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Future opportunities and challenges in the design of new energy conversion systems

Thomas A. Adams II*

McMaster University, Department of Chemical Engineering, 1280 Main St West, Hamilton, ON L9H 4L7, Canada

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ABSTRACT

In this perspective, an overview of the key challenges and opportunities in the design of new energy systems is presented. Recent shifts in the prices of natural energy resources combined with growing environmental concerns are creating a new set of challenges for process design engineers. Due to the massive scale and impact of energy conversion processes, some of the best solutions to the energy crisis lie in the design of new process systems which address these new problems. In particular, many of the most promising solutions take a big-picture approach by integrating many different processes together to take advantage of synergies between seemingly unrelated processes. This paper is an extended version of a paper published as part of the proceedings of the 8th International Conference on the Foundations of Computer-Aided Process Design (FOCAPD 2014) Adams (2014).

1. Introduction

The current “energy crisis” is the result of the sum of human activity, which essentially is to make and use energy. This crisis is the result of several trends crashing together: the rise in population, the rise in global standards of living (measurable by energy consumption), the depletion of finite energy and water resources, the emission of greenhouse gases, and the sheer massive scale of these activities. Complicating matters are geopolitics, the uneven distribution of resources, social and political opinions, the complexity of global trade, and seven billion people making independent decisions about their own best interests. It is a global problem with no easy solution.

One good approach is the design of new energy conversion process systems. There is a significant need to design new systems which not only take into account recent advances in technology and shifts in resource availability and demand, but also consider sustainability as an integral part of the design methodology. This means that any new candidate process system should not only be environmentally sustainable, but also economically sustainable, as well as politically or socially sustainable. A process which satisfies all three categories meets what is called the “triple bottom line” of sustainability (Elkington, 1997). In other words, the best processes are those that are a good economic choice for a company to make willingly without overly large government involvement; that have a minimally negative (or even positive) environmental impact; and that the general population is either supportive of or at least not vocally opposed to the activity. Processes that satisfy the triple bottom line are the most likely candidates to help deal with issues related to the energy crisis because they are the most likely to be commercialized at meaningful scales, and they simultaneously are better for the environment than the status quo. Because of the sheer size of many energy conversion processes, even small improvements to efficiency or emissions can have a massive effect when applied to the global scale. This summarizes the grand challenge of the process design engineer.

A convenient way of understanding the energy challenge is to examine the energy return on energy invested (EROEI) for many common energy conversion processes in use today and in the past, as shown in Fig. 1. The EROEI is computed by taking the energetic content of the product delivered divided by the energy required to produce it. Ideally, the energy required for production includes the “cradle-to-gate” energy expenditures along the entire supply chain leading up to the production of that product over the entire life time of that supply chain. This includes the direct energy consumed during regular production of the product, but also the indirect energy consumption associated with aspects further up the supply chain (Poisson and Hall, 2013). This includes transportation fuels required to transport intermediate products from place to place, resource extraction, and the energy consumed during construction,

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* Tel.: +1 905 525 9140x24782.
E-mail address: tadams@mcmaster.ca

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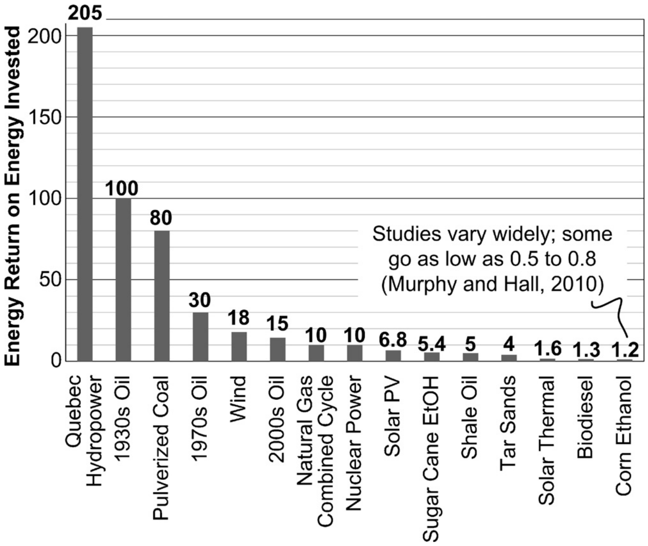

Fig. 1. The energy return on energy invested for selected energy conversion processes. Data are approximate and can vary for each specific process and application. All data from Murphy and Hall (2010), except Tar Sands (Poisson and Hall, 2013), and Hydropower (Gagnon et al., 2002).

commissioning, and decommissioning of each stage (where significant). The reader is referred to Murphy et al. (2011) for a full description various EROEI methodologies.

For example, in the 1930s, the EROEI of oil production was about 100, meaning that about 100 barrels of oil could be produced by consuming 1 barrel of oil (equivalent) to power the oil pumping and related processes. In the 1970s, this dropped to 30 and is around 14 starting in the 2000s. Unconventional oil is worse, with tar sands and shale oil at 4–5. Essentially, all of the “low hanging fruit” has been plucked, not just for oil, but for all natural resources as reserves deplete, forcing upstream recovery to move to deeper waters and more extreme climates. This is also reflected in renewable technologies, where we are currently developing (quite necessarily) areas such as biofuels and solar thermal to prepare for an eventual low-resource future. Unfortunately, the processes seen as most promising also have the most abysmal EROEIs at just above one (anything below one is mathematically unsustainable for fuel production). We are gradually moving towards lower and lower EROEIs for energy conversion in general, which is why quality process design is such a critical component of the global solution.

In this perspective article, a brief overview of the state of natural resources are presented, followed by a discussion of the new design challenges and opportunities that result. Several energy conversion process opportunities are identified which have the potential for significant global impact, either through the design of new processes which take advantage of new or emerging unit operations, or by the innovative integration of existing technologies into new processes. The scope is restricted to thermochemical conversion of non-renewable resources with a North American perspective.

2. What we have to work with

2.1. Non-renewable resources

It is helpful to examine the current state of our limited resources in order to understand our options for future processes. Recently, a significant price disparity has arisen between oil and gas, as shown in Fig. 2. Prior to the energy crisis of 2008, gas and oil had approximately the same price on an energy-content basis. However, in 2009, discoveries of shale gas reserves and advances in recovery technologies sent a price shock from the sudden new supply of gas. As a result, the oil price is currently 3.5 times the price of natural gas on an energy-content basis (on February 1, 2015), even though the price of crude has tumbled by almost $30 per barrel in the past five months. This price disparity is driving a rush of new interest into using natural gas as a raw material to create energy products traditionally produced by oil, which will be discussed in Section 4.

Based on the ratio of reserves to production, there is enough supply of petroleum to meet current demand for 53 years. This number should not be taken literally since it has actually been rising as more oil becomes discovered or technically recoverable. In fact, in 1984, the world oil supply was only at about 35 years (BP, 2014). Nevertheless, as shown in the gradually diminishing EROEI in Fig. 1, oil is becoming increasingly more difficult to obtain as recovery shifts more towards tar sands, deep waters, and polar regions. The quality of oil is also diminishing; the average API gravity refined in the US has steadily declined by about 2° over the past thirty years (Bacon and Tordo, 2005).

Conventional natural gas has a similar supply of about 55 years with almost no change in this number from 1984 to 2014 (BP, 2014). However, technically recoverable shale gas reserves are roughly just as large (EIA, 2013b), bringing the total combined reserve to around 109 years at present usage rates. Moreover, the future of fossil methane will not likely end there, since there could be as much as 10×10^{12} t of carbon (as CH_4) locked into gas hydrates located deep in rock beds offshore and in polar areas (Hester and Brewer, 2009). Although it is not yet economical to unlock these deposits, it makes sense to transition towards an increased use of gas now, expecting to eventually replace the conventional and shale gas sources with gas hydrates.

Coal is cheap and available, with a 113-year world supply (BP, 2014). For the range shown in Fig. 2, the cost of bituminous coal has essentially always been cheaper than oil or gas on a per-energy basis by a significant margin, and enjoys a much reduced variability. Despite the lower fuel prices, coal-based processes are generally much more expensive in terms of capital due to the difficulty of solids handling, contaminants, and higher carbon content per Joule, which results in generally more CO_2 produced than gas in most cases. Nevertheless, despite the dirtier nature of coal, several new energy conversion processes have the potential to use coal wisely such that all three aspects of the triple bottom line are satisfied.

Uranium, a non-fossil but non-renewable resource, is also relatively abundant in economic quantities, with about an 80-year world supply and rising (World Nuclear Association, 2012). Although its primary (peaceful) use is for electricity production and growth in this area is slowing, it is possible that new energy systems will be able to economically exploit its energy content for other forms of energy production, which is discussed in Section 4.3. Similarly, thorium is about three times as abundant as uranium, and may be used as well, though this has not yet been widely commercialized (World Nuclear Association, 2014).

2.2. Renewable resources

Theoretically, renewable solar resources (which include wind, biomass, and hydroelectric) may be able to provide for all current world energy needs of about 17 TW for all sectors including electricity, heat, industry, and transportation (de Castro et al., 2011). Although estimates vary widely, wind energy could supply as much as 38 TW (de Castro et al., 2011), hydroelectric up to 1.6 TW, and direct solar (photovoltaic and concentrated solar thermal) as much as 580 TW (Jacobson and Delucci, 2011). Although this means it is still possible that humanity can exist at its present size and standard of living using only renewables, this will not be possible for many decades. For example, even though it is growing very quickly (about 25% annually), only about 0.05 TW of wind energy is in use today, meaning that it will take 15 years to reach just 1 TW (de Castro et al.,