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The levelized cost of exergy: a technoeconomic framework for energy system comparison

Jordan D. Kocher,^{ib}*^{ab} Aravindh Rajan,^c Jason Woods,^{ib}^a Walter P. Parker Jr,^{ab}
Samuel Woolsey^b and Akanksha K. Menon*^{ab}

While the levelized costs of electricity and heat have been quantified before, these two metrics cannot be directly compared, due to the different exergy content of heat and work. To address this, we develop a levelized cost of exergy (LCOEx) framework that enables direct comparisons between energy sources and processes. We find that moderate- and high-grade heat have an LCOEx that is comparable to electricity (5–10 ¢ per kWh_{ex}), while low-grade heat sources have much higher LCOEx values (>50 ¢ per kWh_{ex}). The LCOEx of a system's output is affected by (i) the LCOEx of the system input, (ii) the CAPEX of the system, and (iii) the exergetic efficiency of the system. We use our framework to identify which processes are already achieved with relatively high cost effectiveness (production of fuels, hydrogen, and ammonia) and which have room for improvement (dehumidification, food production).

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Broader context

Growing populations demand efficient and cost-effective sources of food, water, and energy. To quantify the cost to produce commodities, researchers have developed “levelized cost” metrics, including the levelized cost of electricity (LCOE), levelized cost of heat (LCOH), levelized cost of water (LCOW), and levelized cost of ammonia (LCOA). However, these quantities cannot be directly compared, given the different units of measure. Even LCOE and LCOH, which are both quantified in cost per unit energy, should not be compared, since one unit of electrical work is not thermodynamically equivalent to one unit of heat transfer. In this work, we develop a broadly applicable “levelized cost of exergy” (LCOEx) metric. Our framework allows a direct comparison between the cost of exergy (or “useful energy”) within different energy sources, chemicals, and foods. Applying the framework to an energy system reveals how the system's output is influenced by (i) the LCOEx of the system input, (ii) the exergetic efficiency of the system, and (iii) the system CAPEX. The framework then indicates which thermodynamic processes have room for cost reduction, as well as those which are already cost-optimized. Of those with room for improvement, cost reduction can be achieved by switching to a process that produces the same output with a cheaper exergy source, improving process efficiency, and/or reducing CAPEX.

Introduction

As populations grow and urbanization intensifies, it becomes increasingly important to efficiently and cost-effectively utilize global energy resources. Low-grade heat, which for the purposes of this work is defined as heat delivered at temperatures ≤ 150 °C, is used in a variety of applications.^{1–6} For example, steam is used for sterilization,^{7–9} food and beverage processes,^{10,11} and thermal desalination.^{12–17} Hot water is used to heat buildings^{18,19} and regenerate liquid desiccants in dehumidifiers,^{20,21} and solar absorbers are used to regenerate sorbents in atmospheric water harvesting^{22–24} (AWH) and CO₂ direct air capture²⁵ (DAC) systems.

Low-grade heat is often far cheaper (per unit energy) than electricity; for example, Gilbert *et al.* found that industrial steam (at 150 °C) generated with natural gas (NG) has a levelized cost of 1.25 ¢ per kWh_{th},²⁶ while electricity produced by natural gas combined cycles (NGCC) often has a levelized cost around 6 ¢ per kWh.^{27,28} Solar- and waste-heat also seem attractive, given that they have no fuel cost. However, Geffroy *et al.* showed that the necessary capital investment and low conversion efficiency of low-grade waste heat yield unfavorable economics when using this heat to produce electricity.¹ Moderate-grade heat (above 150 °C) has more potential to generate electricity, in which case Rankine²⁹ and organic Rankine cycles³⁰ have proven cost-effective in valorizing waste heat. Beyond power generation, a broader technoeconomic analysis is needed to evaluate the viability of different energy sources (from electricity to low-grade and high-grade heat, hydrocarbon fuels, and more), which is the focus of the present work.

On a per unit energy basis, heat and electricity cannot be directly compared. This is because heat has less potential to do

^a National Laboratory of the Rockies, Golden, CO, USA.
E-mail: jordan.kocher@nrel.gov

^b George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA. E-mail: akanksha.menon@me.gatech.edu

^c Orca Sciences, Kirkland, WA, USA



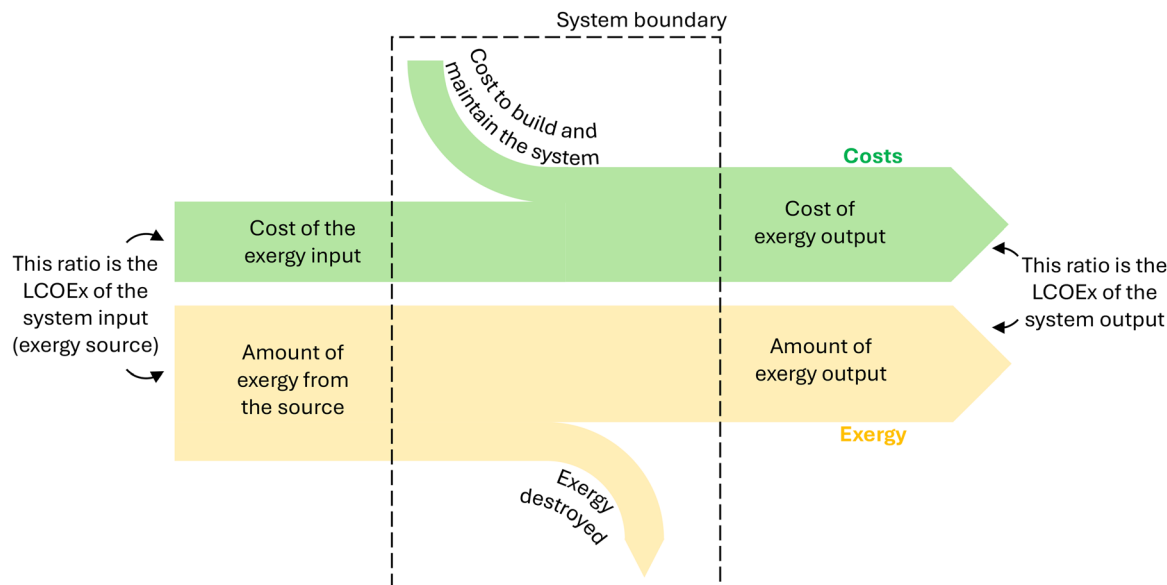


Fig. 1 Generalized LCOEx Sankey diagram.

cost per unit exergy of the system input ($LCOEx_{in}$), (ii) how exergy intensive the process is (Σ_{rev}), which is independent of the system performance and only depends on the thermodynamics of the process, and (iii) how close the system gets to the reversible limit (η_{ex}). This formulation is particularly useful as a litmus test for emerging concepts/processes: even in the reversible limit ($\eta_{ex} = 1$), would the process use a high LCOEx input? Or does it have a high specific exergy consumption? If the answer to either of these questions is yes, then the unit output cost will be high.

To visualize how the LCOEx increases when going from energy input to output of a system (or series of systems), we introduce an LCOEx Sankey diagram; a generalized version is shown in Fig. 1. The overall illustration consists of two separate Sankey diagrams: the top one is for cost (in green), while the bottom one is for exergy (in yellow). The ratio of cost to exergy represents the LCOEx. When that ratio is calculated before the system boundary (left side of the figure), it represents the LCOEx of the system's energy source. For example, in the case of a reverse osmosis (RO) plant, this would be the LCOEx of the electricity input. For a NGCC power plant, it is the LCOEx of the NG fuel. When the cost to exergy ratio is calculated after the system boundary (right side of the figure), it represents the LCOEx of the system output. For the RO plant example, this would be the cost per unit exergy of the fresh water produced by the plant. For the NGCC power plant, it is the electricity produced. Notably, the LCOEx always increases from system input to system output, because exergy is destroyed in any real process. Furthermore, there are costs associated with building and maintaining the system (CAPEX), which must be added to the cost of the exergy source. For the LCOEx of the system output to be as low as possible, the Sankey diagram in Fig. 1 reveals that the system should have the following three attributes: (i) it should utilize an exergy source with a low LCOEx,

(ii) the cost to build and maintain the system itself should be low, and (iii) the system should have a high exergetic efficiency. For a system with multiple subsystems, or for multiple different systems being used in series (e.g., a NGCC power plant generates electricity which is then used by an RO plant), the cost and exergy flow can be visualized through each of the systems sequentially, and the LCOEx at different points in the process can be calculated by taking the cost to exergy ratio before and after each system. The detailed methodology for constructing these diagrams with the appropriate units is described in Note S1.

Because Fig. 1 reveals that the LCOEx of a system's output largely depends on the LCOEx of the exergy source, we first present results for the LCOEx of various exergy sources, including electricity, high-grade and low-grade heat, fuels, and food. We then discuss which of these sources are used by different technologies, as well as the associated exergetic efficiencies. We then identify which processes and energy systems stand to benefit the most from switching to lower LCOEx sources and from exergetic efficiency improvements. Finally, we demonstrate that electrically-driven systems can reduce costs in certain cases (due to the relatively low LCOEx of electricity), while other systems will not benefit from using electricity as the energy source, due to high capital costs and/or low exergetic efficiencies.

Results

The LCOEx of heat

We apply our LCOEx framework first to heat as a source of exergy. We use the LCOH values that Gilbert *et al.*²⁶ calculated for four different applications (industrial steam at 150 °C, a hot water heater at 80 °C, ethane cracking at 850 °C, and a glass



furnace at 1200 °C). When NG is used as the heat source (and the cost of carbon is not considered), Gilbert *et al.* found the LCOH to be 1.25, 3.52, 3.70, and 5.94 ¢ per kWh_{th} for steam, hot water, ethane cracking, and glass furnaces, respectively.²⁶ In Fig. 2 we use these LCOH values to plot the LCOEx as a function of the temperature at which the heat is delivered. For example, steam generated using NG (in the industrial sector) has an LCOH of 1.25 ¢ per kWh_{th}. At a temperature of 150 °C, it would have an LCOEx of 4.3 ¢ per kWh_{ex} (from Fig. 2). If that steam were then used as the energy source to heat feed water in a desalination system at 80 °C, the delivered heat would have an LCOEx of 8.3 ¢ per kWh_{ex}. Several major findings result from this analysis. First, electricity is usually a cheaper method of delivering exergy to a system than low-grade (*i.e.*, ≤100 °C) heat. Second, the LCOEx from industrial steam is on-par with electricity, as is the heat used in ethane crackers (~5 ¢ per kWh_{ex}) and glass melters (~7 ¢ per kWh_{ex}). It is notable that, despite its lower exergy factor, steam at 150 °C is produced at a lower LCOEx than the high-grade heat applications. This is due to the lower CAPEX and higher thermal efficiency of the 150 °C steam

boiler,²⁶ giving electrically-driven heat little margin to compete with NG at these temperatures. Notably, the curves in Fig. 2 correspond to the particular assumptions made by Gilbert *et al.* regarding capacity factors, exergetic efficiencies, *etc.* Because these parameters vary by application and system design, Fig. 2 represents a common, but not comprehensive, range of LCOEx values for different heat sources.

Fig. 2 reveals that NG-fired hot water heaters produce heat at relatively high LCOEx values. This is partially due to the low temperatures of this heat: converting the chemical exergy of NG to heat at <100 °C is incredibly exergetically inefficient. This is also due to the fact that the hot water heater has a higher LCOH than the steam boiler. The high LCOH and low exergy factor of low-grade heat lead to LCOEx values in excess of 10 ¢ per kWh_{ex} at temperatures ≤80 °C. The hot water heater curve in Fig. 2 corresponds to heat as the end product. If creating hot water as the end product is expensive on a per unit exergy basis, then providing heat at similar temperatures to drive thermodynamic processes (*e.g.*, desiccant regeneration) will also be expensive. Thus, low-grade heat is typically a high LCOEx energy source



Fig. 2 The levelized cost of exergy (LCOEx) of different heat sources, with different levelized costs of heat (LCOH), as a function of the heat delivery temperature. Curves correspond to LCOH values taken from Gilbert *et al.*²⁶ for industrial steam (red curve), hot water heater (orange curve), ethane cracker (purple curve), and glass furnace (blue curve) with NG as the fuel source. The pink point corresponds to an incredibly simple (low CAPEX) solar thermal collector (see Note S3). The green band corresponds to the range of LCOEx for electricity from NGCC plants.²⁸



the CAPEX over two valuable products (instead of just hydrogen in conventional electrolysis).

Opportunities exist for electrically-driven systems to reduce cost

Following our analysis of exergy sources above, we now demonstrate the utility of the LCOEx framework in comparing systems that achieve the same process with different exergy sources. Due to its ubiquity as an energy source, the cost of electricity is a logical benchmark for LCOEx. Furthermore, electricity has a very competitive LCOEx compared to other energy sources (*e.g.*, heat, hydrocarbon fuels, *etc.*, shown in Fig. 2 and Table 1). One factor that has led to this is the high exergetic efficiency of NGCC power plants, which first convert the chemical exergy of NG to high-grade heat and then convert the heat to work, all with relatively low exergy destruction. Other electricity generation technologies must then compete with the LCOEx of NGCC electricity.

In Fig. 4, the LCOEx framework is applied to a historical example – desalination – to illustrate how the cost of a commodity can be reduced. Per eqn (3), the LCOEx of the system output depends on two quantities: $LCOEx_{in}/\eta_{ex}$, which represents the cost to convert the exergy input to output (if the system CAPEX were zero), and the actual (non-zero) system CAPEX. In Fig. 4(a), we plot historical desalination cost and efficiency data (see Methods). The LCOEx of fresh water produced with desalination is plotted against $LCOEx_{NG}/\eta_{ex}$, where $LCOEx_{NG}$ is the LCOEx of NG (1.37 ¢ per kWh_{ex}), and η_{ex} is the exergetic efficiency if NG were used as the primary energy

source (*i.e.*, going from NG and saline water to clean water). A clear trend emerges: the older, heat-driven technology (multi-stage flash, MSF) was inefficient at converting the chemical exergy in NG to fresh water, because of losses incurred when NG is converted to low-grade heat and because of losses in the heat-driven desalination system itself. This led to a high $LCOEx_{NG}/\eta_{ex}$ value in 1970 (Fig. 4(b)), which in turn caused the desalinated water to be expensive.

The first major improvement came when an electrically-driven technology was implemented (mechanical vapor compression, MVC), because the conversion of NG to electricity has a higher exergetic efficiency than NG to low-grade heat. Thus, using electricity as the exergy source improved the overall NG-to-water exergetic efficiency, which reduced $LCOEx_{NG}/\eta_{ex}$. Upon switching from distillation to MVC, $LCOEx_{H_2O}$ was reduced by less than $LCOEx_{NG}/\eta_{ex}$, indicating that the power plant + MVC combination had a higher CAPEX than the natural gas distillation system.

The next improvement came by increasing the exergetic efficiency of the desalination process itself, first by switching from MVC to RO, and then by improving the efficiency of RO (Fig. 4(c)). This highlights why (i) electricity is a favorable exergy source compared to low-grade heat, and (ii) processes that are exergetically efficient through the entire production chain (from primary energy source to final product) are usually preferable. This paradigm, revealed by the evolution of desalination, can serve as a roadmap to improve other processes. The exception, however, is when CAPEX is too high, which would result in a higher $LCOEx_{out}$, even with a lower $LCOEx_{in}/\eta_{ex}$.



Fig. 4 Comparison of work- and heat-driven desalination. (a) Plot of output (fresh water) LCOEx against the LCOEx of natural gas divided by exergetic efficiency. Desalination cost and efficiency data from Beltrán and Koo-Oshima.¹⁰⁷ (b) Heat-driven system, where a boiler destroys a large portion of the exergy from the fuel source when producing low-grade steam, and the heat-driven desalination plant destroys additional exergy, producing little water per unit fuel input. (c) Work-driven system, where the exergy from the fuel source is converted to electrical work with little exergy destruction, and the desalination plant has a high exergetic efficiency, so it produces a large amount of water per unit fuel input.



While desalination serves as an exemplary process for comparing work- and heat-driven technologies in the industrial sector, air conditioning can be used as a representative process in buildings. This is illustrated in the Sankey diagrams in Fig. 5. In Fig. 5(a), NG is used in a highly efficient power plant (61% exergetic efficiency for NGCC^{33,37}) and electricity is transmitted with little loss (95% exergetic efficiency for transmission¹⁰⁸) to a vapor compression refrigerator, which has an exergetic efficiency of 11% (Methods). Meanwhile, in Fig. 5(b), NG is used to directly heat an absorption refrigerator, where much of the NG chemical exergy is destroyed when converted to low-grade heat (assumed to be 90 °C¹⁰⁹), and then most of the remaining exergy is destroyed because of the relatively low exergetic efficiency of the absorption refrigerator (assumed to be 11%, which is the same as the vapor compression refrigerator).

Similar to the conclusion for desalination, we find that work-driven refrigeration tends to have a lower LCOEx at the system output compared to absorption refrigeration, owing to fewer exergetic losses. If absorption refrigerators

were designed to utilize very high-grade heat (as is used in power plants), then the overall exergetic efficiencies of vapor compression and absorption refrigeration would be comparable. However, engineering residential and commercial technologies to utilize this high-grade heat is unrealistic and would increase the CAPEX of absorption refrigeration. Instead, some absorption refrigerators utilize waste heat in large combined heat and power (CHP) plants;¹¹⁰ despite the low exergy factor of low-grade waste heat, the economics are favorable when the CAPEX of the heat exchanger to transfer this heat to the refrigerator is not too high. In the illustrative example in Fig. 5, it is assumed that both the vapor compression and absorption refrigeration systems have a CAPEX of \$1000 per ton (which is likely a generous assumption for absorption refrigeration), a lifetime of 10 years, and a utilization factor of 20% (*i.e.*, they run for 20% of the year). A discount rate of 7% was used to obtain the values in the illustration. The exergetic efficiency of 11% approximately corresponds to a COP of 4 for vapor compression and 0.7 for



Fig. 5 LCOEx Sankey diagrams for (a) vapor compression and (b) absorption refrigeration. Both systems use natural gas (NG) as the primary energy source, but the process of converting the chemical exergy within NG to high-grade heat, which is used to produce electricity and drive vapor compression refrigeration is significantly more exergetically efficient than using NG to produce low-grade heat and drive absorption refrigeration. This leads to cost benefits for vapor compression refrigeration.



absorption refrigeration when the indoor temperature is 26.7 °C and the outdoor temperature is 35 °C.

Air conditioning^{111–113} (cooling) has seen electrically-driven systems become the dominant technology (*i.e.*, vapor compression refrigeration) due to the paradigm mentioned above – the generation of electricity with high-grade heat is generally more exergetically efficient and cost-effective than using low-grade heat to power an absorption refrigeration cycle. However, the paradigm is somewhat different for heating in the built environment. As is the case with cooling, it is generally more exergetically efficient to generate electricity at a centralized power plant and then use that electricity to drive a heat pump than it is to burn natural gas to provide the low-grade heat needed in buildings. However, the low CAPEX of a NG furnace (compared to a heat pump) and the low cost of NG mean that, in certain cases, the less exergetically efficient method of burning NG to provide heat in buildings is still the more cost effective one. In other cases, such as in the southern U.S., where heating is not often needed and a vapor compression system is already required for cooling, the heat pump option may be preferable. In general, the LCOEx of the output heat of a natural gas furnace can be calculated, and if it is lower than the local electricity price, then there is no chance that the heat pump can compete (without subsidies or incentives). If, however, the LCOEx of the heat from a natural gas furnace is higher than the LCOEx of electricity, then the heat pump could be an attractive option (depending on the heat pump CAPEX and exergetic efficiency).

It is important to remember that both the LCOEx of a system's energy source and the exergetic efficiency of the system greatly affect the LCOEx of the system output. Perhaps no technology better demonstrates this than dehumidifiers. Currently, the vast majority of dehumidifiers use vapor compression refrigeration to condense moisture out of the supply air. This method is driven by electricity, which has a relatively low LCOEx; however, condensation dehumidification suffers from a very low exergetic efficiency.^{114,115} Thus, while the LCOEx of the energy source is low, the dehumidifier's low exergetic efficiency will cause the output LCOEx to be high. Researchers have explored heat-driven desiccant dehumidifiers as alternatives,^{116,117} but the LCOEx of low-grade heat input is high (Fig. 2), and desiccant systems sometimes have exergetic efficiencies that are not significantly greater than traditional air conditioning.¹¹⁸ Thus, there is an opportunity to lower the cost of dehumidification by creating systems that are driven by low LCOEx energy sources (such as electricity) but also have significantly higher exergetic efficiencies than current (electrically-driven) cold surface condensation dehumidifiers. Some liquid desiccant-based systems approach this by regenerating the desiccant with the heat from the condenser and cooling the supply air with the evaporator.²¹ Generally, the LCOEx framework favors this concept: these systems use existing vapor compression components that are already present in a traditional air conditioner (to avoid a significant CAPEX increase), while utilizing electricity as the energy source (low LCOEx

input), and improving the COP over a traditional air conditioner (higher exergetic efficiency).

Certain processes are more likely to benefit from using electricity as the input

To understand where an electrically-driven process could compete with traditional heat- or fuel-driven alternatives, we present the regime maps in Fig. 6. This can be divided into 3 categories: (i) electrically-driven processes that cannot compete with conventional (*e.g.*, thermochemical) processes, even when electricity is incredibly cheap (hydrocarbons and hydrogen), (ii) electrically-driven processes that can compete with traditional processes, but only if electricity becomes incredibly cheap (ammonia, moderate-grade heat), and (iii) electrically-driven processes that can already compete with traditional processes (high-grade heat). The regime maps also indicate whether the output cost of a given process is CAPEX-limited or efficiency-limited. For example, both green hydrogen and green ammonia are in the CAPEX-limited regime, such that improving the exergetic efficiency will have a negligible effect on cost.

We first discuss the fuels – hydrocarbons (Fig. 6(a)), hydrogen (Fig. 6(b)), and ammonia (Fig. 6(c)). An electrically-driven system could produce any of these chemicals with the molecules present in the atmosphere: water vapor for hydrogen, CO₂ for carbon, and air for nitrogen. Alternatively, liquid water could be used as the hydrogen source, though this would change the input LCOEx slightly, given its nonzero cost and exergy. NG is an incredibly cheap fuel, indicated by its low LCOEx. An unrealistically low CAPEX would be required to synthetically produce cost-competitive NG *via* electricity and feedstocks at the dead state (*i.e.*, atmospheric) or near-dead state (*i.e.*, low specific exergy, such as liquid water), even when electricity is incredibly cheap (1 ¢ per kWh_e). Jet A-1, the most common jet fuel,¹¹⁹ has a higher LCOEx, but it will still be difficult for electricity to directly produce it at a competitive cost. A more feasible avenue for electricity to compete with fuels is as an energy source in the transportation sector (*i.e.*, electric vehicles); the regime map for battery electric vehicles is given in Note S6.

Hydrocarbons are also used to produce plastics; for example, ethylene is the feedstock for polyethylene (~\$1 per kg cost¹²⁰ and ~12.8 kWh_{ex} kg⁻¹ chemical exergy¹²¹). The question then arises as to whether the production of plastic feedstocks could switch to electricity as the energy source and use dead state hydrogen and carbon (*i.e.*, atmospheric H₂O and CO₂) without a significant premium. While the LCOEx of polyethylene is somewhat more forgiving than NG, it would still require a relatively low CAPEX, revealing the challenges facing a hypothetical “electrically-driven atmospheric plastic production” process as a means of establishing an alternative plastic supply chain.

Green hydrogen production *via* electrolysis has been widely discussed in recent years. However, Fig. 6(b) casts doubt on its viability as an economically competitive fuel. Assuming an exergetic efficiency of 65% for electrically-produced hydrogen, the blue curve indicates the LCOEx of H₂ produced with cheap electricity (1 ¢ per kWh_e). If the electrolyzer CAPEX is \$3 per W





Fig. 6 LCOEx regime maps for various commodities. Electricity can be used to produce (a) synthetic hydrocarbons, (b) hydrogen, (c) ammonia, (d) protein, (e) high-grade heat, and (f) medium-grade heat. Each plot shows the LCOEx of different commodities produced *via* conventional means (e.g., thermochemistry) with horizontal dashed lines. Then, the LCOEx of the same commodity, produced *via* an electrically-driven system (either hypothetical or already realized) is plotted against the CAPEX of the electrically-driven system. The red curve corresponds to a reversible electrically-driven process, so no electrically-driven system can exist within the shaded red region.

and the plant operates around the clock (*i.e.*, a capacity factor of unity), then electrically-produced hydrogen will fail to compete with both SMR and methane pyrolysis, even when electricity is cheap. If the electrolyzer CAPEX is only \$1.5 per W to the levelized cost of hydrogen, the electrically-produced hydrogen

would be cheaper than methane pyrolysis but still more expensive than SMR.

Green ammonia (Fig. 6(c)), produced *via* electrolyzed hydrogen fed to a Haber-Bosch plant, has also been discussed as a potential fuel source and fertilizer. To evaluate the former



use-case, the LCOEx of green ammonia should be compared to the LCOEx of other fuel sources. To evaluate the latter use-case, the LCOEx of green ammonia should be compared to that of grey ammonia. The CAPEX of a green ammonia plant can be approximated as that of a conventional (gray) ammonia plant, minus the CAPEX of the SMR portion of the plant, plus the CAPEX of an electrolyzer to replace the SMR. Thus, the “green premium” incurred on the ammonia CAPEX is less significant than in a green hydrogen plant, since it only affects a portion of the overall plant (and 1 kg of green hydrogen produces 5.63 kg of green ammonia). Regardless of whether the electrolyzer CAPEX is \$1.5 per W or \$3 per W, green ammonia would be cost competitive with grey ammonia if 1 ¢ per kWh_e electricity were continuously available. This indicates a potential pathway for green ammonia to serve as a fertilizer. However, firm electricity at this cost will be difficult to produce. If the cheap electricity is only available intermittently, the capacity factor of the plant decreases, which increases the levelized CAPEX. As such, we have plotted points for a capacity factor of 0.25 (6 h of operation per day), which are significantly more expensive than conventionally-produced (gray) ammonia. Thus, green ammonia needs both very cheap and firm electricity to avoid a green premium. Furthermore, given the LCOEx of green ammonia – between 6 and 10 ¢ per kWh_{ex} – its use as a fuel source in the industrial and transportation sectors is not practical. It would be very cost ineffective to use 1 ¢ per kWh_{ex} electricity to produce green ammonia, an exergy/fuel source that is 6–10× more expensive than the electricity used to make it, and then use that ammonia to power some other system. Exergy is lost and cost is incurred by converting the cheap electricity into ammonia and then using that ammonia to power another process. Even green hydrogen, with an LCOEx of 4 ¢ per kWh_{ex} (when the CAPEX is \$1 per kg and electricity is 1 ¢ per kWh_e) would be an expensive exergy source relative to the electricity used to make it. Thus, our framework reveals the exergetic and economic inefficiencies associated with using electrically-produced fuels to power different sectors of the economy, though electrically-produced chemicals do have potential for other uses (*e.g.*, as fertilizer).

While Fig. 6(a) reveals the significant challenges of using electricity to produce a cheap, high specific exergy fuel, Fig. 6(d) reveals a potential opportunity for electricity to produce the opposite – a more expensive, lower exergy material, such as protein. Poultry has a relatively high LCOEx, but electrochemically produced protein would likely not compete with meats, due to the fact that they are consumed in part for their taste. Instead, electrically-driven protein production would compete with protein isolates. Per Table 2, the specific cost of soybeans is 38.79 ¢ per kg, and there are 348 g of protein per kg of soybean, equating to a cost of \$1.11 per kg of protein. Based on the exergy of protein, this corresponds to an LCOEx of ~16 ¢ per kWh_{ex} for the protein within soybeans. However, Table 2 reveals that soy protein isolate has an LCOEx of ~40 ¢ per kWh_{ex}; this increase in cost is due to the exergetic losses and costs incurred when going from soybean to soy protein isolate. This high LCOEx of protein isolate gives

electrochemistry a chance to compete, and Fig. 6(d) sets the CAPEX values that must be met for it to do so. The exergetic efficiency of electricity to single-cell protein (SCP) biomass is approximated as 4% based on Wang *et al.*⁹⁵ When the system CAPEX is high (>\$10 per kg protein), the exergetic efficiency has little bearing on output cost. Conversely, if the system CAPEX is low (<\$1 per kg protein), the exergetic efficiency has a significant effect on output cost, while a reduction in CAPEX would yield negligible benefits.

When utilizing intermittent electricity from renewable energy sources, “firmed” (or consistently available) requires some form of energy storage. Furthermore, the question remains as to whether this electrically-driven heat should be produced *via* dissipative heating (*e.g.*, resistive heating) or *via* heat pumps. In Fig. 6(e) and (f), we investigate the LCOEx of firmed heat that is produced by an intermittent electricity source (with an LCOE of 1 ¢ per kWh_e). In this case, we assume the electric resistance heater CAPEX is negligible, so we plot the LCOEx as a function of the CAPEX of the energy storage system. Fig. 6(e) reveals that, from an exergetic standpoint, high-grade heat will be the easiest to switch the exergy source to electricity (though practical challenges, such as durability at high temperatures, must be considered). This is because electric resistance heaters, which have a lower CAPEX than heat pumps, destroy little exergy when dissipating their electricity as heat at high temperatures. The combination of low CAPEX and high exergetic efficiency, and low input LCOEx of electric resistance heaters will allow the LCOEx of high temperature electric resistance heaters to approach that of the electricity input. Electricity at 1 ¢ per kWh_e would thus lead to incredibly cheap high-grade industrial heat, but even electricity at 6 ¢ per kWh_e would be close to the cost of high-grade industrial heat from NG (~5 ¢ per kWh_e). While electrochemical storage has a high CAPEX, thermal storage could enable low-cost electrically-driven heat if current cost targets are achieved¹²² as the technology readiness improves. Fig. 6(f) reveals that moderate-grade heat (150–400 °C) will be harder to source *via* electricity, for several reasons. First, NG has both lower LCOH and lower LCOEx values at these temperatures than high-grade heat (due to lower CAPEX and higher thermal efficiency²⁶). Second, dissipative electric heaters will destroy far more exergy at these temperatures. For example, a dissipative heater (whether electric resistance or microwave) with a thermal efficiency of unity (the best-case scenario) would only have an exergetic efficiency of 20% at 100 °C and 55% at 400 °C. Fig. 6(f) shows that at 200 °C, electric resistance could compete with NG heat, but only if the cost of intermittent electricity input falls to 1 ¢ per kWh_e. This indicates that the production of moderate-grade heat *via* electricity is feasible but difficult. At these temperatures, the less CAPEX-heavy electric resistance option has significantly more exergetic losses than when producing high-grade heat. Meanwhile, the more exergetically efficient heat pump option leads to a higher CAPEX, and the exergetic benefits are not as significant as when producing low-grade heat. So while electric resistance heating can be attractive for high-grade heat and heat pumps



can be attractive for low-grade heat,³⁸ it is unclear if either option can compete with NG for moderate-grade heat production.

Conclusions

The LCOEx framework enables a direct comparison between different energy sources, systems, and processes on a common basis (\$ per kWh_{ex}). Among different energy sources, electricity delivers exergy at a relatively low cost, while low-grade heat does not carry much exergy per unit energy and thus has a relatively high LCOEx. In the theoretical ideal case, the LCOEx of a system's output would be equal to the LCOEx of the energy source/input, because there would be zero exergy destruction (reversible) and zero system CAPEX. However, any real system will have some capital cost and will destroy some of the input exergy, so the LCOEx of the output will always be greater. This highlights the importance of designing systems that:

- (i) Utilize low LCOEx energy sources.
- (ii) Achieve high exergetic efficiency.
- (iii) Have low CAPEX.

We use this work to demonstrate the new LCOEx framework, illustrate its utility through examples, and evaluate the price per unit exergy of different commodities (chemical fuels, electricity, water, heat, cooling, and food). Our analysis is not comprehensive given the wide breadth of processes to which it can be applied, and future studies can utilize the framework to analyze different commodities in greater depth.

Applying the LCOEx framework to different processes reveals which have significant room for improvement and which are already optimized, with LCOE values used as a benchmark for LCOEx. The opportunity to reduce cost should, however, be taken in context of the history of a given technology. For example, both air conditioning (~173 ¢ per kWh_{ex} output per Fig. 5) and desalination (~70 ¢ per kWh_{ex} output per Fig. 4) produce outputs with LCOEx values more than 10× that of electricity. This indicates room for improvement, but it is important to recognize that both processes are already electrically-driven, and they have experienced more than a century of engineering.^{123,124} As such, we believe it is unlikely that drastically higher exergetic efficiencies can be achieved without a significant increase in CAPEX.

Using the LCOEx metric not as a replacement for other levelized cost metrics, but rather as a complement to them, allows for a useful perspective. For example, the levelized cost of heat, water, hydrogen, ammonia, and energy storage are all useful metrics in assessing the economic viability of different energy systems, when compared to systems that produce the same output. These metrics, however, provide no insight into how fundamental thermodynamics influence the cost of an output, based on the cost of the inputs and the efficiency of the process. By combining conventional levelized cost metrics (*i.e.*, the green portion of the Sankey diagram in Fig. 1) with exergy analysis (*i.e.*, the yellow portion of the Sankey diagram in Fig. 1), a new perspective on the cost-effectiveness and efficiency of a thermodynamic process is gained.

The LCOEx framework is also useful in identifying fundamental cost bounds for different processes. For example, AWH is limited by the LCOEx of the exergy input and the specific exergy of the harvested water. AWH uses exergy sources with an LCOEx ~ 6 ¢ per kWh_{ex} (*e.g.*, electricity or heat) and the specific exergy consumption is high (~80 kWh_{ex} m⁻³ for reversible operation in arid regions per Note S5). Thus, even when the CAPEX is negligible, the cost to produce water will be ~\$4.80 per m³, a value too high to compete with RO desalination (~\$1 per m³).³⁵ In other cases, the reversible limit is potentially acceptable; for example, the reversible exergy consumption of DAC¹²⁵ is ~200 kWh_{ex} per ton of CO₂, such that the reversible exergy input accounts for merely \$12 per ton CO₂ when the input LCOEx is 6 ¢ per kWh_{ex}. However, for processes like DAC, exergetic efficiencies and CAPEX hinder economic viability. These thermo-economically constrained processes need to leverage thermodynamic advantages to either lower the input LCOEx (*e.g.*, point source carbon capture and hydrogen production *via* sulfur depolarized electrolysis^{105,106,126,127}) or lower the specific exergy of the product (*e.g.*, DAC *via* enhanced rock weathering). Otherwise, they will struggle to progress beyond lab-scale demonstrations and may never see meaningful market penetration.

Finally, we developed LCOEx regime maps for electrically-driven systems. By comparing the LCOEx of conventionally-produced commodities to electrically-driven alternatives, we identified (i) commodities that electricity would struggle to produce with cost parity (*e.g.*, fuels), (ii) the CAPEX and exergetic efficiencies needed for emerging electrically-driven process (*e.g.*, electrochemical protein synthesis), and (iii) for which processes electricity already makes sense as the exergy source (*e.g.*, high-grade heat). We found that electrically-produced ammonia (specifically for fertilizers) and moderate-grade heat could reach cost parity if inexpensive electricity (1 ¢ per kWh_e) becomes available, but if this electricity is intermittent the reduced capacity factor will make these electrically-driven commodities expensive. Alternatively, we believe that moderate-grade heat could be electrically-produced with more expensive electricity if better heat pumps are developed (*i.e.*, lower CAPEX and higher exergetic efficiencies), but the margin for exergetic efficiency improvement that a heat pump presents over electric resistance heating is smaller at moderate-grade temperatures than with low-grade heat. Ultimately, while our analysis reveals the cost-effectiveness of electricity as an exergy source, further research is required to understand if the CAPEX and efficiency targets that we present for electrically-driven systems can be achieved. If these targets prove feasible, then the technology readiness of these emerging, electrically-driven processes must be addressed.

Methods

Calculating LCOEx and specific exergy content values in Table 2

The mass of protein, fat, and carbohydrates per kg of corn were calculated for a moisture content of 15.5%, which is the



standard moisture content for a bushel of corn.¹²⁸ The mass of protein, fat, and carbohydrates per kg of soybeans were calculated for a moisture content of 13%, which is the standard moisture content for a bushel of soybeans.¹²⁹ For the protein, fat, and carbohydrates within wheat, USDA nutrition data for durum wheat was used, even though common wheat makes up the vast majority of global wheat production¹³⁰ (because common wheat nutritional information was not given on the USDA website). For eggs, prices are reported in \$ per dozen, and it was assumed that 1 dozen eggs weigh 1.5 lbs.

For beef, the hot carcass weight was assumed to be 63% of the live weight, whereas the boneless trimmed beef weight is 40% of the live weight.^{131,132} The carcass contains fat which is discarded as a byproduct, and that fat contains some exergy, though that exergy is not considered in this work. Instead, we take the nutritional exergy of the boneless trimmed beef for our LCOEx value of beef in Table 2. Lean beef consists of 22.3% protein by weight and 1.8% fat by weight.¹³³ Thus, 8.9% of the live animal weight is edible protein and 0.72% is edible fat.

For chicken, the edible share of live weight is 60%,¹³² and of this meat, 22.8% and 0.9% by weight are protein and fat, respectively.¹³³ Thus, of the live animal weight, 13.7% is edible protein and 0.54% is edible fat.

For protein isolate, the bulk production cost per kg of soy protein isolate was used,⁹³ along with soy protein isolate nutritional data.¹³⁴

Historical desalination data

The desalination plot in Fig. 4 was created using historical data for seawater desalination in Spain, spanning from 1970 to 2005.^{12,107} The primary energy source (*e.g.*, natural gas, coal, solar, wind) was not given for any of these systems, so it is impossible to know the true input LCOEx. Instead, we used the LCOEx of NG as a proxy, and we approximated the hypothetical NG-to-water exergetic efficiency to make a direct comparison between the heat- and work-driven technologies. For the heat-driven system (MSF), it was assumed that the reported SEC in the dataset was an “equivalent” electrical SEC, which is simply the thermal SEC multiplied by a factor of 0.3 (the standard power plant efficiency used to convert thermal SEC values to electrical SEC in desalination literature¹²). Thus, we took the reported SEC values from the dataset and divided by a factor of 0.3 to return the original thermal SEC (*e.g.*, a reported SEC of 22 kWh_e m⁻³ for MSF becomes 73.3 kWh_{th} m⁻³). It was assumed that this SEC corresponds to the steam used to deliver heat to the MSF system; a boiler efficiency of 0.8 was assumed, such that the steam SEC was divided by 0.8 to return the amount of NG heat used to produce the steam that was used (*e.g.*, the calculated steam SEC of 73.3 kWh_{th} m⁻³ for MSF becomes 91.7 kWh_{th} m⁻³). Then, to find the original exergy within the NG, the exergy factor of 1.03 (which corresponds to NG³⁷) was used (*e.g.*, the calculated NG thermal SEC of 91.7 kWh_{th} m⁻³ for MSF becomes $\Sigma = 94.4$ kWh_{ex} m⁻³). Then, to find the exergetic efficiency, the minimum separation exergy for seawater desalination (~ 0.9 kWh_{ex} m⁻³) was divided by the

exergy input to find the exergetic efficiency (*e.g.*, $\Sigma = 94.4$ kWh_{ex} m⁻³ becomes $\eta_{\text{ex}} = 9.5\%$).

For the electrically-driven systems (MVC and RO), the hypothetical NG-to-water exergetic efficiency was found by first assuming that the electricity could be generated with a NGCC power plant possessing a thermal efficiency of 55% (slightly lower than the state of the art³³). For example, a reported SEC of 3 kWh_e m⁻³ for RO becomes 5.5 kWh_{th} m⁻³ of heat from NG used to generate the electricity needed to drive RO. Then, the exergy factor of NG³⁷ (1.03) was used to find the original exergy within the NG used to generate the electricity (*e.g.*, the calculated NG thermal SEC of 5.5 kWh_{th} m⁻³ for RO becomes $\Sigma = 5.6$ kWh_{ex} m⁻³). Finally, the minimum separation exergy for seawater desalination (~ 0.9 kWh_{ex} m⁻³) was again divided by the exergy input to find the exergetic efficiency (*e.g.*, $\Sigma = 5.6$ kWh_{ex} m⁻³ becomes $\eta_{\text{ex}} = 16.0\%$).

Air conditioning exergetic efficiency

To estimate the exergetic efficiency of air conditioning, we assumed that the vapor compression system has a COP of 4 (based on current SEER2 standards¹³⁵) at the EER2 standard testing conditions of 80 °F indoor dry-bulb temperature and 95 °F outdoor dry-bulb temperature.¹³⁶ At these standard testing conditions, the reversible COP would be 36. If the actual COP is 4 and the reversible COP is 36, then the exergetic efficiency is $\sim 11\%$.

CAPEX and exergetic efficiency values in electrically-driven regime maps

For hydrogen electrolysis, we found that an LCOEx of 14.3 ¢ per kWh_{ex} (\$5.50 per kg) results when the electrolyzer CAPEX contributes roughly \$2 per kg of the levelized cost of hydrogen (assuming 65% exergetic efficiency during electrolysis and an input electricity cost of 6 ¢ per kWh_e). This levelized CAPEX contribution of \$2 per kg_{H₂} corresponds to an electrolyzer cost of \$3 per W (when a discount rate of 7% and electrolyzer lifetime of 14 years are assumed). While this agrees with some existing literature,^{137,138} an electrolyzer CAPEX contribution of \$1 per kg (\$1.5 per W) is also commonly reported.¹³⁹ As such, we provided results for both values, for both hydrogen and ammonia. For both ammonia and hydrogen synthesis, we assumed the exergetic efficiency of electrically-driven synthesis is 65% (given that the hydrogen to ammonia exergetic efficiency is nearly unity¹⁴⁰). For green ammonia plant CAPEX, we assume the NH₃ and N₂ subsystems CAPEX contribute a levelized cost of \$0.10 per kg NH₃, while the electrolyzer levelized CAPEX in units of \$ per kg H₂ can be converted into units of \$ per kg NH₃ by accounting for the fact that 1 kg of H₂ produces 5.6 kg of NH₃.

For industrial heat, we used a thermal storage CAPEX of \$5 per kWh_{th}, based on values reported by Rondo for their thermal storage system.¹²² For electrochemical batteries, we used a CAPEX value of \$100 per kWh_e, which is typical for current Li-ion batteries.¹⁴¹



Author contributions

Conceptualization, J. D. K.; methodology, J. D. K.; investigation, J. D. K., A. R., W. P. P., and S. W.; writing – original draft, J. D. K.; writing – review & editing, J. D. K., A. R., J. W., W. P. P., S. W., and A. K. M.; funding acquisition, J. D. K., J. W., S. W., and A. K. M.; supervision, J. D. K. and A. K. M.

Conflicts of interest

There are no conflicts to declare.

Data availability

All data generated or analyzed during this study are included in the manuscript and its supplementary information (SI). Supplementary information is available. See DOI: <https://doi.org/10.1039/d5ee05267j>.

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