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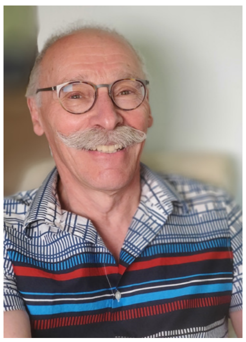
GUEST EDITORIAL

Sustainable Energy and the Second Law of Thermodynamics: An Introduction to the Special Issue



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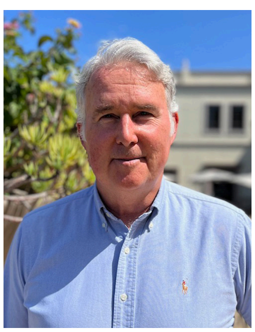

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Second law of thermodynamics, sustainable energy, thermodynamics, science paradigm, novel energy concepts, paradigm shift

At the end of the 19th century, the field of physics was considered nearly complete, encouraging triumphal statements by some of the most eminent physicists of the day; for instance, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement" (William Thompson, Baron Kelvin of Largs).

Only a few random clouds troubled this bright horizon; for instance, the vexing negative result of the Michelson-Morley experiment (the speed of light in moving reference frames), some puzzling aspects of the photoelectric effect (light ejecting electrons from metals), and the lack of a coherent explanation for the blackbody radiation spectrum (light emitted from hot materials). There was nothing terribly serious, nothing that wouldn't be mopped up eventually. In fact, the first would soon be key to Einstein's revolutionary special theory of relativity, the second would win him the Nobel prize in physics, and the third, in the able hands of Max Planck, would crack open the door to the paradigm-shattering quantum world. Indeed, every moment is the end of physics or its beginning—depending on one's curiosity.

Viewed through the lens of Thomas Kuhn's *The Structure of Scientific Revolutions*, physics' sudden turnabout was to be expected. Whenever experts consider a field complete, beware and be amused, for it will likely erupt in revolution. This is because the nature of knowledge itself guarantees scientific paradigms will invariably germinate the seeds of their own destruction. They must. When a paradigm is established, it is incumbent upon scientists to explore it as fully as possible, to extend its domain to the fullest possible extent. This process of discovery and confirmation—the filling in of decimal places—while fleshing out the paradigm, inevitably reveals inconsistencies that must be either ignored, somehow incorporated into the paradigm, discredited and rejected, or else give rise to a new paradigm, a so-called *paradigm shift*. The latter is rarely sought or done lightly, and, in general, most scientists would prefer that it not be done at all. Paradigm shifts come in all shapes and sizes, but big ones—like the Copernican revolution, the Darwinian revolution, special and general relativity, the shift from classical to quantum worldviews—typically happen in stages that can last years, decades, or even centuries. Paradigm shifts are usually messy affairs that are costly to the instigators in the short term (years to decades), as well as to the defenders of the status quo in the long term (decades to centuries).

At the end of the 20th century, physicists were again triumphant, claiming to have finally slain the long-lived (and long-loved) Maxwell demon, the most infamous challenge to the most indisputable of physical principles: the second law of thermodynamics. The demon, a hypothetical microscopic creature, was purported to be able reorganize disorder at the molecular level and, thereby, violate the second law. Sadly, this microscopic heat fairy never actually existed and never posed any real threat to the second law; sadder still, the resolution proffered for its demise was fatally flawed, suffering from circular reasoning (Earman & Norton, 1999). Nevertheless, thermodynamicists danced gleefully on its grave.

Karmically, dancing on the demon's shallow grave summoned new and authentic threats to the second law: so-called Maxwell zombies, dozens of them (Sheehan, 2018). Some of these are found in this special edition of the *JSE*. It was time for the thermodynamic community to pick on someone its own size. And since the mid-1990s it has stepped up and done exactly what Kuhn predicted it would do: ignored the situation.[1]

The articles of this special issue of the *JSE* derive largely from the presentations at the virtual symposium *Energy Concepts Challenging the Second Law of Thermodynamics*, hosted as part of the *4th Annual Advanced Propulsion and Energy Workshop* (January 22, 2022). Additional papers were solicited from the second law examination and interpretation community. These presentations include some of the most potent and potentially commodifiable / commercializable second law challenges yet proposed.

These challenges are eclectic, drawing from the kinetic theory of gases, electrochemistry, biochemistry, and vacuum fluctuations. Two attributes link several of them, specifically: (i) physically active boundaries that facilitate the storage, control, and conversion of thermal energy into useful work; and (ii) asymmetries and broken symmetries (e.g., physical, chemical, geometric). These commonalities are tantalizing and perhaps point to a more general theory of second law challenges that has yet to be formalized.

The history of technological development indicates a general path from scientific discovery to engineering scalability, followed by commercialization, usually starting modestly; after all, *all great things begin small*. Semiconductor technology, for example, began with single transistors in the 1950s and now creates complex 2D and 3D massively integrated circuitry capable of directing many critical aspects of civilization. Given enough concentrated will, research, and development (i.e., time and money) the currently proposed second-law–violating energy systems might someday be scaled up to commercial levels.[2]

The potential implications of second law research are obvious. What is at stake is virtually all the energy in the world.[3] The total thermal energy content of the atmosphere, ocean, and upper crust is estimated to be 10,000 times greater than that of known carbon fuel and fission fuel reserves. In quantity, the energy stores of thermal energy are almost boundless and, because second-law–violating devices allow conversion of waste heat back into work over and over again without limit, the energy stores can be considered effectively infinite.

If environmental heat can be economically converted into useful work on a wide scale—electrical, mechanical, chemical—the effects on the energy sector, the global economy, societal and ecological welfare, warfare, and virtually all aspects of civilization and its relationship to Nature are difficult to predict, but they are likely to be profound—and, we hope, mostly salutary. Of course, every technology is two-edged, depending on its application.

In light of second law developments since the mid-1990s, now might seem a good time to start preparing for a world in which thermal energy will be the coin of the realm. Actually, probably not. Technological revolutions typically take decades to unfold. The carbon fuel revolution involving coal, oil, and gas took a couple of centuries to blossom fully, and the semiconductor revolution (still in progress) has taken more than 70 years to mature. Given the imperative of weaning off carbon fuels, perhaps the second law revolution will be quicker, but history, as well as the vast economic and political forces aligned against such changes, does not favor this scenario.

Despite this, it is the belief of these editors that the articles herein may offer the best hope of demonstrating a path toward engineering these second law concepts into useful energy devices. It is hoped that they will help usher in a new paradigm of inexpensive, democratically available, non-polluting, and sustainable energy production.

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NOTES

1. Historically, this has usually been the case. When faced with a potential paradigm shift, the first instinct of the scientific community has been to head for the pub, have a pint, and wait for things to blow over.
2. In the end, it may not matter whether the law is actually being violated by a particular device so long as it is net-beneficial to humanity; that is, not requiring vast amounts of expensively processed, polluting, exotic material and processes to produce useful energy outputs.
3. This excludes energy that might be derived from the nuclear fusion of light elements (e.g., hydrogen, helium, lithium), a proposition that has consumed billions of dollars in investment as well as the some of the best scientific and engineering minds for the better part of a century and is expected to remain unfulfilled for many decades.

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