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Energy efficiency, primary energy, and apples vs. oranges

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Energy is a major cost when desalinating seawater, and plant designers strive to reduce that cost. When water and power are coproduced, the energy cost is the additional fuel (*primary energy*) added to the power plant to drive the desalination plant. But comparing the energy for coproduction to the energy for a stand-alone plant brings complications.

Two forms of energy transfer – heat and work – are used to separate fresh water from salt water. Thermodynamicists use the term "work" whenever a force to moves something – electrons, for example. Electrical work is most often used in desalination, mainly for pumping. High pressure then drives water through selective membranes. Alternatively, we can use heat, usually low temperature steam, to produce pure water vapor from saline feed.

In either case, the end result is to provide the chemical exergy needed to separate fresh water from salt water. This exergy is a thermodynamic property of the mixture, called the least work of separation, which depends only on the feed salinity, the product purity, and the fraction of water recovered. The least work to recover 50% of the water from seawater is about 1 $\mathrm{kWh_e/m^3}$ of fresh water.

No real system can ever reach this limit. The engineering challenge is to make the heat and/or work inputs to the desalination system as close as to this minimum as economics allow. To see how well we are doing, we compare the input exergy to the least exergy. Work is simply exergy. Heat at a temperature T_{hot} has exergy as well, i.e., the equivalent work it could do when flowing to a lower temperature, T_{cold}: heat exergy = $Q \cdot (1-T_{\mathrm{cold}}/T_{\mathrm{hot}})$. In other words, you can do more work with high temperature heat than low temperature heat.

All early desalination systems were thermally driven, and designers quickly found that they needed to reduce fuel costs. They also learned that scaling became intractable when the top temperatures were too high. The innovations that followed incorporated the multieffect evaporation systems pioneered by Norbert Rillieux in the 1830s and led to the power-water coproduction that accompanied multistage flash systems in the 1960s.

MSF coproduction, in particular, takes advantage of the fact that high temperature heat from combustion has a high exergy. (MSF inventor Robert Silver used the term "high availability").

The high temperature steam can first turn a turbine to produce electricity. The steam leaves the turbine at lower temperature, having lost both energy and exergy during power production. But if the steam is taken at a temperature above the final coolant temperature, its remaining exergy can drive evaporation in an MSF plant.

No power plant can convert all of its fuel energy to electricity. The rest must be rejected into the environment as heat. A modern combined cycle gas turbine plant (or CCGT) can convert about 60% of steam's energy to electricity. An ideal power plant, with no irreversibilities at all, could convert only a bit more than 80%—the maximum, or Carnot, efficiency at the corresponding temperatures.

Thus, any power plant rejects a great deal of heat. We can extract some portion of that heat at low temperature and send it to a thermal desalination plant. To avoid cutting into the electricity production for the grid, some additional fuel needs to be burned. But we still save a lot. In the 1970's, El Seyed and Silver used a thermodynamic analysis to show that the added fuel in coproduction can be as little as one-third of what's needed when burning fuel for stand-alone desalination.

So, we arrive at a well-known question: is fuel efficiency better when desalinating with thermal energy or electrical energy? The work-based reverse osmosis process has a high energy efficiency. The electrical work input to an entire RO plant may be 3 to 5 kWh_e/m^3. That's just 3 to 5 times the minimum possible value. The energy used in RO component of the plant by itself is only about 2.5 times the minimum, depending of course on many details of the design.

Thermal plants, in contrast, need electricity for water circulation and as well as low temperature heat for distillation. A comparison then requires converting this heat to exergy. I won't get into the weeds with thermo today. However, when we do this conversion, the exergy input to most MSF plants is several times larger than for a comparable RO plant. Advanced MED plants can be within a factor two of RO. But these differences are significantly reduced when we think in terms of fuel energy.

We care about the cost of energy as opposed to energy efficiency itself. For a purely electricity-driven desalination system, the price per kWh_e tells the whole story about energy cost. If we provide heat and electricity to a plant from different sources, each cost must be evaluated separately. This evaluation should be based on a levelized cost that incorporates the capital and operational cost of the heat supply. Even solar power and "waste heat" are never free!

The question is different for a coproduction plant. Here, we ask how much additional fuel must be burned to supply the desalination plant with heat and electricity. And this brings us to a second important issue: the energy efficiency of the power plant itself.

El Seyed and Silver noted that an inefficient power plant favors using heat rather than electricity for desalination. For a given fuel temperature, an inefficient plant needs more fuel to produce some amount of power. How inefficient must a power plant be on that basis? This depends on the efficiency of the thermal desalination plant and the steam extraction temperature. So, several variables affect the comparison.

In general, power plant efficiency must be below today's CCGT plants (at high fuel temperature) and below today's nuclear plants (at low fuel temperature) for established thermal technologies to reach RO's primary energy efficiency. Still, inefficient plants remain in use and thermal technologies continue to improve, so I won't draw a sweeping conclusion. Further, power plant selection will consider many other factors, such as energy security and carbon emissions.

A final thought that I'd like to share: comparing the energy efficiency of different desalination plants can be like comparing apples to oranges. Are the feed conditions the same? Is the water recovery ratio the same? Are there special requirements on product water quality? What about the plant intake and outfall requirements? And so on.

An analogy is found in power plant efficiency. A more efficient gas-fueled plant burns less fuel per kWh_e than a less efficient gas-fueled plant. But the high energy efficiency of a CCGT plant relative to a nuclear plant tells us nothing about the relative fuel cost or the electricity price. We'd do better to look at the levelized costs of electricity. Similarly, a difference in energy efficiency between two desalination plants may not reveal much when the conditions and constraints differ.

Energy use is just one factor that affects the economics of a desalination plant and the levelized cost of water. We can make any plant more efficient by raising CAPEX: use greater membrane area, more stages, or larger heat exchangers. The result, however, may be a higher price for water. In the end, plant design must focus on economics, not thermodynamics alone.

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