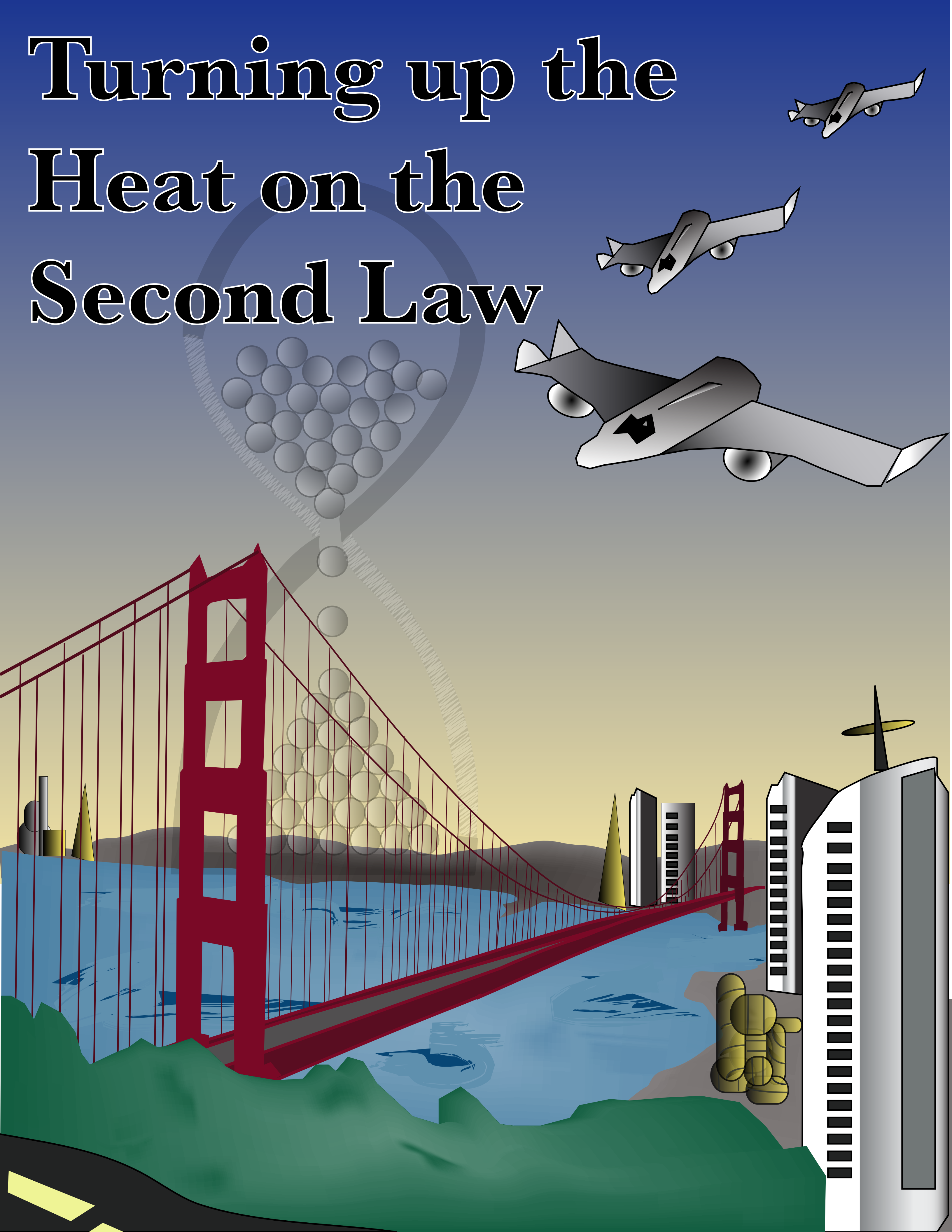
Turning up the Heat on the Second Law



(***Recent discoveries in physics suggest that the second law of thermodynamics might not be universal. What's at stake — besides one of the central laws of nature? Virtually limitless, clean energy.***)

Imagine cars and supersonic aircraft speeding cross-country nonstop, never needing a drop of fuel, whose only exhausts are thin plumes of cold air. Imagine a civilization drawing nearly limitless energy "out of thin air," whose citizens never pay a power bill and whose countrysides are free of power plants, transmission lines and air pollution.

Such dreams seem hopelessly futuristic because we've come to expect that *energy* means consuming fuels, making pollution, and maintaining intricate and expensive infrastructures. Indeed, *energy makes the world go round* and the world's appetite for it is voracious. Currently, global power usage is about thirteen trillion watts, the equivalent of about fifteen thousand nuclear power plants, or comparable to detonating a WWII atomic bomb every six seconds. This figure is expected to grow 50% in the next twenty years. Roughly 20% of the world economy is devoted to the discovery and recovery of fuels and to the generation, distribution, and consumption of energy. Today our energy comes mostly from oil, coal, natural gas, uranium, hydroelectricity, solar and wind; most of these are non-renewable and are rapidly being depleted. Fossil fuels are implicated in the degradation of the biosphere and global warming, both of which are predicted to become increasingly problematic in the coming decades.

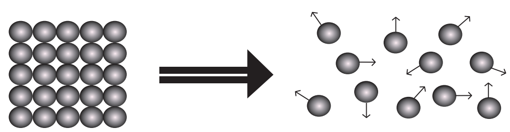
As a society we have come to believe that energy is a rare commodity that requires substantial investment; it must be recovered from exotic places — the bottoms of the oceans, scorching deserts, deep underground — and inevitably it will become scarce and expensive. Economies are defined by it. Nations rise and fall by it. Wars are fought for it. And the more scarce energy becomes, the more dearly we'll pay for it.

In fact, however, we are swimming in a virtually limitless ocean of energy — more than we could ever use — in the form of *heat*. Heat is the microscopic kinetic energy of molecules and atoms. It's everywhere. It surrounds us, infuses us. Everything composed of more than a few atoms has some. Consider the Earth. The total thermal content of the atmosphere is about 10^{25}J; the oceans' capacity is ten thousand times greater and just the upper portion of the Earth's crust holds ten times more than this. At our current usage, it would take hundreds of millions of years to expend this much energy. Furthermore, sunlight and the decay of natural radionuclides in the earth replenish these heat reserves orders of magnitude faster than civilization could possibly exhaust them. In other words, all the energy we could ever want already surrounds us as heat.

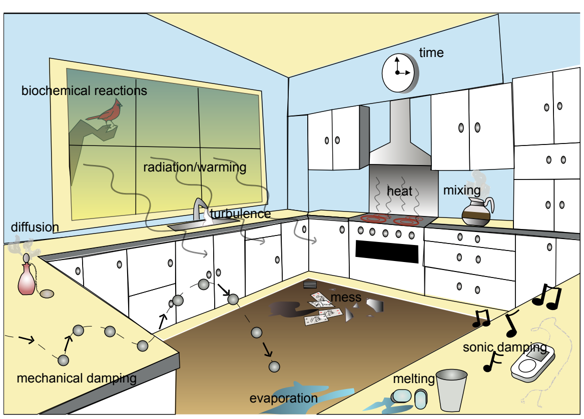
If we are literally swimming in this energy, then why aren't we tapping it? This nearly boundless reservoir of unused thermal energy is beyond our reach — like a mirage in the desert — because of what is possibly the most depressing law of nature: the second law of thermodynamics.

Second Law Rules

The second law has been called "the supreme law of nature" because it governs every aspect of our life from the moment of our conception until our death; every process in the universe is subject to it; the cosmos itself lives and will eventually die by it. Even the direction that time flows — from past to present to future — has been attributed to it. There are many ways to state it, but one handy way is "For any physical process the disorder (entropy) of the universe never decreases, but instead tends to increase." This sounds innocuous enough, but its ramifications are profound because it guarantees that work — organized energy, the means by which we get useful things done in everyday life — degrades inevitably into the disorganized, less useful form: thermal energy. Once randomized, heat is nearly impossible to reorganize back into useful work — and even trying just wastes more energy.



(a) The second law "drives" the universe toward greater disorder, degrading useful energy (work) into less useful energy (heat).



(b) The second law is necessary for everyday life — e.g., turning sunlight into life-sustaining heat, keeping fluids mixed, damping sounds, evaporating fluids, melting solids, guiding biochemical reactions — and, ultimately, allowing nature to "forget" and reset.

Figure 1: Second Law — microscopic and macroscopic

The second law is so much a part of everyday experience that it has many colloquial expressions, like "A mess expands to fill the space available," or "The only way to deal with a can of worms is to find a bigger can." The second law, however, is not all bad. It helps guide the biochemical reactions in our bodies that keep us alive; it motivates the flow of nutrients and wastes in and out of our tissues. It allows the cream in your coffee to stay stirred, the brakes to stop your car through friction, the music in a concert hall to fade away gracefully, the sunlight to warm your face on a summer day. Virtually everything that happens in the world is touched by the second law. It is one of nature's favorite ways to get things done, but it is also nature's way of forgetting — erasing the slate — so new things can happen.

When it comes to doing work, however, the second law is generally bad news. Consider, for instance, the fate of a tank of gasoline. Let's say you fill up with 15 gallons and go for a long drive. When you return to the gas pump, that immense amount of chemical energy — roughly equal to a comparable weight in TNT — has been completely dissipated into environmental heat, none of which is ever likely to serve anyone again. This one-way flow of work into useless heat is repeated countless times and on massive scales around the world everyday and it accounts for civilization's insatiable energy appetite. Once spent, work energy is usually gone forever and must be replaced by new energy. It is said that the second law (and its partner laws of thermodynamics) are like playing poker in hell: *You can't win. You can't break even. And you can't leave the game.*

Breaking the Law

But maybe you can. In the last 10 years, several independent research groups worldwide have advanced more than two dozen challenges to the second law's universal status — more than during the rest of its 150-year history combined. (Some versions of the second law have been rigorously proved for simple, idealized systems, but it cannot be proved for most systems, leaving open the question of its *universality*. A physical law is *universal* only if it is true at all times and all places in the universe. Once even a single exception is found, it is no longer universal.)

The recently proposed *second law devices* (SLDs) are diverse. They span classical and quantum mechanical physical regimes, range from nanoscopic to planetary in size, operate from above the melting point of steel down to a fraction of a degree above absolute zero. They make use of plasmas, microscopic semiconductors and superconductors, quantum electrical circuits, biomembranes, and exotic catalysts. What they have in common is that most inhabit extreme physical regimes that were unheard of when the second law was first formulated by Clausius and Thomson in the 1850's, but which are now routinely realized in the laboratory. For the first time in over a century the status of the second law has been thrown seriously into question, and within the next few years definitive laboratory tests of it will be made. Several experiments are now in progress or under construction. If the second law breaks down, it will mark a fundamental paradigm shift in science and engineering. Societally, it could precipitate major changes as well, particularly with respect to energy.

Over the last 15 years, the research group that now comprises Paradigm Energy Research Corporation has investigated several potential SLDs in the fields of plasma, chemical, gravitational and solid state physics. These have culminated in a series of laboratory testable micro- and nanoscopic silicon engines that we believe will soon put the second law to the test.

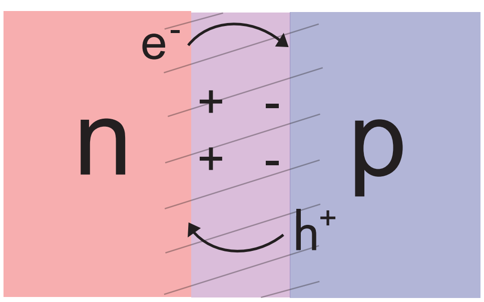


Figure 2: Joined slabs of n- and p-doped silicon trade mobile charges and set up an intense electric field in the silicon lattice (slashed lines).

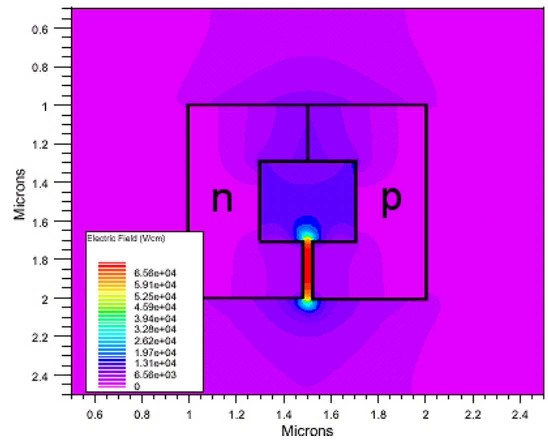


Figure 3: This electric field can be re-expressed across a narrow vacuum gap to create a microscopic *thermal capacitor*, capable of doing work without an external power source. (Results of numerical semiconductor simulator, Silvaco International's Atlas tool.)

Crystalline silicon is the primary material of the world's semiconductor industry. Its electrical characteristics are exquisitely tuned by introducing tiny amounts of impurity elements (perhaps just a few parts per million) into its lattice. By adding an electron donating species (e.g., arsenic or phosphorus) a lattice is given an excess of mobile electrons. On the other hand, by adding an electron withdrawing impurity (e.g., boron or aluminum) it becomes electron deficient and, therefore, has an excess of mobile positive holes. When these two impurity-doped lattices are joined, the excess mobile negative electrons and positive holes from each lattice cross-diffuse into the other. The resulting charge separation creates an intense, microscopically thin electric field inside the silicon at their junction (Figure 2).

Now, if these conjoined silicon lattices (n-type and p-type, for negative and positive) are suitably shaped (Figure 3), a second electric field can be established in a vacuum gap between them. This electric field can be even more intense than the one in the silicon junction, nearly as strong as those associated with lightning strikes, just on a much smaller size scale. But as with lightning, this field contains energy. The gap with its electric field is remarkable because (a) it stores electrostatic energy like an electric capacitor; (b) the field is generated fully by thermal (heat) processes and does not require an external power source; (c) this capacitor can remain poised for discharge indefinitely; and, (d) after it is discharged, it can recover its charge, field and energy again. This last property severely undercuts the second law since if the capacitor does work while discharging, but recovers its original charged state afterward, then it must have transformed heat solely into work. Turning heat solely into work this way is a flagrant violation of the second law.

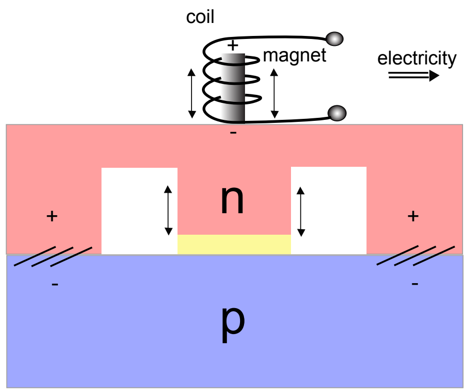


Figure 4: Utilizing the electric field (yellow) from n- and p-doped silicon junctions (shaded lines), resonant electromechanical oscillations are set up in a microcantilever. These oscillations generate electricity solely from heat, in violation of the second law.

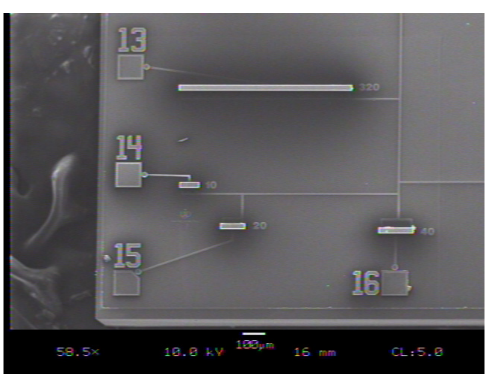


Figure 5: Electron micrograph of four prototype polysilicon thermomechanical resonators (TMRs) connected to numbered bond-pads. Cantilever arm lengths 10μm, 20μm, 40μm, and 320μm. Length scale of this photo approximately 1.5 mm.

As a concrete example of how this process might be used, let's create a silicon motor that runs on environmental heat. As shown in Figure 4, this device is constructed from n- and p-doped silicon. The vacuum electric field is situated between a fixed base (*anvil*) and a movable *hammer* that is attached to two silicon cantilever springs. (Silicon makes excellent micro-springs — flexible and durable.) The hammer and anvil surfaces carry opposite electric charges so they attract one another. The hammer bounces up and down on the anvil like a diver bouncing on the ends of two conjoined springboards.

The hammer-anvil works by the same general principle as a playground swing: resonance. It has two mutually-sustaining types of oscillations. The first, purely mechanical, indicated by the hammer's oscillation up and down into the anvil, has its frequency set by the stiffness of the cantilever spring and the hammer's mass. The second, an electrical oscillation, reflects the electrical discharging and recharging of the hammer-anvil silicon surfaces as they make and break physical contact. When its mechanical and electrical frequencies are matched — much like on a swing where you match the rhythmic push and pull of your arms and legs with the natural pendulum frequency of the swing — the hammer-anvil executes self-sustained resonant electromechanical oscillations up and down. In this *thermomechanical resonator* (TMR), the electric field provides the force to bring the hammer down and the cantilever springs provide the force to retract it. We've tested desktop versions of the TMR, as well as fabricated prototypes on the micro-scale, and so far it behaves just as expected. In order to match the mechanical frequency with the high electrical frequency of the p-n junction, thus challenging the second law, the device must be made microscopic.

The TMR will be small — about a tenth the size of an ant — and its power output tiny, but if a large assembly of them worked in unison, their effect could be sizable, on the order of 10-100 MW / m^3. A volume the size of an SUV could generate power on par with a modern-day nuclear power plant. (Of course, heat must be fed continuously into this assembly at a corresponding rate, otherwise it would freeze itself to a stop in just a few seconds.)

Prototype TMRs have been fabricated (Figure 5) and are currently undergoing laboratory tests, but because their silicon is not doped with impurities they must be driven with external power and so they themselves won't challenge the second law. Soon, however, we expect to fabricate n,p-doped TMRs — and put the second law to the test.

Chilling at Home

The second law devices we're currently exploring are only tests of principle. If the law can indeed be broken, we expect SLDs will one day be commercially feasible, in which case the heat energy in every home (or business) will be enough to power all its utilities and appliances indefinitely. To get an idea how much energy resides domestically, consider the chair you're sitting on right now. It may seem solid and steady enough, but actually it is molecularly thrumming with energy. How much? Well, if its individual molecules were unbound from one another and set free to move with merely their random thermal motions, your solid chair would instantly disintegrate into a gas, expanding at the speed of sound, propelling you toward the ceiling. It would literally explode as if packed with dynamite. Fortunately, your reading is not likely to be interrupted this way because chair molecules are actually bound together tightly by intermolecular forces and, also, their numerous momenta are randomly oriented so that they cancel each other out, thus leaving your chair intact and stationary.

To envision how small an SL generator for the home could be, consider a tube about the size of a coffee can (Figure 6). On one end is a fan and inside a series of baffles — like a radiator — packed with millions of TMRs. The TMRs convert atmospheric thermal energy into electricity, some of which powers the fan to pull air through the tube, but the vast majority of which is available to run the household. For modest, self-generated air flow (5m/s) and modest heat recovery (a drop in temperature of about 20 degrees), this coffee can-sized generator should produce between 1 and 2 kilowatts of electricity nonstop — roughly enough to power an average US household — from the very air we breathe. Alternatively, SLDs could be incorporated into meter-wide, millimeter-thick panels embedded in the walls. These would not only furnish household electricity, but, as a bonus, they would also cool the room like an air conditioner. (A simple variation can turn them into heaters.)

For the kitchen, self-heating pots and pans or self-cooling cups and refrigerators could be engineered. The heat exported from the refrigerator as electricity might run the lights or the microwave oven. SL clothes would import or export heat as needed to maintain an optimal body temperature, regardless of the outside temperature. Further, since all electricity is eventually degraded into heat, it can be recycled again and again by the SLDs. Homes, businesses and industries could become energy self-sufficient. There would no longer be a need to plug anything into the wall.

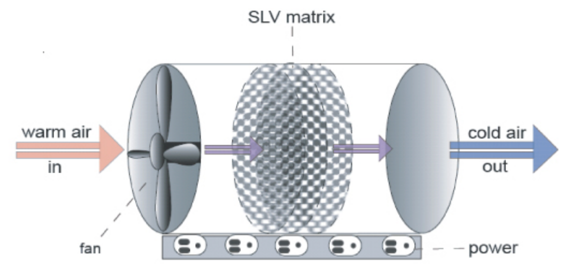


Figure 6: Household SL generators draw air over a panel of micro-TMR devices, convert atmospheric heat into electricity, and exhaust colder air. A coffee can-sized generator could power a typical U.S. home.

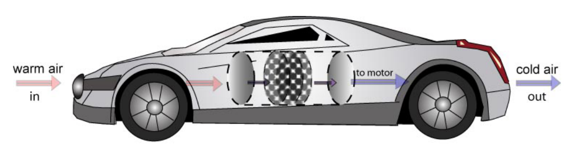


Figure 7: Larger, more powerful SLVs could power cars, ships, and aircraft. The "terminal cruising speed" of an SLV car could be half the speed of sound.

On the road, an SL-car would also "run on air," taking in ambient-temperature air in the front, passing it through internal SL baffles, converting atmospheric heat into electricity for electric motors, and finally exhausting colder air out the back. An SL car would produce no pollution, aside from a trailing plume of cold air. (So much for burning up the road!) Normally we think of cars as straining to attain higher speeds — not so with an SLV. The faster it goes, the more air it takes in, hence the more power it generates, and so the faster it goes ... but only up to a point. Calculations show that an SL-car could cruise at about half the speed of sound (300 mph), balancing its power generation against air resistance. Similarly, an SLV-aircraft could cruise supersonically — also using no fuel. Virtually any energy-consuming device could be redesigned to be energy self-reliant. Environmental heat could become the primary energy currency of civilization.

Some Like it Hot

In principle, heat is superior to virtually any other energy resource. The terrestrial heat reserves in the atmosphere, ocean, and upper crust alone are virtually inexhaustible, exceeding by orders of magnitude all presently exploited energy reserves combined (coal, oil, gas, uranium, alternative). They are exceeded perhaps only by the energy recoverable from thermonuclear fusion of the deuterium (a heavy isotope of hydrogen) in the oceans. Homes and work places have more than enough environmental heat to satisfy their own energy needs.

Heat energy is recyclable. SLDs convert heat into energy for useful work, most of which will inevitably be degraded back into heat, which can be recovered again and again. Unlike any other energy resource, *heat is the only fully recyclable and renewable form of energy.*

Heat is clean energy. SLVs create no chemical wastes and no pollution since they consume no matter, only heat. They are compatible with virtually any modern mechanical or electronic device, from lightbulb to locomotive. (Only for the most energetic systems, like rockets, would they be infeasible.) SLVs could be incorporated directly into many technologies — refrigerators, pots, pans, clothes, cars, aircraft — obviating wires and plugs. Proposed SLVs can operate in the Saharan noonday or the Antarctic midnight, 10 kilometers deep in the Earth's crust or 200 kilometers up in space; they could even provide power in the intergalactic void reclaiming 2.73K cosmic microwave radiation. In summary, SLVs make heat an attractive, versatile, ubiquitous, clean and nearly inexhaustible energy resource, unlike any other.

Paradigm Lost

In addition to revising a central law of nature, the introduction of SLVs could precipitate a paradigm shift in the energy economy. One might guess that this transformation would take decades or more, as has been predicted for conversion to other alternative energies like wind or solar, but this might not be the case since SLVs do not play by the same rules. Unlike other energy sources, heat does not require discovery, extraction or conversion since it is found everywhere in abundance. It does not require large generation plants or transmission infrastructure since heat-to-electricity conversion can be accomplished on site. Energy storage (e.g., batteries) would be unnecessary for all but the most high-power applications.

The short-term economic and political impacts of cheap and abundant SLVs would be hard to overestimate. Vast fortunes in mineral wealth would be wiped out. The oil empires of the Middle East would crumble as oil and gas became nearly worthless. The economic clout and political leverage derived from energy resources would vanish and the necessities for military interventions to control them would end as bountiful energy became freely available to everyone everywhere. The energy exploration, extraction and delivery industries would collapse. Oil and gas wells, coal mines, tanker fleets and gas stations would be idled. Pipelines, refineries, power plants, and the power grid would be scavenged for spare parts. The 20% of the world economy devoted to energy would have to be re-thought and reinvented as quickly as SLVs were introduced. For purely economic and political considerations it seems unlikely that this scenario would be permitted to unfold; thus, even if SLVs were proven economically superior to competing technologies, they would be unlikely to be introduced quickly.

On the bright side, the long-term economic, political, and ecological benefits of SLVs could be profound. The release of the world economy from the constraints of limited and expensive energy should be invigorating. Politically and militarily, there would be one less critical resource to fight over. Cheap, ubiquitous energy should reduce the cost of virtually all other products and help unlock other critical resources. For example, energy from SLVs might allow widespread desalination of seawater and its pumping over long distances to thirsty lands and populations. Pollution from fossil fuel burning and attendant greenhouse gases could be eliminated. (Perhaps SLV cars could use a fraction of their power to scrub excess carbon dioxide from their air intake, thereby reversing the pollution of their forebears.) Lands scarred and ecosystems maimed by civilization's thirst for energy could be left to heal.

The violation of the second law of thermodynamics would surely precipitate a major paradigm shift in science and engineering, but its potential for positive societal change is even more profound. We predict that in the next several years, as laboratory SLVs are tested, the heat will be turned up on the second law.

More to Explore

Challenges to the Second Law of Thermodynamics: Theory and Experiment. Vlada Čápek and Daniel P. Sheehan. Springer, 2005.

Quantum Limits to the Second Law. Edited by Daniel P. Sheehan, American Institute of Physics, 2002.

Biographical Sketches

Daniel Sheehan teaches physics and Jeffrey Wright teaches mathematics at University of San Diego. Daniel's father, a chemistry professor, introduced him to thermodynamics as a child; it has troubled him deeply ever since. Jeffrey started his career as a cogeneration engineer for Pacific Gas and Electric Company in Northern California. Eventually he saw the light and entered academia. This article is dedicated to Shannon and his dream.