-pumps/

Chavan, N., S. Pinnow, G.D. Polcyn, and T. Turek. (2015). "Non-isothermal model for an industrial chlor-alkali cell with oxygen-depolarized cathode." *Journal of Applied Electrochemistry*, 45(8), 899-912. https://doi.org/10.1007/s10800-015-0831-2

Covestro (2023). Covestro successfully starts up a new world-scale chlorine plant in Tarragona. https://www.covestro.com/press/covestro-successfully-starts-up-a-new-world-scale-chlorine-plant-in-tarragona/

Covestro. (2017). Innovative and energy efficient chlorine production with Oxygen Depolarized Cathode (ODC) technology as a key contribution to energy revolution. Covestro Deutschland AG, Germany.

Dai, M., X. Lu, and P. Xu. (2021). "Causes of low delta-T syndrome for chilled water systems in buildings." *Journal of Building Engineering*, 33(May 2020), 101499. https://doi.org/10.1016/j.jobe.2020.101499

Danfoss. (2021). Refrigerant options now and in the future. https://www.danfoss.com/en/about-danfoss/articles/dcs/refrigerant-options-now-and-in-the-future/

De Oliveira, J., A. Nied, and R.P. Días. (2011). Study on Energy Efficiency of Induction Motor Soft-Starting with Torque Control, Advances in Motor Torque Control, Dr. Mukhtar Ahmad (Ed.), ISBN: 978-953-307-686-7, InTech, http://www.intechopen.com/books/advances-in-motor-torquecontrol/study-on-energy-efficiency-of-induction-motor-soft-starting-with-torque-control

Delfrate, A., and C. Schmitt. (2010). Integration of Fuel Cells Systems into Chlor Alkali Plants: The Chlorine Industry Perspective. 18th World Hydrogen Energy Conference 2010 – WHEC 2010. Proceedings of the WHEC, May 16.-21. 2010, Essen

Dias, A.C. (2013). Chlor-alkali membrane cell process: study and characterization [PhD, University of Porto].

Dols, J., B. Fortenbery, M. Sweeney, and F. Sharp. (2014). "Efficient Motor-Driven Appliances Using Embedded Adjustable-Speed Drives." *ACEEE Summer Study on Energy Efficiency in Buildings,* 9: 90–99. https://www.aceee.org/files/proceedings/2014/data/papers/9-886.pdf.

Dow. (2014). Annual report 2014. https://www.annualreportowl.com/Dow%20Chemical/2014/Annual%20Report/Download

DSIRE. (2023). 3rd Party Solar PV Power Purchase Agreement (PPA). https://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2023/11/DSIRE_3rd-Party-PPA_Nov_2023.pdf

Dutta N., K. Palanisamy, P. Shanmugam, U. Subramaniam, and S. Selvam. (2023). "Life Cycle Cost Analysis of Pumping System through Machine Learning and Hidden Markov Model." *Processes*. 11(7):2157. https://doi.org/10.3390/pr11072157

EECA (2010). Energy Efficiency Best Practice Guide: Steam Systems, Hot Water Systems and Process Heating Systems. Energy Efficiency and Conservation Authority (EECA), New Zealand. https://genless.govt.nz/assets/Business-Resources/process-heat-best-practice-guide-jan-2011.pdf

Efficiency Partnership. (2004). Industrial Product Guide—Manufacturing and Processing Equipment: Compressed Air Equipment. Flex Your Power. San Francisco, Calif.

Electrical Apparatus Service Association (EASA). (2006). ANSI/EASA Standard AR100-2006: Recommended Practice for the Repair of Rotating Electrical Apparatus. St. Louis, Mo.

Electrical Apparatus Service Association (EASA). (2015). The Effect of Repair/Rewinding on Premium Efficiency/IE3 Motors. St. Louis, Mo. https://easa.com/resources/resource-library/the-effect-of-repairrewinding-on-premium-efficiencyie3-motors

Electrical Apparatus Service Association (EASA). (2019).EASA Standard AE100-2015: Recommended Practice for the Repair of Rotating Electrical Apparatus. St. Louis, Mo. https://www.apprep.com/Site/articles/EASA_AR100-2015_0815_0.pdf

Emerson. (2017). Yarway Steam Traps: The Industrial Steam Trapping Handbook. https://www.emerson.com/documents/automation/industrial-steam-trapping-handbook-en-5105184.pdf

Energy Efficiency & Renewable Energy (EERE). (n.d.). Heating, Ventilation, and Air Conditioning (HVAC). https://rpsc.energy.gov/tech-solutions/hvac

EU-MERCI. (2018). Technical analysis – Chemical sector (NACE C20). WP4: Picture of efficiency projects implemented by the Industry sector-by-sector and process-by-process. HORIZON 2020 Project Nr. 693845

European Commission. (2019). Demonstration of a combined heat and power 2MWe PEM fuel cell generator and integration into existing chlorine production plant. https://cordis.europa.eu/docs/results/621/621256/final1-final-publishable-summary-v6.pdf

Evans, P. (2018). Chiller Types and Application Guide. The Engineering Mindset. http://theengineeringmindset.com/chiller-types-and-application-guide/

Federal Energy Management Program (FEMP). (2024). Purchasing Energy-Efficient Water-Cooled Electric Chillers. Washington, D.C. https://www.energy.gov/femp/purchasing-energy-efficient-water-cooled-electric-chillers

Federal Energy Management Program (FEMP). (n.d.). Magnetic-Bearing Chiller Compressors. U.S. Department of Energy. Washington, D.C. www.energy.gov/eere/femp/magnetic-bearing-chiller-compressors

Ferreira, F.J.T.E. (2009). Strategies to Improve the Performance of Three Phase Induction Motor- Driven Systems. PhD thesis, University of Coimbra, Portugal. http://hdl.handle.net/10316/8549

Folsom, S. (2020). The Pros and Cons of Single-stage and Two-stage Rotary Screw Air Compressors. Compressed Air Best Practices. https://www.airbestpractices.com/technology/air-compressors/pros-and-cons-single-stage-and-two-stage-rotary-screw-air-compressors

Fuhr, P. (2010). Easy Ways to Save Energy Now - Take Care of those Steam Traps. Save Energy Now Webcast Series. United States Department of Energy. https://www.energy.gov/sites/prod/files/2013/11/f4/webinar_steamtrap_2010_0605_0.pdf

Galitsky, C., S.C. Chang, E. Worrell, and E. Masanet. (2005). Energy Efficiency Improvement and Cost Saving Opportunities for the Pharmaceutical Industry: An ENERGY STAR Guide for Energy and Plant Managers. Lawrence Berkeley National Laboratory, Berkeley, Calif. Report LBNL-57260.

Garfield, D.J., P.N. Jadun, S. Hwang, M. O'Malley, and M.F. Ruth. (2021). Opportunities for Industry to Provide Flexibility While Increasing Profitability. United States. https://doi.org/10.2172/1822824.

Gooding, H. (2020). The Skinny on Steam Traps: An introduction to steam traps and how steam trap maintenance programs can reduce energy consumption and greenhouse gas emissions. Energy Solutions Center. https://www.energysolutionscenter.org/publication/steam-trap-surveys-steam-trap-systems-gooding/

GSA. (2016). Chiller plant control optimization systems. GPG findings 028. U.S. General Services Administration (GSA). https://www.gsa.gov/climate-action-and-sustainability/center-for-emerging-building-technologies/completed-assessments/energy-management/chiller-plant-control-optimization

Guandalini, G., S. Foresti, S. Campanari, J. Coolegem, and J. ten Have. (2017). "Simulation of a 2 MW PEM Fuel Cell Plant for Hydrogen Recovery from Chlor-Alkali Industry." *Energy Procedia*, 105, 1839-1846. https:/doi.org/10.1016/j.egypro.2017.03.538

Hamer, G. (2002). "Increase your profits by installing energy efficient pumps." *World Pumps*. 426, p. 19-21. https://doi.org/10.1016/S0262-1762(02)80047-5.

Hare, N., M.G. Rasul, and S. Moazzem. (2010). A review on boiler deposition/foulage prevention and removal techniques for power plant. EE'10: Proceedings of the 5th IASME/WSEAS international conference on Energy & environment. February 23-25, 2010. United Kingdom.

Hart, D. (2018). Improve the efficiency of refrigeration systems. Energy in Buildings & Industry. Produced in association with the Energy Institute. June 2018. London, United Kingdom. https://www.energyinst.org/?a=666330

Hennecke, I.F.W. (2006). A Comparative Study of Pump Life Cycle Costs. Paper Technology. October/November 2006. Pump Life Cycle. https://www.hydra-cell.co.uk/docs/2027.pdf

Hodgson, J., and T. Walters (2002). Optimizing Pumping Systems to Minimize First or Life-Cycle Costs. Proceedings of the 19th International Pump Users Symposium, Houston, Texas, February 25-28, 2002.

Hovstadius, G. (2007). Key Performance Indicators for Pumping Systems. Proceedings Efficiency in Motor Driven Systems (EEMODS) '07 Conference, Beijing, China, June 10-13, 2007.

Hung, Y.-T., L.K. Wang, M.-H.S. Wang, N.K. Shammas, and J.P. Chen. (2017). *Waste Treatment in the Service and Utility Industries (1st ed.)*. CRC Press. https:/doi.org/10.1201/9781315164199

Hydraulic Institute, Europump and the U.S. Department of Energy. (2004). Variable Speed Pumping: A Guide to Successful Applications. https://www.energy.gov/eere/amo/articles/variable-speed-pumping-guide-successful-applications-executive-summary

Industrial Assessment Centers (IAC). (2024). IAC Recommendations. https://iac.university/searchRecommendations

INEOS. (2022). INEOS enterprises to acquire ASHTA Chemicals Inc. from Bigshire Mexico. https://www.ineos.com/news/shared-news/ineos-enterprises-to-acquire-ashta-chemicals-inc.-from-bigshire-mexico/

INEOS. (2024). BICHLOR™ Electrolyser: State-of-the-art Chlor-alkali Production Technology. INEOS Technologies Ltd. Cheshire, United Kingdom. https://www.ineos.com/globalassets/ineos-group/businesses/ineos-electrochemical-solutions/products/electrolysers/en---ineos---bichlor-electrolyser---mar-2024.pdf

Ingersoll Rand. (2001). Air Solutions Group: Compressed Air Systems Energy Reduction Basics. www.air.ingersoll-rand.com

International Energy Agency (IEA). (2016). Daylighting and lighting retrofit to reduce energy use in non-residential buildings: A literature review. A Technical Report of IEA SHC Task 50. Paris, France. https://task50.iea-shc.org/Data/Sites/1/publications/Technical_Report_T50_D2_final.pdf

International Energy Agency (IEA). (2023). Electrification - Overview. Paris, France. https://www.iea.org/energy-system/electricity/electrification

Iowa State University. (2005). Energy-Related Best Practices: A Sourcebook for the Chemical Industry. https://invenoeng.com/wp-content/uploads/2017/08/Energy-Best-Practices-Chemical-Industry-Sourcebook.pdf

IREDA. (2003). Investors manual for energy efficiency. Confederation of Indian Industry, New Delhi. https://www.scribd.com/doc/155466942/IREDA-InvestorManual

Jia, J. (2006). Introduction of Heat Recovery Chiller Control and Water System Design. HVAC Technologies for Energy Efficiency, Vol. IV-6-2. Proceedings of the Sixth International Conference for Enhanced Building Operations, Shenzhen, China, November 6 – 9 (2006).

John, N., J.H. Wesseling, E. Worrell, M.P. Hekkert. (2022). “How key-enabling technologies’ regimes influence sociotechnical transitions: the impact of artificial intelligence on decarbonization in the steel industry.” *Journal of Cleaner Production,* 370, https://doi.org/10.1016/j.jclepro.2022.133624

Jordan, D. (2021). Cheap Chills: Decarbonizing Industrial Process Cooling. Sumer Study on Energy Efficiency in Industry 2021. American Council for an Energy-Efficient Economy (ACEEE). Washington, D.C. https://www.aceee.org/sites/default/files/pdfs/ssi21/panel-3/Jordan.pdf

Jovic, S. (2016). Intensification of chlorine processing Eindhoven. [PhD Thesis, Chemical Engineering and Chemistry] Technische Universiteit Eindhoven, The Netherlands. https://research.tue.nl/en/publications/intensification-of-chlorine-processing

Kalaiselvan, A.S.V., U. Subramaniam, P. Shanmugam, and N. Hanigovszki. (2016). “A comprehensive review on energy efficiency enhancement initiatives in centrifugal pumping system.” *Applied Energy*, Volume 181, p. 495-513. https://doi.org/10.1016/j.apenergy.2016.08.070.

Kananeh, A.B., and J. Peschel. (2012). “Fouling in Plate Heat Exchangers: Some Practical Experience,” in *Heat Exchangers – Basic Design Applications*, ed. Jovan Mitrovic. https://doi.org/10.5772/34026

Karlsen-Davies, N.D., and G.A. Aggidis. (2016). “Regenerative liquid ring pumps review and advances on design and performance.” *Applied Energy*, 164, p. 815-825. https://doi.org/10.1016/j.apenergy.2015.12.041.

Katunský, D., E. Dolníková, B. Dolník, and K. Krajníková. (2022). “Influence of Light Reflection from the Wall and Ceiling Due to Color Changes in the Indoor Environment of the Selected Hall.” *Appl. Sci.*, 12. https://doi.org/10.3390/app12105154

Kaya, D., F.C. Kiliç, and H.H. Öztürk (Eds.). (2021). *Energy Management and Energy Efficiency in Industry: Practical Examples*. Cham: Springer. https://doi.org/10.1007/978-3-030-25995-2

Kemp, I.C. (2006). Pinch Analysis and Process Integration: A User Guide on Process Integration for the Efficient Use of Energy, Elsevier Science & Technology. ProQuest Ebook Central, https://ebookcentral.proquest.com/lib/uunl/detail.action?docID=284028.

Khasawneh, H., M.N. Saidan, M. Al-Addous. (2019). “Utilization of hydrogen as clean energy resource in chlor-alkali process.” *Energy Exploration & Exploitation*, 39, 1053–1072. https://journals.sagepub.com/doi/10.1177/0144598719839767

Kim, I.-T., Kim, Y.S., Nam, H., and Hwang, T. (2018). "Advanced Dimming Control Algorithm for Sustainable Buildings by Daylight Responsive Dimming System." *Sustainability*, 10(11): 4087. https://doi.org/10.3390/su10114087

Klemes, J. (2013) Handbook of Process Integration (PI): Minimisation of Energy and Water Use, Waste and Emissions. Oxford, UK: Woodhead Publishing. http://site.ebrary.com/id/10815624.

Koepke, J. (2009). The Benefits of VFDs on Cooling Towers. HPAC Engineering.

Konrad, A. (2024). “How artificial intelligence can be used in the chemical industry.” *Journal of Business Chemistry*. https://www.businesschemistry.org/article/how-artificial-intelligence-can-be-used-in-the-chemical-industry/

Kovacs, T. (2015). Alfa Laval's new 4-effect caustic evaporation system reduces steam consumption by 25%. https://www.alfalaval.com/globalassets/documents/microsites/achema-2015/the-worldss-first-4-effect-caustic-evaporation-system-reduces-steam-consumption-by-25..pdf

Kumana, J. (2000). Personal communication.

Kyburz, M., G.W. Meindersma, and G. Bargeman. (2021). "Nanofiltration in the Chemical Processing Industry," in *Nanofiltration: Principles, Applications and New Materials (2nd ed.)*, eds. A.I. Schäefer and A.G. Fane, 543-597. https://doi.org/10.1002/9783527824984.ch12

Lanciki, A. (2019). Optimizing chlor-alkali production through online chemical analysis. Metrohm white paper. https://gcms.labrulez.com/paper/17577

LANXESS. (2018a). Case study about chlor-alkali brine purification in a chemical plant in south India. https://lanxess.com/en/Products-and-Brands/Brands/Lewatit/Case-Studies-and-Stories/Brine-purification-with-finely-dispersed-ixr

LANXESS. (2018b). Lewatit® MDS TP208 – Significant Cost Savings Offered by Chelating Resin with Special Small-sized Monodisperse Beads.

Lenntech. (n.d.). Removal of sulfate from chlor alkali brine by nano filtration. Retrieved March 2023 from https://www.lenntech.nl/applications/removal-of-sulfate-from-chlor-alkali-brine-by-nano-filtration.htm

Li, C., L. Zhu, and T. Fleiter. (2014). "Energy Efficiency Potentials in the Chlor-Alkali Sector - A Case Study of Shandong Province in China." *Energy & Environment*, 25, 661-686. https://doi.org/10.1260/0958-305X.25.3-4.661

Li, K., Q. Fan, H. Chuai, H. Liu, S. Zhang, and X. Ma. (2021). "Revisiting Chlor-Alkali Electrolyzers: from Materials to Devices." *Transactions of Tianjin University*, 27(3), 202-216. https://doi.org/10.1007/s12209-021-00285-9

Lima, P.R., A. Mirapalheta, M. Henrique dos Santos Andrade, E.O. Vilar, C. L. de Pavia e Silva Zanta, and J. Tonholo. (2010). "Energy loss in electrochemical diaphragm process of chlorine and alkali industry – A collateral effect of the undesirable generation of chlorate." *Energy*, 35(5), 2174-2178. https:/doi.org/10.1016/j.energy.2010.01.039

Lindsley, D., J. Grist, and D. Parker. (2018). Thermal power plant control and instrumentation: The control of boilers and heat recovery steam generators (2nd ed.).

Linnhoff, B., D.W. Townsend, D. Boland, G.F. Hewitt, B.E.A. Thomas, A.R. Guy, and R.H. Marsland. (1992*). A User Guide on Process Integration for the Efficient Use of Energy (1992 edition)*. Institution of Chemical Engineers, Rugby, UK.

MacHarg, J. P., and B. Sessions. (2013). "Modular pumps bring efficiencies." *IDA Journal of Desalination and Water Reuse*, 5(2), 106–113. https://doi.org/10.1179/2051645213Y.0000000013

Mady, C., R. de Jardin Junior, and S. de Oliveira Junior (2015). Is MVR an efficient alternative to optimize the energy use in an evaporation unity of electrolytic caustic soda production? An exergy approach to the diaphragm arrangement. Proceedings of ECOS 2015 – The 28th international conference in efficiency, cost, optimization, simulations and environmental impact on energy systems June 30-July 3, Paris, France.

Maillard, J. (2008). Coating Technology Increases Pump Performance. Coating Technology Increases Pump Performance. Belzona International Ltd. Runcorn, United Kingdom. https://www.belzona.com/pumps/assets/pdf/en/articles/coatingtechnologyincreasespumpperformance.pdf

Makaremi N., S. Schiavoni, A.L. Pisello, and F. Cotana. (2019). "Effects of surface reflectance and lighting design strategies on energy consumption and visual comfort." *Indoor and Built Environment*. 28(4) p.552-563. https://doi.org/10.1177/1420326X18793170

Mao, S., B. Wang, Y. Tang, and F. Qian. (2019). "Opportunities and challenges of artificial intelligence for green manufacturing in the process industry." *Engineering*, 5(6), 995-1002. https://doi.org/10.1016/j.eng.2019.08.013.

Martin, N., M. Ruth, L. Price, R.N. Elliott, A.M. Shipley, and J. Thorne. (2000). Emerging Energy-Efficient Industrial Technologies. Berkeley: Lawrence Berkeley National Laboratory and Washington, D.C.: ACEEE.

Maycock, K., C. Kotzo, F. Muret, Z. Twardowski, and J. Ulan. (2007). "Commercialisation of Kvaerner Chemetics' Sulphate Removal System," in Modern Chlor-Alkali Technology, ed. J. Moorehouse, 140-151. https://doi.org/10.1002/9780470999479.ch11

Merritt, C. (2015). Process Steam Systems: A practical guide for operators, maintainers, and designers. John Wiley & Sons, Incorporated.

Metrohm. (n.d.). Online analysis of calcium and magnesium in brine. AN-PAN-1005. https://www.metrohm.com/en_us/applications/application-notes/prozess-applikationen-anpan/an-pan-1005.html

Milenkovic, I., V. Reljic, S. Dudić, and V. Mladenovic. (2023). "Energy efficient compressed air filtration: An experimental study on the effect of filters selection and configuration on pressure drop." *Thermal Science*, 28. 144-144. https://doi.org/10.2298/TSCI230212144M

Motor Decisions Matter (MDM). (2012). Motor Planning Kit. Boston, MA. https://www.teco.com.au/getmedia/d0916e62-8ff6-4469-b7ef-b73feb1713bd/mpkv22.pdf

Moussallem, I., S. Pinnow, N. Wagner, and T. Turek. (2012). "Development of high-performance silver-based gas-diffusion electrodes for chlor-alkali electrolysis with oxygen depolarized cathodes." *Chemical Engineering and Processing: Process Intensification*, 52, 125-131. https:/doi.org/10.1016/j.cep.2011.11.003

Mrayed, S., M.B. Shams, M. Al-Khayyat, and N. Alnoaimi. (2021). "Application of pinch analysis to improve the heat integration efficiency in a crude distillation unit." *Cleaner Engineering and Technology*, 4, https://doi.org/10.1016/j.clet.2021.100168.

MRETS. (2021). Midwest Renewable Thermal Tracking System – Operating Procedures. https://www.mrets.org/wp-content/uploads/2024/01/M-RETS-Thermal-Tracking-System-6-2021.pdf

Nadel, S., M. Shepard, S. Greenberg, G. Katz, and A. de Almeida. (2002). Energy Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities. American Council for an Energy-Efficient Economy (ACEEE), Washington, D.C.

National Electrical Manufacturers Association (NEMA). (2012). American National Standard—Motors and Generators. American National Standards Institute, Rosslyn, Va.

National Electrical Manufacturers Association (NEMA). (2017). NEMA MG 10-2017. Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors. Rosslyn, Virginia, United States. https://www.nema.org/standards/view/energy-management-guide-for-selection-and-use-of-fixed-frequency-medium-ac-squirrel-cage-polyphase-induction-motors

National Productivity Council (NPC). (2017). Good Practices Manual: Chlor-Alkali Sector. https://www.npcindia.gov.in/NPC/Uploads/Competencies/Manual%20Chlor-alkali%20Sector.pdf

National Renewable Energy Laboratory (NREL). (2011). Saving energy in commercial buildings – Office lighting checklist. Colorado, United States. https://www.nrel.gov/docs/gen/fy11/51273.pdf

Newkirk, A., P. Rao, and P. Sheaffer. (2021). U.S. Industrial and Commercial Motor System Market Assessment Report Volume 2: Advanced Motors and Drives Supply Chain Review. Lawrence Berkeley National Laboratory. https://escholarship.org/uc/item/2k1942nd

NIST. (2023). Industrial Artificial Intelligence Management and Metrology (IAIMM). Project/Program Summary. National Institute of Standards and Technology U.S. Department of Commerce. https://www.nist.gov/programs-projects/industrial-artificial-intelligence-management-and-metrology-iaimm

Nobian. (2021). Sustainability report 2021. https://cms.nobian.com/uploads/Content%20pages/Sustainability/Sustainability-Report-Nobian-2021.pdf

Nobian. (2022). Sustainability report 2022. https://cms.nobian.com/uploads/Downloads/Sustainability-Report-Nobian-2022.pdf

Northwest Energy Efficiency Alliance (NEEA). (2020). Power Drive Systems – Energy Savings and Non-Energy Benefits in Constant & Variable Load Applications. Portland, Oregon. https://www.nema.org/docs/default-source/motor-and-generator-guides-and-resources-library/power-drive-systems-energy-savings-and-non-energy-benefits-in-constant-and-variable-load-applications.pdf

O'Brien, T., T. Bommaraju, and F. Hine. (2005). *Handbook of Chlor-Alkali Technology*. https://doi.org/10.1007/b113786

Oak Ridge National Laboratory (ORNL). (2008). Combined Heat and Power: Effective Energy Solutions for a Sustainable Future. Prepared by Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/files/Pub13655.pdf

Oak Ridge National Laboratory (ORNL). (2013). Combined Heat and Power: Enabling Resilient Energy Infrastructure for Critical Facilities. Prepared by ICF International.

Olin. (2022). Caustic Soda – Sodium hydroxide product stewardship manual. Olin Corporation. https://olinchloralkali.com/wp-content/uploads/2024/04/Olin-Sodium-Hydroxide-Product-Stewardship-Manual.pdf

OxyChem. (2022). Caustic Soda Handbook. Dallas, Texas. https://www.oxy.com/siteassets/documents/chemicals/products/chlor-alkali/caustic.pdf

Parker, S.A., W.D. Hunt, K.M. Fowler, W.F. Sandusky, G.P. Sullivan, B.K. Boyd, K.L.M. Stoughton, T.M. Koehler, and R. Pugh. (2015). Metering Best Practices: A Guide to Achieving Utility Resource Efficiency, Release 3.0. Prepared for the United States Department of Energy. Pacific Northwest National Laboratory, Richland, Washington.

Pattison, P.M., M. Hansen, and J.Y. Tsao. (2018). "LED lighting efficacy: Status and directions." *Comptes Rendus Physique*, 19(3), p. 134-145, https://doi.org/10.1016/j.crhy.2017.10.013.

Perdahci, C.A., Akin, H.C., and Cekic, O. (2018). A comparative study of fluorescent and LED lighting in industrial facilities. IOP Conference Series: Earth and Environmental Science. 154. 012010. https://doi.org/10.1088/1755-1315/154/1/012010

PETRODMO. (2004) The Caustic Soda Solution Handbook. United States. https://www.petrodmo.com/wp-content/uploads/2021/04/Caustic-soda-solution-handbook.pdf

Petroleum Conservation Research Association (PCRA). (n.d.). Reduction in furnace oil consumption by process modification. Ministry of Petroleum & Natural Gas, Government of India.

Pontes, R.F.F., W.M. Yamauchi, and E.K.G. Silva. (2019). "Analysis of the effect of seasonal climate changes on cooling tower efficiency, and strategies for reducing cooling tower power consumption." *Applied Thermal Engineering*, 161, https://doi.org/10.1016/j.applthermaleng.2019.114148.

Prajapati, S. (2021). 3 Types of Cooling Systems and How They Work. Sensorex. https://sensorex.com/blog/2018/02/21/how-cooling-towers-work/

Process Cooling. (2021). Microchannel Heat Exchangers Optimized for Use With Low GWP Refrigerants. https://web.archive.org/web/20210619055857/www.process-cooling.com/articles/90340-microchannel-heat-exchangers-optimized-for-use-with-low-gwp-refrigerants

Radgen, P., and E. Blaustein (Eds.). (2001). Compressed Air Systems in the European Union, Energy, Emissions, Savings Potential and Policy Actions, Fraunhofer Institute for Systems Technology and Innovation, Karlsruhe, Germany.

Radgen, P., J. Oberschmidt, and W.T.W. Cory. (2008). EuP Lot 11: Fans for ventilation in non-residential buildings. Final Report. Fraunhofer Institute Systems and innovation Research. Karlsruhe, Germany. https://publica-rest.fraunhofer.de/server/api/core/bitstreams/5a642c80-21b6-46dd-b053-be727230eaf2/content

Rao, P., P. Sheaffer, Y. Chen, B. Jones, J. Cropp, and J. Hester. (2021). U.S. Industrial and Commercial Motor System Market Assessment Report Volume 1: Characteristics of the Installed Base. Lawrence Berkeley National Laboratory (LBNL): Energy Technologies. https://escholarship.org/uc/item/42f631k3

Rao, P., P. Sheaffer, Y. Chen, U. Karki, and P. Fitzgerald. (2022). U.S. Industrial and Commercial Motor System Market Assessment Report Volume 3: Energy Saving Opportunity. Lawrence Berkeley National Laboratory (LBNL): Energy Technologies. https://escholarship.org/uc/item/16x3d348

Sampaio, A. (2018). Piping System Cuts Condensation Concerns for Brewing. Process Cooling. https://www.linkedin.com/pulse/piping-system-cuts-condensation-concerns-brewing-angela-sampaio

Sanada, C. and O. Oharriz. (2020). The Science Behind It: Coating Technology for Pump Energy Savings. Coatings & Linings. Material Performance (MP). https://www.materialsperformance.com/articles/corrosion-basics/2018/01/the-science-behind-it-coating-technology-for-pump-energy-savings

Scales, W., and D.M. McCulloch. (2007). Best Practices for Compressed Air Systems (Second Edition). Compressed Air Challenge®, Washington, D.C. https://www.compressedairchallenge.org/bookstore Scherpbier, E., and H. Eerens. (2021). "Decarbonisation options for the Dutch chlor-alkali industry," in Den Haag: PBL.

Schmittinger, P., T. Florkiewicz, L.C. Curlin, B. Lüke, R. Scannell, T. Navin, E. Zelfel, and R. Bartsch. (2011). "Chlorine," in *Ullmann's Encyclopedia of Industrial Chemistry*. https:/doi.org/10.1002/14356007.a06_399.pub3

Schoeneberger, C.A., C.A. McMillan, P. Kurup, S. Akar, R. Margolis, and E. Masanet. (2020). "Solar for industrial process heat: A review of technologies, analysis approaches, and potential applications in the United States." *Energy*, 206, 118083. https://doi.org/10.1016/j.energy.2020.118083

Schofield. (2022). Optimizing pump systems to save electrical energy. In World Pumps.Com. https://www.worldpumps.com/content/blogs/optimising-pump-systems-to-save-electrical-energy/

Scott, Doug. (2004). Personal communication with Doug Scott, PG&E Consultant, November 2004.

Shinkevich, A.I., T.V. Malysheva, Y.V. Vertakova, and V.A. Plotnikov. 2021. "Optimization of Energy Consumption in Chemical Production Based on Descriptive Analytics and Neural Network Modeling." *Mathematics*, 9(4): 322. https://doi.org/10.3390/math9040322

SolarWall. (2009). 3M Canada – Case Study. SolarWall. https://www.solarwall.com/wp-content/uploads/2018/09/3MCanada-SolarWallCase.pdf

SolarWall. (2011). Toyota Motor Manufacturing France – Case Study. SolarWall. https://www.solarwall.com/wp-content/uploads/2018/09/ToyotaFrance_SolarWallCaseStudy_Y11.pdf

SolarWall. (2018). SolarWall® 2 Stage – High Performance Solar Air Heating. SolarWall. https://www.solarwall.com/wp-content/uploads/2018/09/SolarWall2-Stage_Spec.pdf

Sonnenrein, G., A. Elsner, E. Baumhögger, A. Morbach, K. Fieback, and J. Vrabec. (2015). "Reducing the power consumption of household refrigerators through the integration of latent heat storage elements in wire-and-tube condensers." *International Journal of Refrigeration*, 51, p. 154-160, https://doi.org/10.1016/j.ijrefrig.2014.12.011.

Southern California Edison (SCE). (2003). Southern California Edison Educational Publication: Saving Money with Motors in Pharmaceutical Plants. Rosemead, Calif.

Spirax Sarco. (2014). Pressurized Deaerator Head. https://content.spiraxsarco.com/-/media/spiraxsarco/international/documents/gb/ti/pressurised_deaerator_head-ti-uk-pdah-uk.ashx?rev=def7171ee60042b1be045912ec4fae16

Spirax Sarco. (2020). Steam & Condensate Management Solutions. Blythewood, SC, United States. https://content.spiraxsarco.com/-/media/spiraxsarco/international/documents/us/sb/condensate_recovery-spb1037-us.ashx?rev=e51f74ffb97f41cf89573cb443659c3e&_gl=1*zeskxx*_gcl_au*NzU3MzcyODk3LjE3MTg4MDA0OTA.*_ga*OTQxNDYzMzI4LjE3MTg4MDA0OTE.*_ga_R5SZJX7NH1*MTcxODgwMDQ5MS4xLjAuMTcxODgwMDQ5MS42MC4wLjA.

Stone, T. (2021). The In’s and Out’s of Temperature Control Units. Process Cooling. https://web.archive.org/web/20210731105911/https://www.process-cooling.com/articles/90402-the-ins-and-outs-of-temperature-control-units

Stringer, R., and P. Johnston. (2001). “Chlorine and the Environment: An Overview of the Chlorine Industry.” *Environmental Science and Pollution Research*, 8. https://doi.org/10.1007/BF02987309

Studebaker, P. (2007). 2007 Best Practice Award Winners. Plant Services. https://www.plantservices.com/home/article/11341011/best-practices-2007-best-practices-awards-plant-services

Sullivan, G.P., A.P. Melendez, R. Pugh, and W.D. Hunt. (2010). Operations & Maintenance Best Practices – A Guide to Achieving Operational Efficiency (Release 3.0). Pacific Northwest National Laboratory. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-19634.pdf

Suntivarakorn, R., and W. Treedet. (2016). “Improvement of Boiler's Efficiency Using Heat Recovery and Automatic Combustion Control System.” *Energy Procedia*, 100, p. 193-197, https://doi.org/10.1016/j.egypro.2016.10.164.

SWEP. (2019). Clean Power When ORC System Recovers Waste Heat. www.swep.net/globalassets/applications/case-stories/clean-power-when-orc-system-recovers-waste-heat/orc_4_pages.pdf

SWEP. (2021). Refrigeration Handbook. Sweden. https://www.swep.net/refrigerant-handbook/refrigerant-handbook

Taylor, B. (2021). Do I Need a Refrigerated or Desiccant Air Dryer? Fluid-Aire Dynamics. https://fluidairedynamics.com/blogs/articles/do-i-need-a-refrigerated-or-desiccant-air-dryer

tekWorx. (n.d.). www.tekworx.us

Terrien, T. (2020). Refractometers—How They Are Used and Why They Are Important! G&D Chillers. https://gdchillers.com/basic-refrigeration/refractometers-how-they-are-used-and-why-they-are-important

The Chlorine Institute. (2022). Pamphlet 10 North American Chlor-Alkali Industry Facilities and Production Data Report-2021 Edition. https://www.chlorineinstitute.org/products/pamphlet-10

Thekdi, A., S. Nimbalkar, S. Sundaramoorthy, K. Armstrong, A. Taylor, J. Gritton, T. Wenning, and J. Cresco. (2021). Technology Assessment on Low-Temperature Waste Heat Recovery in Industry. Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/Files/Pub164247.pdf

Thyssenkrupp. (2023). Chlor-alkali electrolysis - Three best-in-class technologies. Thyssenkrup Nucera. https://thyssenkrupp-nucera.com/wp-content/uploads/2023/03/Chlor-Alkali-Brochure-thyssenkrupp-nucera.pdf

Timms, S. (2019). Understanding distillery chilling systems. G&D Chillers. https://gdchillers.com/basic-refrigeration/understanding-distillery-chilling-systems

TLV. (no date). Steam-Using Equipment Energy Saving Tips. https://www.tlv.com/steam-info/steam-theory/energy-saving/steam-equipment-energy-saving-tips

Tolvanen, J. (2008). "LCC approach for big motor-driven systems savings". *World Pumps*, Vol. 2008, Issue 506, p. 24-27, https://doi.org/10.1016/S0262-1762(08)70314-6

Torregrossa, D., and F. Capitanescu. (2019). "Optimization models to save energy and enlarge the operational life of water pumping systems." *Journal of Cleaner Production*, Volume 213, p. 89-98, https://doi.org/10.1016/j.jclepro.2018.12.124.

Trane. (2022). HVAC Industry Update. https://www.trane.com/content/dam/Trane/Commercial/global/about-us/decarbonization/REFR-PRB001H-EN_09132022.pdf

Turner, W.C., and S. Doty. (2013). Energy Management Handbook. 8th ed. Lilburn, GA: Fairmont Press. https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=573937.

United States Agency for International Development (USAID) (2015). Sahab Factory Improves Production, Saves Resources, and Investigates Solar Initiative. https://pdf.usaid.gov/pdf_docs/PA00KK3F.pdf

United States Agency for Toxic Substances and Disease Registry (ATSDR). (2010). Toxicological profile for chlorine. https://www.atsdr.cdc.gov/toxprofiles/tp172.pdf

United States Census Bureau. (2012). Annual Survey of Manufactures: Statistics for Industry Groups and Industries in the U.S.: 2007-2011.

United States Department of Energy (DOE) and Compressed Air Challenge (CAC). (2016). Improving Compressed Air System Performance: A Sourcebook for Industry. Third edition. Office of Energy Efficiency and Renewable Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2016/03/f30/Improving%20Compressed%20Air%20Sourcebook%20version%203.pdf

United States Department of Energy (DOE). (2001). Pump Life Cycle Costs: A Guide to LCC Analysis for Pumping Systems. Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, Washington, D.C. DOE/GO-102001-1190.

United States Department of Energy (DOE). (2002). United States Industrial Electric Motor Systems Market Opportunities Assessment. Office of Industrial Technologies, Washington, D.C.

United States Department of Energy (DOE). (2003a). Ford Cleveland: Inside-Out Analysis Identifies Energy and Cost Savings Opportunities at Metal Casting Plant. Office of Industrial Technologies, U.S. Department of Energy, Washington, D.C. https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/mc_cs_ford_cleveland.pdf

United States Department of Energy (DOE). (2003b). Improving Fan System Performance: A Sourcebook for Industry. Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, Washington, D.C. DOE/GO-102003-1824.

United States Department of Energy (DOE). (2006). Improving Pumping System Performance: A Sourcebook for Industry. Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, Washington, D.C. DOE/GO-102006-2079.

United States Department of Energy (DOE). (2007). Pumping Systems Tip Sheet #12. Control Strategies for Centrifugal Pumps with Variable Flow Rate Requirements. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C.
https://www.energy.gov/sites/prod/files/2014/05/f16/centrifug_pumps_control.pdf

United States Department of Energy (DOE). (2011). Common Industrial Lighting Upgrade Technologies. Office of Energy Efficiency & Renewable Energy, U.S. Department of Energy, Washington, D.C.
https://www.energy.gov/eere/amo/articles/common-industrial-lighting-upgrade-technologies

United States Department of Energy (DOE). (2012a). Improving Steam System Performance: A Sourcebook for Industry. Second Edition. Advanced Manufacturing Office, Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/05/f15/steamsourcebook.pdf

United States Department of Energy (DOE). (2012b). Motor Systems Tip Sheet #7. Eliminate Voltage Unbalance. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C.
https://www.energy.gov/eere/amo/articles/eliminate-voltage-unbalance

United States Department of Energy (DOE). (2012c). Motor Systems Tip Sheet #1. When to Purchase Premium Efficiency Motors. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/eere/amo/articles/when-purchase-premium-efficiency-motors

United States Department of Energy (DOE). (2012d). Motor Systems Tip Sheet #10: Turn motors off when not in use. Advanced Manufacturing Office Energy Efficiency and Renewable Energy. Washington, D.C.
https://www.energy.gov/eere/amo/articles/turn-motors-when-not-use

United States Department of Energy (DOE). (2012e). Steam Tip Sheet #16. Minimize Boiler Short Cycling Losses. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C.
https://www.energy.gov/eere/amo/articles/minimize-boiler-short-cycling-losses

United States Department of Energy (DOE). (2012f). Steam Tip Sheet #7. Clean Firetube Boiler Waterside Heat Transfer Surfaces. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/05/f16/steam7_surfaces.pdf

United States Department of Energy (DOE). (2012g). Steam Tip Sheet #23. Install an Automatic Blowdown-Control System. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C.
https://www.energy.gov/sites/prod/files/2014/05/f16/steam23_control_system.pdf

United States Department of Energy (DOE). (2012h). Steam Tip Sheet #4. Improve Your Boiler's Combustion Efficiency. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C.
https://www.energy.gov/sites/prod/files/2014/05/f16/steam4_boiler_efficiency.pdf

United States Department of Energy (DOE). (2012i). Steam Tip Sheet #24. Upgrade Boilers with Energy-Efficient Burners. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C.
https://www.energy.gov/sites/prod/files/2014/05/f16/steam24_burners.pdf

United States Department of Energy (DOE). (2012j). Steam Tip Sheet #25. Consider Installing Turbulators on Two- and Three-Pass Firetube Boilers. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/05/f16/steam25_firetube_boilers.pdf

United States Department of Energy (DOE). (2012k). Steam Tip Sheet #3. Use Feedwater Economizers for Waste Heat Recovery. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/05/f16/steam3_recovery.pdf

United States Department of Energy (DOE). (2012l). Steam Tip Sheet #10. Recover Heat from Boiler Blowdown. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/05/f16/steam10_boiler_blowdown.pdf

United States Department of Energy (DOE). (2012m). Steam Tip Sheet #17. Install Removable Insulation on Valves and Fittings. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/05/f16/steam17_valves_fittings.pdf

United States Department of Energy (DOE). (2012n). Steam Tip Sheet #2. Insulate Steam Distribution and Condensate Return Lines. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/05/f16/steam2_insulate.pdf

United States Department of Energy (DOE). (2012o). Steam Tip Sheet #1. Inspect and Repair Steam Traps. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/05/f16/steam1_traps.pdf

United States Department of Energy (DOE). (2012p). Steam Tip Sheet #13. Use a Vent Condenser to Recover Flash Steam Energy. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/eere/amo/articles/use-vent-condenser-recover-flash-steam-energy

United States Department of Energy (DOE). (2012q). Steam Tip Sheet #3. Use Feedwater Economizers for Waste Heat Recovery. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/05/f16/steam3_recovery.pdf

United States Department of Energy (DOE). (2012r). Motor Systems Tip Sheet #5. Replace V-Belts with Notched or Synchronous Belt Drives. Advanced Manufacturing Office Energy Efficiency and Renewable Energy U.S. Department of Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/04/f15/replace_vbelts_motor_systemts5.pdf

United States Department of Energy (DOE). (2012s). Technical Evaluation of Side Stream Filtration for Cooling Towers. U.S. Department of Energy, Energy Efficiency and Renewable Energy. https://www.energy.gov/femp/articles/technical-evaluation-side-stream-filtration-cooling-towers

United States Department of Energy (DOE). (2014a). Continuous Energy Improvement in Motor Driven Systems. Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, Washington, D.C. https://www.energy.gov/sites/prod/files/2014/04/f15/amo_motors_guidebook_web.pdf

United States Department of Energy (DOE). (2014b). Improving Motor and Drive System Performance: A Sourcebook for Industry. Office of Energy Efficiency and Renewable Energy. Washington, D.C. https://www.energy.gov/sites/prod/files/2014/04/f15/amo_motors_sourcebook_web.pdf

United States Energy Information Administration (EIA). (2012). Combined heat and power technology fills an important energy niche. www.eia.gov/todayinenergy/detail.php?id=8250

United States Energy Information Administration (EIA). (2020). How much carbon dioxide is produced when different fuels are burned? www.eia.gov/tools/faqs/faq.php?id=73&t=11

United States Energy Information Administration (EIA). (2021). 2018 Commercial Buildings Energy Consumption Survey Building Characteristics Highlights. https://www.eia.gov/consumption/commercial/

United States Energy Information Administration (EIA). (2022a). Average retail price of electricity.

United States Energy Information Administration (EIA). (2022b). Carbon Dioxide Emissions Coefficients. https://www.eia.gov/environment/emissions/co2_vol_mass.php

United States Energy Information Administration (EIA). (2022c). How much carbon dioxide is produced per kilowatthour of U.S. electricity generation? Retrieved April 2023 from https://www.eia.gov/tools/faqs/faq.php?id=74&t=11

United States Energy Information Administration (EIA). (2022d). United States natural gas price. Retrieved July 2022 from https://www.eia.gov/dnav/ng/hist/n3035us3A.htm

United States Energy Information Administration (EIA). (2023). Appendix A: British Thermal Unit Conversion Factors. https://www.eia.gov/totalenergy/data/monthly/pdf/sec12.pdf

United States Environmental Protection Agency (EPA). (2003). Save energy, money and prevent pollution with light-emitting diode (LED) exit signs. Washington, D.C. https://www.energystar.gov/sites/default/files/buildings/tools/led_exitsigns_techsheet.pdf

United States Environmental Protection Agency (EPA). (2006). Teaming Up to Save Energy—Protect Our Environment Through Energy Efficiency. Prepared by ICF International. Washington, D.C.

United States Environmental Protection Agency (EPA). (2012). Waste Heat to Power Systems. Washington, D.C.

United States Environmental Protection Agency (EPA). (2015). Catalog of CHP Technologies. Washington, D.C.

United States Environmental Protection Agency (EPA). (2021). National emission standards for hazardous air pollutants: Mercury cell chlor-akali plants residual risk and technology review. Retrieved from https://www.federalregister.gov/documents/2021/01/08/2021-00174/national-emission-standards-for-hazardous-air-pollutants-mercury-cell-chlor-alkali-plants-residual

United States Environmental Protection Agency (EPA). (2023a). Emissions & Generation Resource Integrated Database (eGRID). https://www.epa.gov/egrid

United States Environmental Protection Agency (EPA). (2023b). Greenhouse Gas Inventory Guidance Direct Emissions from Stationary Combustion Sources. https://www.epa.gov/sites/default/files/2020-12/documents/stationaryemissions.pdf

United States Geological Survey (USGS). (various years). Asbestos Statistics and Information. https://www.usgs.gov/centers/national-minerals-information-center/asbestos-statistics-and-information

Unites States Census Bureau. (2017). Annual Survey of Manufactures: Statistics for Industry Groups and Industries in the U.S.: 2013-2016.

Unites States Census Bureau. (2021). Annual Survey of Manufactures: Summary Statistics for Industry Groups and Industries in the U.S.: 2018 - 2020.

United States Nuclear Regulatory Commission (NRC). (2024). Backgrounder on Tritium Exit Signs. Office of Public Affairs. https://www.nrc.gov/docs/ML0835/ML083510118.pdf

Ursillo, C. (2013). Energy Savings Result from Compressed Air Dryer Selection. Compressed Air Best Practices. https://www.airbestpractices.com/technology/air-treatment/n2/energy-savings-result-compressed-air-dryer-selection

Vallette, J., C. Murtagh, M. Dedeo, and R. Stamm. (2018). Chlorine and Building Materials A Global Inventory of Production Technologies, Markets, and Pollution Phase 1: Africa, The Americas, and Europe. https://www.researchgate.net/publication/326631987_Chlorine_and_Building_Materials_A_Global_Inventory_of_Production_Technologies_Markets_and_Pollution_Phase_1_Africa_The_Americas_and_Europe

van Delft, K., and R. de Kler. (2017). Matching processes with electrification technologies - Final report of the E-match project. https://publicaties.ecn.nl/PdfFetch.aspx?nr=ECN-E--17-008

Venkatasubramanian, V. (2019). "The promise of artificial intelligence in chemical engineering: Is it here, finally?" *AIChE J.*, 65: 466-478. https://doi.org/10.1002/aic.16489

Verhage, A.J.L., J.F. Coolegem, M.J.J. Mulder, M.H. Yildirim, and F.A. de Bruijn. (2013). "30,000h operation of a 70 kW stationary PEM fuel cell system using hydrogen from a chlorine factory." *International Journal of Hydrogen Energy*, 38(11), 4714-4724. https:/doi.org/10.1016/j.ijhydene.2013.01.152

Williams, B. (2013). The Six Basic Types of Liquid Cooling Systems. Compressed Air Best Practices. Retrieved May 12, 2021, from www.airbestpractices.com/technology/cooling-systems/six-basic-types-liquid-cooling-systems

Worrell, E., and G. Boyd. (2022). "Bottom-up estimates of deep decarbonization of U.S. manufacturing in 2050." *Journal of Cleaner Production*, 330. https://doi.org/10.1016/j.jclepro.2021.129758

Yarime, M. (2009). From End-of-Pipe Technology to Clean Technology: Environmental Policy and Technological Change in the Chlor-Alkali Industry in Japan and Europe. [PhD, Universiteit Maastricht]

Yokogawa. (2022). Industrial AI, Building next generation autonomous operations. Yokogawa Electric Corporation. Japan. https://web-material3.yokogawa.com/1/32168/files/Yokogawa_Industrial_AI_ebook_ENG.pdf?_ga=2.245390020.1933373787.1724148758-810414604.1724148750

Yoon, S.G., J. Lee, and S. Park. (2007). "Heat integration analysis for an industrial ethylbenzene plant using pinch analysis." *Applied Thermal Engineering*, 27, p. 886-893, https://doi.org/10.1016/j.applthermaleng.2006.09.001.

Yu, F.W., and W.T. Ho. (2019). "Load allocation improvement for chiller system in an institutional building using logistic regression." *Energy and Buildings*, 201, p. 10-18, https://doi.org/10.1016/j.enbuild.2019.07.044.

Zahedi, P., S.E. Mousavi, S. Moosavian, M. Jalali, and E. Karimi. (2017). "Sulfate removal from chlor-alkali brine using nanofiltration: Parameters investigation and optimization via Taguchi design method." *Desalination and Water Treatment*, 100. https://doi.org/10.5004/dwt.2017.21714

Zhao, Z., S. Gao, Y. Tian, and H. Zhang (2021). "Study on performance of high temperature heat pump system integrated with flash tank for waste heat recovery employed in steam production". *Int J Energy Res.* https://doi.org/10.1002/er.7116

Zietlow, D. (2016). *Optimization of Cooling Systems*. Momentum Press.

Zolkowski, J. (2016). Pneumatic vs. Electric Tool Calculations and Considerations. Compressed Air Best Practices. https://www.airbestpractices.com/technology/pneumatics/pneumatic-vs-electric-tool-calculations-and-considerations