The Energy Challenge: Unsolved Problems

J. Pendergast, F. Marechal, R. Schneider, I. Wolf, J. Bravo, M. F. Doherty

From the earliest times of human existence people have used materials from the environment in pursuit of an improved quality of life. Even in ancient times, it would be disingenuous to suppose that this has been done without impact, and indeed severe impact. There is compelling evidence that some species were brought to extinction or near extinction by early civilizations as early and diverse as those in Egypt and Rome. Entire forests disappeared to provide wood for shelter, cooking, and heating; animal and bird species were hunted to extinction for food, feathers and furs; sections of mountains disappeared by quarrying for limestone, marble and other materials for building; the list of examples is long. At the same time there was recognition in certain places and among certain peoples that living in harmony with the environment provided a sustainable way of life. Later, preservationists promoted preserving the environment by not destroying salt marshes such as the Great Salt Marsh on Cape Ann, Massachusetts, the Everglades in Florida, or by the creation of national parks and wilderness areas.

For the last two hundred years fossil fuels, particularly liquid fuels, gaseous hydrocarbons, and coal have been the primary source of energy for transportation, electricity generation, and heating. This largely hydrocarbon based energy system is now widely regarded as unsustainable in the present incarnation due to the increase in carbon dioxide levels in earth's atmosphere. There is widespread and firmly substantiated evidence by and across the scientific community that the hydrocarbon era as presently practiced will require drastic modification and / or compromises during this century if we are to avoid catastrophic climatic impacts on our planet (1, 2, 3). The hydrocarbon era will not end because we run out of hydrocarbons, just as the Stone Age did not end because we ran out of stones, but the transition from hydrocarbons to other fuels will be a disruptive transformation. Many hurdles will need to be overcome, both technological and sociological. Some of them are considered below. It is not our purpose to declare what the solutions are going to be, but merely to point out what some of the challenges are likely to be. It is also our purpose to propose some suggestions for what some steps may be to consider as partial solutions to a very large problem.

The energy challenge is a multi-layer systems problem and should be addressed on multiple layers of society and approached with the "systems thinking" to avoid point solutions that have negative consequences. On the upper layer are (or should be) government policies and international treaties that provide a legal framework and attempt to provide a level playing field for all participants while protecting the environment for all. On the lower layer are individual consumers of energy who have come to rely on and expect that cheap, or at least affordable, energy is *always* available (without interruption or rolling blackouts) for all applications from heating and cooling to transportation. In between these layers there are the energy providers (including their indemnifiers, technologists, business leaders and investors) who must satisfy consumer demand while adhering to prevailing government policy. A major aspect of government policy should be to ensure that resources are allocated properly. One of the scarcest resources that we have is capital, and energy projects often require billions of dollars of investment (the largest require tens and hundreds of billions) that must be amortized over many decades (normally 40-60 years). Thus decisions that are made today will still be felt at the end of the twenty first century.

Another critical aspect of an overall policy is the correct pricing, incentivizing, and taxing of energy so that multiple goals are achieved simultaneously. Consumers must be able to afford energy if we are to assume that our present living standards are to continue at more or less the same level as those at present and that the standards in developing nations will increase as well. The energy must not be so inexpensive that consumers will squander the resource. Investors must be rewarded to the point that investors are not neglected and that investments are unattractive. Education is an important ingredient so that everybody understands and values the access to energy that they have. "You don't know what you have 'til it's gone," is the mantra. This was very much brought to the forefront to the British public during the coal miners' strike in the early 1970's, again to the entire western world during the late 1970's OPEC oil embargo, and yet again in California in the early 2000's during the rolling blackouts caused by electricity shortages. These episodes unfortunately appear to be soon forgotten, so continuing education seems to be necessary. Along with all of this is the issue of energy subsidies to encourage the migration of energy systems in certain preferred directions. These have sometimes suffered from the law of unintended consequences that have helped to promote regressive energy directions that were not envisioned initially as well as fractures in markets that caused damage to adjacent industries. All of this is an enormous challenge that will take the most creative minds in the world of policy, law, science, engineering, economics, and politics.

The energy challenge requires sustainable processes and sustainable businesses. Many of the energy, petroleum, and chemical companies in business today were already in business 100 years ago. Thus, one possible definition of a sustainable business is its continued existence 100 years from now. A major ingredient in maintaining a sustainable business is the existence of sustainable processes. But for how long does a process need to be sustainable – surely not forever. The energy mix has changed significantly over the last 2-3 centuries (consider water, wood, wind, coal, hydrocarbons, nuclear, etc.) and will surely change during the next century (consider fusion, photovoltaics, biofuels, etc.). This begs the question as to what exactly is a sustainable process. Is it one with only low carbon emissions? Is a coal-fired power plant with CO_2 capture on its stationary combustion emissions a sustainable process? If so, what about the other metrics of sustainability such as energy efficiency, cost, water usage, worker safety, and so on? It takes a great deal more water to produce a unit of biofuel than an identical unit of natural gas (4). How does the issue of water consumption and other resources enter the picture?

Intensified Processes Technologies and Systems. There are several elements of the Chemical Process Industries (CPI) that are relevant to the energy problem. In relatively recent times, work in the area of Process Intensification (PI) has advanced to a stage where there are many concrete demonstrations that it is possible to reduce the capital cost and, at the same time, the energy consumption of the overall process. Some of the best known of these techniques include heat exchanger network design, complex distillation column arrangements, dividing wall columns (a form of complex column design), reactive distillation, alternative separation methods such as membrane separation and adsorption, along with others (5-8). Each of these has limits, constraints, and economic considerations, but it is certainly fair to say that a modern process can be conceived, designed and completed that substantially reduces both the capital requirements and the energy requirements per unit of product delivered relative to processes built in the mid-twentieth century or earlier.

The area of PI and energy reduction has a subtlety that is not often recognized, but is an area for potential meaningful investigation and success in reducing resource usage. As mentioned earlier, many facilities have long life spans, and this is certainly true of CPI facilities.

Plants may operate for spans of 20 or 30, or 40 years, and while the plants undergo routine upgrades during that lifetime, the basic configuration of the process may be unchanged over time scales that approach half a century. The fact is that in today's business environment energy savings alone will generally not justify replacing an existing, operational asset that is producing products at an acceptable rate and quality. There may well be other reasons to replace the asset such as safety or environmental compliance, but energy efficiency will not by itself generally justify replacement.

One interesting line of investigation in Process Systems Engineering is how to best implement modern Process Intensification methods and concepts into existing facilities. In additional to the levels of detail normally considered, finer details such as shell limitations and safe operating margins must be considered when optimizing the revamped process.

The topic of sustainable processes must be discussed in terms of economics and risk. While much of enormous value has been done by the academic, governmental, and industrial communities regarding methods for carbon capture and storage (CCS) the barrier that exists is not at present solely a technological barrier but rather a barrier of economics and risk management. The technology exists today to capture and sequester CO_2 emissions from stationary sources such as power plants. At issue is the cost of this activity, and the risk assumed by companies that will sequester CO_2 "indefinitely." One fruitful avenue of discussion, in the authors' opinion, and one of our suggestions for moving this debate forward, is the assignment of the economic optimum fraction of CO_2 that should be the target for capture from stationary sources, whether industrial or utility sources. The generally accepted target for capture is 90% of the CO_2 from large stationary sources. This may not be the economic optimum, and it may be that more could be captured at a lower fraction because of substantially lower capital and energy costs associated with the sequestration.

The energy challenge needs systematically extended system boundaries. Extending system boundaries from process units to entire plants, from plants to communities, communities to regions, and then to nations and internationally allows for tighter integration and hence increased overall energy efficiency (less wasted energy). To give a concrete example and provide a potentially fruitful area of investigation, consider the following: there is currently a massive amount of low grade heat that is wasted at power plants and at industrial manufacturing facilities (9) that is too low a temperature to reuse within the facility on a cost effective basis.

The methods of utilizing this heat and the thermodynamic limitations are well understood, and within a company portfolio, all projects must compete for capital. As a result of this competition, this heat is rejected to cooling water or to the atmosphere and wasted. Extending system boundaries provides one way of allocating energy resources more effectively. Thus, the solution to an energy problem (and many other problems) depends quite significantly on the boundaries drawn. The optimal boundary should be part of the solution to a problem not part of the specification. This will require new problem formulations so that inferior local solutions are avoided and optimal boundaries are identified and justified. Process systems engineering should not only consider industrial processes but urban systems also. However, a key performance indicator for industry is to maximize profit while consumers try to minimize their expenses, thus as the system boundaries are enlarged the problem statement becomes more complicated. Coordination among the stakeholders may be essential to finding new and better solutions.

Energy and water are coupled in many parts of the world. To provide a stark example, water-related energy use in California consumes 19% of the state's electricity, 30% of its natural gas, and 88 billion gallons of diesel fuel, and demand is growing (10). As system boundaries are enlarged, including water usage in the problem statement will become essential to finding better energy solutions. We will find that water and energy cannot be considered independently. Society as a whole is starting to understand the energy-water-food nexus better and the role it plays in sustainability. Competition for water between energy and food production is one of the very visible manifestations of the nexus.

Solutions to the energy problem will require a paradigm shift. A key is to think bottom-up. Consumers want a certain functionality (e.g., a certain comfort temperature in their homes). They may not mind how this temperature is achieved (this is where education comes in – to assess consumer fears of certain kinds of energy generation, either real or imagined). The real need should be defined first so that the solution is not pre-ordained.

The energy challenge requires a solution for the energy storage problem. Renewable energy is transient and must be stored effectively. Batteries are one way to store electrical energy, but they are not the only way. Moreover, energy need not be stored as electrical energy. Alternatives include chemical energy, and thermal energy. From another angle one can look at the energy density of a resource as a key indicator of adoptability. We have grown accustomed, and our society is now dependent, on high energy density resources, the two densest being fossil hydrocarbons and nuclear isotopes. With energy density comes the risk of emissions and need for disposal. Low density resources such as biomass and incident sunlight or the wind require work in the form of capital, materials, and sometimes energy to provide fuels of adequate energy density for applications such as long range transportation and aviation. So energy storage and energy transport or transfer become key in a system where very diverse sources of varying energy densities are to be part of the system.

Some of the methods and people for solving the energy challenge are already in place. Scientists and biologists are needed to develop new and/or better energy generation and transformation technologies. Materials scientists are needed to develop better materials for batteries, fuel cells, etc., and process systems engineers are needed to develop large-scale integration and optimization of energy and water systems. The energy challenge is very complex, where many problems and their solutions are intertwined. Good solutions are likely to involve cooperation between government, industry and academia which may require new organizations to manage the whole enterprise. Engineering students have good problem-solving skills, but more of them need to be trained to identify and formulate these energy-challenge problems. Academics need to become more involved in public discussions and to provide independent scientific assessments of proposed energy solutions. This is likely to require enormous scientific effort to quantify the impacts rather than to simply pass an opinion which merely adds to the chatter without providing any clarity about potential outcomes. Moreover, academics should avoid producing single optimal solutions but an array of solutions (a Pareto front) so that decision makers and the public are better informed.

Many of the PSE methods for tackling these energy-challenge problems are already in place (e.g., problem and time-scale decomposition, optimization in the presence of constraints and uncertainty, scenario simulation, superstructure optimization, etc.) (11). However, more robust and faster algorithms are likely to be needed to solve the very large-scale problems envisaged. It is also likely that the best solutions will be so tightly coupled that they are effectively impossible to operate. To overcome this difficulty it may be necessary to find novel decoupling strategies. Some may be technical, but others may require new types of vendors, companies, government agencies and new areas of human expertise.

In summary, chemical engineers will play an important role in addressing the energy challenge but they cannot solve it alone and should not try to do so because the problem is too big and too complex to be solved by any single discipline.

References

(1) US National Academies, “Understanding and Responding to Climate Change,” 2008 Edition.
(2) The Royal Society, “Resilience to Extreme Weather,” 2014.
(3) The Royal Society, “A Short Guide to Climate Science,” 2014.
(4) Wu, M., M. Mintz, M. Wang and S. Arora, “Consumptive Water Use in the Production of Bioethanol and Petroleum Gasoline,” Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, December (2008).
(5) Linnhoff, B. and E. Hindmarsh, “A Pinch Design Method for Heat Exchanger Networks,” *Chem. Eng. Sci., 38*, 745 (1983).
(6) Shah, V. H. and R. Agrawal, “A Matrix Method for Multicomponent Distillation Sequences,” *AIChE J., 56*, 1759 (2010).
(7) Doherty, M. F. and M. F. Malone, “Conceptual Design of Distillation Systems,” McGraw-Hill (2001).
(8) Seider, W. D., J. D. Seader, D. R. Lewin and S. Widagdo, “Product and Process Design Principles,” John Wiley (2009).
(9) Waste Heat Recovery: Technology and Opportunities in US Industry. Report prepared by BCS, Inc. for the U.S. Department of Energy, March (2008). According to this report the industrial sector uses the largest share of energy in the United States, accounting for approximately 30% of all energy consumed. Roughly one third of the energy consumed by industry is discharged as thermal losses directly to the atmosphere or to cooling systems.
(10) Klein, G. et al, “California’s Water-Energy Relationship,” California Energy Commission, CEC-700-2005-011-SF, November (2005).
(11) Biegler, L. T., I. E. Grossman and A. W. Westerberg, “Systematic Methods of Chemical Process Design, Prentice Hall (1997).