

requires mechanical approaches (such as magnetic and electrostatic separation) and chemical processing (such as froth flotation). These are inefficient: they must contend with the complex compositions of mined ores, use large volumes of chemicals, and produce lots of waste and radioactive by-products. Improvements are sorely needed.

The recycling of rare earths from discarded products is increasing. Bespoke processes could be designed because the chemical and physical compositions of the products are well defined. A variety of metallurgical and gas-phase extraction methods have been explored, but recycled rare earths are not yet part of most supply chains^{9,10}. Research is needed to reduce the ecological impact of key items containing rare earths over their whole life cycle.

Benzene derivatives from each other. The supply chains of many polymers, plastics, fibres, solvents and fuel additives depend on benzene, a cyclic hydrocarbon, as well as on its derivatives such as toluene, ethylbenzene and the xylene isomers. These molecules are separated in distillation columns, with combined global energy costs of about 50 GW, enough to power roughly 40 million homes.

The isomers of xylene are molecules with slight structural differences from each other that lead to different chemical properties. One isomer, para-xylene (or *p*-xylene), is most desirable for producing polymers such as polyethylene terephthalate (PET) and polyester; more than 8 kilograms of *p*-xylene is produced per capita each year in the United States. The similar size and boiling points of the various xylene isomers make them difficult to separate by conventional methods such as distillation.

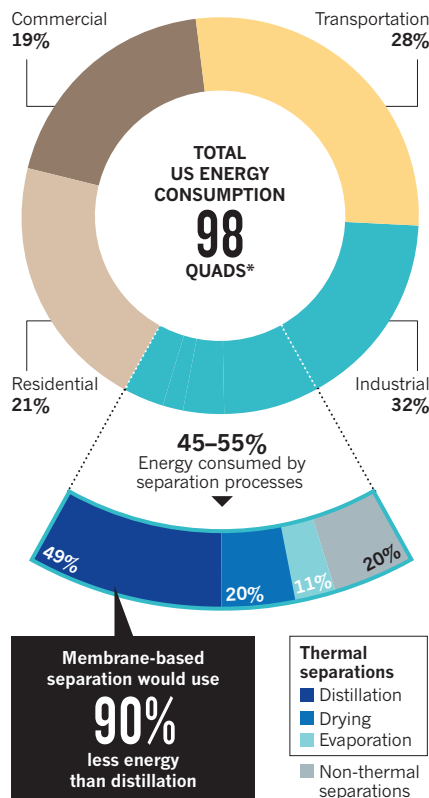
Advances in membranes or sorbents could reduce the energy intensity of these processes. As for other industrial-scale chemical processes, implementing alternative technologies for separating benzene derivatives will require that their viability be proved on successively larger scales before commercial implementation. Constructing a chemical plant can cost US\$1 billion or more, so investors want to be sure that a technology will function before building new infrastructure.

Trace contaminants from water. Desalination — whether through distillation or membrane filtration — is energy and capital intensive, making it unfeasible in many dry areas. Distillation is not the answer: thermodynamics defines the minimum amount of energy needed to generate potable water from seawater, and distillation uses 50 times more energy than this fundamental limit.

Reverse-osmosis filtration, a process that applies pressure across a membrane to salty water to produce pure water, requires only

CUTTING COSTS

Chemical separations account for about half of US industrial energy use and 10–15% of the nation's total energy consumption. Developing alternatives that don't use heat could make 80% of these separations 10 times more energy efficient.



*A quad is a unit of energy equal to 10^{15} British Thermal Units (1 BTU is about 0.0003 kilowatt-hours).

25% more energy than the thermodynamic limit⁵. But reverse-osmosis membranes process water at limited rates, requiring large, costly plants to produce a sufficient flow. Reverse osmosis of seawater is already done on commercial scales in the Middle East and Australia. But the practical difficulties of handling more-polluted water — including corrosion, biofilm formation, scaling and particulate deposition — mean that expensive pretreatment systems are also needed.

Developing membranes that are more productive and resistant to fouling would drive down the operating and capital costs of desalination systems to the point that the technique is commercially viable for even highly polluted water sources.

NEXT STEPS

Academic researchers and policymakers should focus on the following issues.

First, researchers and engineers must consider realistic chemical mixtures. Most academic studies focus on single chemicals and infer the behaviour of mixtures using this information. This approach risks missing phenomena that occur only in

chemical blends, and ignores the role of trace contaminants. Academics and leaders in industrial research and development should establish proxy mixtures for common separations that include the main chemical components and common contaminants.

Second, the economics and sustainability of any separation technology need to be evaluated in the context of a whole chemical process. Performance metrics such as cost per kilogram of product and energy use per kilogram should be used. The lifetime and replacement costs of components such as membrane modules or sorbent materials need to be factored in.

Third, serious consideration must be given early in technology development to the scale at which deployment is required. Physical infrastructure such as academic and industrially operated test beds will be needed to take new technologies from the lab to pilot scales so that any perceived risk can be reduced. Managing this will require academia, government agencies and industry partners to collaborate.

Fourth, current training of chemical engineers and chemists in separations often places heavy emphasis on distillation. Exposure to other operations — such as adsorption, crystallization and membranes — is crucial to develop a work force that is able to implement the full spectrum of separations technologies that the future will require. ■

David S. Sholl and Ryan P. Lively are professors in the School of Chemical & Biomolecular Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA. e-mail: david.sholl@chbe.gatech.edu

1. Oak Ridge National Laboratory. *Materials for Separation Technologies: Energy and Emission Reduction Opportunities* (2005).
2. Humphrey, J. & Keller, G. E. *Separation Process Technology* (McGraw-Hill, 1997).
3. US Dept. Energy Advanced Manufacturing Office. *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining* (US Dept. Energy, 2015).
4. Kim, J. *et al. Sep. Sci. Technol.* **48**, 367–387 (2013).
5. Koros W. J. & Lively, R. P. *AIChE J.* **58**, 2624–2633 (2012).
6. Xu, L. *et al. J. Membr. Sci.* **423–424**, 314–323 (2012).
7. Interagency Working Group on Social Cost of Carbon (US Govt.). *Social Cost of Carbon for Regulatory Impact Analysis* (2013).
8. Song, C. *Catal. Today* **115**, 2–32 (2006).
9. Jordens, A., Cheng, Y. P. & Waters, K. E. *Miner. Eng.* **41**, 97–114 (2013).
10. Massari, S. & Ruberti, M. *Resour. Policy* **38**, 36–43 (2013).

CORRECTION

The graphic 'The dirty ten' in the Comment 'Three steps to a green shipping industry' (Z. Wan *et al. Nature* **530**, 275–277; 2016) gave the wrong unit for PM_{2.5} concentrations. It should have been $\mu\text{g per m}^3$, not mg per m^3 .