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EDITORIAL

Do You Really Mean to Call It *Highly Efficient*?

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Research at the interface between chemistry and engineering for advancing energy technologies frequently relies on various metrics of efficiency. While energy conversion efficiency, η, is the most commonly used, other definitions are also employed. A photovoltaic device can be evaluated by its internal/external quantum efficiency, while an electrochemical conversion process can be described by its Faradaic efficiency towards a particular product. Researchers in the photoelectrochemical field are familiar with the applied bias photon-to-current efficiency, and Coulombic efficiency is an important concept for battery development. In these cases, each definition of efficiency refers to a specific type of conversion process and is precise and quantifiable. High efficiency is desirable, and breaking efficiency records is the goal of many researchers in these fields. Thus, it is not surprising that authors are eager to use the term "efficiency" to describe many aspects of their work. However, as a detail-oriented editor, author, and reviewer, I would like to take this opportunity to call into question the common use of the term "efficiency" and rhetorically ask: do you really mean to call that efficient? Case in point: recent Letters in *ACS Energy Letters* have had titles including the phrases "Efficient Hydrothermal Synthesis", "Efficient Optical Orientation", "Efficient Defect Passivation", and "Efficient Exciton Diffusion", to name a few. Of course, I do not question the importance or the quality of the scientific results reported in these papers, but I only wish to examine the use of the term and make suggestions as to its appropriate use.

Broadly, *efficiency* is defined as the ratio of the useful output of a system to the input. While it is most commonly used as a measure of how well a device or process is able to convert energy from one form to another, commonly used definitions extend beyond this to other fields, such as economics and computer science. Importantly, efficiency is a measurable and quantifiable concept, and it is most useful as a dimensionless quantity between 0 and 1 (or 0 and 100%). Indeed, given unavoidable entropic losses, one cannot expect more output than input for a conversion process. Yes, it should be noted that in specific cases (e.g., carrier multiplication in solar cells), efficiency can be defined wherein values exceeding 100% could result, but these are, of course, not rigorously energy conversion efficiencies. Moreover, it should be noted that in many energy conversion processes, efficiency is not the most appropriate or relevant term. For example, in refrigeration, we do not quantify the performance by efficiency, or at least this is not the most relevant quantity. Rather the coefficient of performance (COP) is a measure of the effectiveness of a refrigerator. It is defined as the ratio of the amount of heat removed from the refrigerated space to the amount of work required to remove that heat. The COP is

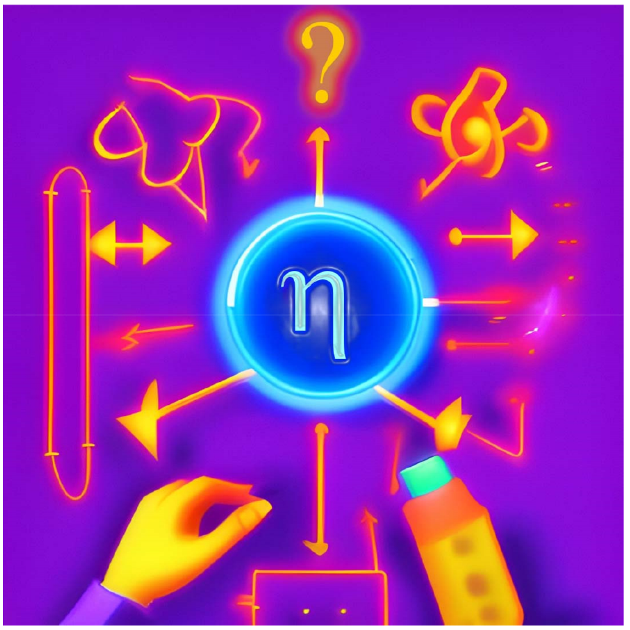

Figure 1. Abstract illustration of the concept of "confusion about energy efficiency of a chemical conversion device". Text-to-image generation from canva.com was used, in part, to create this image.

usually greater than 1, because, instead of merely converting work to heat (which would be a COP of 1 if 100% efficient), a refrigerator uses the inputted work to move heat from one place to another. So, when a refrigerator or heat pump is colloquially described as "efficient", what is probably meant is that the process has a high COP. In this case, since efficiency is not the relevant term, nor is it even necessarily measured, why not describe the refrigerator or heat pump as "high-performance" instead?

Accordingly, as careful authors, should we characterize a chemical synthesis as "efficient"? Well, maybe we can. We could define a ratio based on the net thermodynamic output of the reaction (i.e., the energies of formation of the useful products minus the reactants) to the amount of energy input to the

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reaction to cause the conversion. However, if a researcher does not go through some effort to define this quantity, estimate its value, and compare it to other synthetic routes, then it would be better to use a different term to describe the reaction (e.g., "high-yield", "direct", or "facile"). Similarly, with the concepts of exciton diffusion, optical orientation, or defect passivation, can we define ratios that make sense to establish quantifiable definitions of efficiency here? These seem less straightforward to me. In these cases, a better term may be "effective". Indeed, efficiency is often confused with effectiveness, the latter being a more basic concept of the ability to achieve a desired result and not usually defined by a ratio of input to output (even though certain definitions of effectiveness are well-defined mathematical quantities, like the "power utilization effectiveness" as a measure of data center energy integration).

Another example could be found in electrocatalysis, which is a topic frequently discussed in *ACS Energy Letters*. Often, I read manuscripts that claim the synthesis of a new "efficient" catalyst for an electrocatalytic transformation (e.g., one of the water splitting half reactions). Can a catalyst be described as "efficient"? I say no. Certainly, the catalyst itself cannot be efficient as it is a material and not, by its very nature, a conversion process. Perhaps we could characterize it as "facilitating an efficient catalytic process". Indeed, for an overall electrocatalytic transformation process, efficiency can be clearly defined. Take water splitting to produce H_2 and O_2, for example. An electrolysis device requires a certain input power (voltage times electrical current) to produce H_2 and O_2 at a particular rate. Assuming some energic value of the products (i.e., the lower heating value for H_2 and nothing for O_2), we can compare the input power to the outputted energy storage rate. Since both of these quantities have the same dimensions, we arrive at a dimensionless efficiency. However, the efficiency depends not only on the electrocatalysts used but also on a number of other factors, including cell design and the specific operating conditions (e.g., temperature, pressure, current density). When developing new electrocatalysts for the water splitting reactions, researchers typically measure the observed current density at specific applied potentials. Compared to the standard redox potential, an overpotential to drive the desired reaction at a defined current density can be extracted. Well, then a new catalyst or electrode assembly operating with a lower overpotential compared to existing materials running at the same conditions should therefore be more efficient, right? I am not convinced. Other factors, such as mass transfer resistance or Ohmic losses, which are typically ignored in electrocatalyst development, may result in a lower overall efficiency under real device operation. Therefore, unless a complete device is constructed and an actual efficiency is quantified, it would be better to describe a new electrocatalyst as "yielding low overpotential" and state the measured overpotential under precise conditions.

A final point is the use of terms like "highly efficient", "high efficiency", or similar to describe results. Employing superlative terms like these in scientific literature has been commented on recently,[1] but nevertheless the issue persists. Indeed, a Scopus search for either of the two above-mentioned terms (in quotes) as part of the title gave about 6,400 results for the year 2022, more than doubling from the ca. 3,000 in 2015 (for reference, the total number of papers only increased by ca. 40% during the same period). This significant rise in usage frequency appears to validate the idea that our scientific community promotes these exaggerated statements. However, since the term is now ubiquitous, it has essentially lost any real meaning.

Moreover, using hyperbolic terms like "high efficiency" can have several drawbacks. Firstly, such terms are subjective and lack precise quantitative definition, making it challenging to compare from one device/system to another. Secondly, stating that a system is "highly efficient" can lead to over-generalizations or unsupported claims, as the term often implies a degree of certainty that may not be warranted by evidence presented. This can create unrealistic expectations and may ultimately undermine the credibility of the research.

Lastly, relying on the term "high efficiency" can obscure important nuances or limitations in the work. Indeed, efficiency is only one aspect of overall performance. Stability and scalability are equally important when developing energy conversion systems, and the scientific insights gained on how to increase the performance are generally more important than the performance itself. Highlighting only the efficiency aspect of the research, rather than providing a balanced and nuanced interpretation of the results, can shift the focus away from the interesting scientific story.

Therefore, even when presenting results where an efficiency is clearly defined and perhaps slightly greater than that in competing systems, I would urge authors to omit the term "high efficiency" from their manuscript titles. While it may be tempting given the competitive nature of academic research, it is important to use precise and objective language that accurately reflects the data and the conclusions that can be drawn from it.

To summarize this rhetoric, I would suggest that using the terms "efficiency" and "efficient" should only be reserved for processes wherein actual efficiency is defined as a quantity between 0 and 1 (0 to 100%). I would urge researchers to consider the process under scrutiny, and if a ratio between useful output to input is obvious, then by all means, use the term. Importantly, report the value of efficiency in reference to comparable systems. For cases where the definition is ambiguous and/or no attempt is made to quantify any ratio between the input and output of a conversion process, then please choose another descriptor like "effectiveness" or "efficacy". Perhaps less scientific descriptors like "facile" or "direct" may be more appropriate. In addition, since the term "high efficiency" is imprecise and hyperbolic, please avoid using this type of term to describe work and rather focus on describing the important scientific insights gained. While I am confident that researchers will continue to increase efficiency of all of the energy conversion systems of interest to our community, avoiding the imprecise overuse of the terms "efficiency" and "efficient" would be a benefit to all of our research fields.

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Notes

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