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WHEN CELLULAR SYSTEMS MEET POWER GRIDS

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Although biological energy systems and electrical grids differ in scale and are studied by different disciplines, the strategies from one system could lead to benefits for the other.

Most of us don't think twice about where our power comes from when we flip a switch to turn on the lights or plug in our electronic devices to charge. With our ever-increasing reliance on electricity to power our modern comforts, the task of improving the efficiency of electricity generation, the responsiveness of power grids to changing demands, and the system resiliency in the face of unexpected disruptions is crucial. Furthermore, outages in the traditional US power grid—made up of the Eastern, Western, and Texas power grids—are estimated to cost businesses upward of \$150 billion a year.¹ Recent global trends toward upgrading to a predictive smart grid system and the rising popularity of renewable energy hold immense space for innovation.

Luckily, in addition to already established mechanisms of energy generation, another source of inspiration can potentially help engineer improved electrical grids: nature. Living systems have developed over eons of evolutionary pressures to adapt to fluctuating energy sources, transform multiple types of energy for both immediate and long-term uses, distribute energy in the form of specific compounds throughout intracellular compartments, and use that energy to signal their internal energy state to other members of their environment.

Energy in cells is generated through a process called glycolysis, in which carrier molecules are transmitted to the mitochondria—the powerhouse of cells. Both oxygen and energy are created, the latter in the form of adenosine triphosphate (ATP), which can be put to use wherever it is needed. If there is an excess of energy, it can be stored as glycogen.

Surprisingly, modern electrical grids closely parallel those processes, which can be most clearly seen when considering the five key elements of engineered energy grids: the generation



source, the transmission system, the substation for sharing and redistributing the energy, the storage reservoir, and, ultimately, the consumer.

Investigating those parallels could lead to improved energy grids. Biological systems demonstrate a way to optimize storage, increase resilience, respond to stochasticity, and improve coordination between multiple energy types that isn't yet seen in electrical systems. That functionality is especially important in the face of accelerated climate change and an increased dependence on renewable energy—whose availability may not always be reliable. Optimal control algorithms for stochastically fluctuating data are needed to avoid power imbalances, failures that immediately cause failures of their dependents, and unstable energy transmission. The future of the energy field is in renewable energy and more resilient grid systems. To achieve that future, we explore the ways electrical engineers can learn from biological systems.

Energy through multiple pathways

As renewable-energy sources, such as solar and wind, become increasingly popular, the ability to harness electricity from different resources can improve the reliability of the US power grid.² Living systems already intrinsically synthesize energy from multiple sources. For instance, at a macroscopic level, honey, a slice of bread, and a banana provide different forms of energy, but they can all be converted into ATP through cellular respiration. The ways in which energy

FIGURE 1. DIFFERENT ENERGY SYSTEMS, such as a metabolic pathway in the body (left) and a modern electrical grid (right) are more similar than they might first appear. Both use multiple sources of energy generation and dynamically respond to changing demands by altering energy pathways. Improvements in electrical grids could be inspired by looking at how cells manage a body's energy. (Illustration by Jason Keisling.)

sources are used to produce electricity are also distinct. Solar power, for example, directly excites electrons in a photovoltaic cell, whereas wind energy turns a turbine to generate electricity. Other sources of direct energy, such as nuclear power, coal, and fossil fuels, share a similar energy-generation pathway to ultimately produce electricity. A living organism, however, operates similarly to newer smart grids in that not only are the sources of energy distinct, as shown in figure 1, but the processes by which energy gets converted to a usable form are also distinct.

Biology employs a series of connected chemical reactions, called metabolic pathways, to convert a molecule into an end product. Different forms of carbohydrates, for instance, move through distinct metabolic pathways in the presence and absence of oxygen and varying substrates. Proteins are broken into their constituent amino acids and enter the metabolic process at different points, depending on the amino acid. And lipids are metabolized through yet another pathway. Ultimately, those pathways converge into a single form of energy: ATP. Yet the pathway through which a form of energy travels

in a cell is largely determined by metabolic demands and regulators. The intrinsic ability of biological systems to rapidly switch their source and mechanism of energy production, depending on the host and microenvironment factors, can provide insights relevant for augmenting the self-sufficiency and resilience of existing engineered grids.

Both systems work best when they have a greater likelihood of being able to provide energy when one or more sources become unavailable. Whereas biology has the advantage of billions of years of evolution to integrate its diverse metabolic pathways, the integration of more renewable-energy sources into our existing power grids is an ongoing challenge.

Energy consumption during summer months in the US peaks in the afternoon when temperatures are hottest. But during the winter months, there are two peaks of lesser magnitude in the morning and evening. Power demands, however, can fluctuate throughout the day, and smaller-scale changes in demand can be caused by unpredictable weather damage or random usage.

Power-grid operators in specialized control centers are responsible for monitoring the availability of various generation sources for distribution throughout a grid. That includes the production abilities of both consistently generating nonrenewable sources and more intermittently available renewables, which operators then use to balance supply and demand. That is done through the maintenance of both a baseload of power generation that always matches the minimum power need of the grid and other generation sources that can be quickly turned on or off at any time. Dispatchable sources with slow startup, such as nuclear and coal plants, are thus typically run year-round, and their output is designed to match consistent patterns in demand. Faster-responding dispatchable sources, such as hydroelectric and natural gas, complement the slow sources to meet unexpected high peaks in energy demand and stochastic fluctuations in power usage.

The combination of multiple energy-generation pathways with different strengths allows current power grids to remain as resilient as they are while incorporating new intermittent renewable-energy sources in the face of unexpected disruptions. For all their adaptability, however, grids are not always perfect.

Failure mechanisms and mitigation

The 2021 Texas power grid failed because of a massive drop in electricity generation coupled with a sudden increase in power demand. When cold temperatures froze nonwinterized wind turbines and natural gas pipes, they caused major stress to the power grid. At the same time, the low temperatures led many users to increase their indoor heating, and electricity demand significantly rose to levels typical only during the peak demands of summer. As a result, 46 000 MW of expected power were unavailable while demand rose to 70 000 MW. In response to over half of expected electricity production going offline, the Electric Reliability Council of Texas implemented rolling blackouts by shutting down electricity in neighborhoods for up to 12 hours at a time to reduce demand across the state.³

The growing complexity of advanced electrical grid systems means that they have more developed methods of failure pre-

vention, error detection, and built-in redundancy. But the complexity also increases the ways in which an engineered system can malfunction. Source-side faults are caused by an intermittent supply of input resources, such as a cloudy day unexpectedly disabling solar panels or cold temperatures affecting natural gas transportation. They result in power supply discontinuity and are fixed either by the disruption ending or by better strengthening power-generation systems against the elements. Cable faults and deterioration affect power transmission; they are fixed by finding an alternate transmission pathway and repairing the damaged cables. Data communication faults can be caused by hardware, security, equipment, or human error and lead to poor management of available power resources. They can be fixed with high-performance communications networks, including wireless data systems and satellite systems.

Compare those malfunctions with biological modes of failure and interesting similarities emerge. For instance, the heart fails to pump blood adequately when its muscle cells no longer produce enough ATP to keep it beating properly. The process to produce ATP occurs in the mitochondria and is heavily oxygen dependent. A temporary lack of oxygen or accumulated mitochondrial damage reduces the availability of the ATP necessary to keep the heart pumping. That forces alternate pathways to be used instead and triggers the heart to take in more glucose to compensate. Glucose oxidation decreases in proportion to glycolysis increasing, thus letting the heart still produce some, albeit less, ATP without relying on mitochondria or oxygen transport.

Long-term pathway degradation—an inability to draw enough of a resource for distribution—can occur in both biological systems and power grids. In biology, two common causes of heart failure occur when there is not enough energy

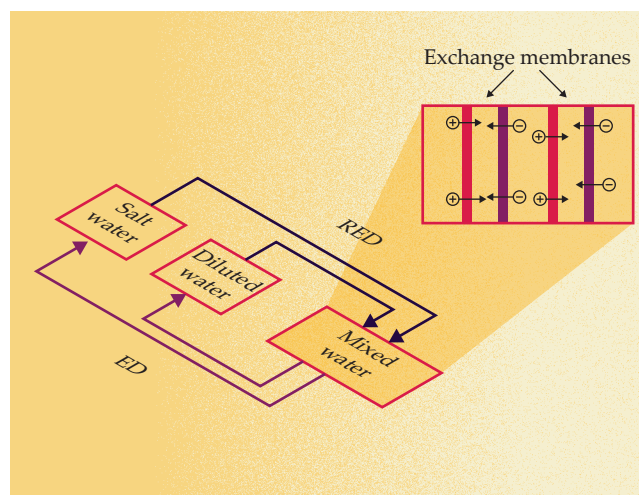


FIGURE 2. CHEMICAL POTENTIAL ENERGY. Two pools of water containing salt water and diluted water are kept separate to store energy. When both are pumped into a third pool and are allowed to mix—a process known as electrodialysis (ED)—charged ions from the salt solution will move past a membrane into the diluted water. An electrical current is generated from the ions passing through membranes. Separating fluids by their salt concentration is known as reverse electrodialysis (RED). (Adapted by Jason Keisling.)

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to power cardiomyocytes, cells in the heart responsible for contraction and expansion. The heart either lacks enough strength to pump out blood or doesn't expand sufficiently to fill up with blood. Medications to mitigate the problem target the energy production, not the cells that aren't working properly. Such a response can be paralleled in new power grids by incorporating two types of resolution: active measures, such as creating fast power-generation system restoration, and proactive measures, such as designing weather-resistant hardware.

Resilience and renewable integration

Biological systems and their way of managing energy intake from diverse sources can serve as inspiration for how engineered systems can be optimized to better predict and respond to fluctuating power demand. Humans have a specific sleep-wake cycle governed by the circadian system.⁴ Although a body demands energy throughout the entirety of the 24-hour cycle, it has a reduced metabolic need during sleep to avoid overprocessing glucose and having an overabundance of unused ATP.⁵ The change in need is accomplished in part by the body's modulating of hormone production to decrease appetite and energy intake and expenditure.^{6,7} That the internal system automatically responds to a regular change in supply is one example of evolved biological sensing mechanisms.

The molecular machinery of sensing and responding to fluctuations in nutrient levels also involves modulating pathways that respond to different nutrient sources and directing each cell's ability to meet its energetic needs. For example, the protein glucokinase acts as a sensor in pancreatic cells to detect hyperglycemia. Glucokinase is responsible for initiating a sequence of events that eventually results in insulin secretion to increase cellular glucose absorption.⁸

Those basic principles are paralleled in newly emerging smart grids: A predictive system is capable of detecting changes to power demand via sensors throughout the grid¹ and changing electricity generation in response.⁹ Renewable-energy systems that include multiple types of energy generation¹⁰ in particular will benefit from efficient control mechanisms. Developments in that area can help create a fully autonomous smart power-grid system, capable of detecting and responding to changes to all five key elements of an engineered energy grid while helping decrease the need for constant manual oversight.

Current hybrid renewable-energy systems often use a predictive model to optimize the use of multiple renewable sources through regression analysis and Monte Carlo simulation techniques.¹¹ They also use real-time monitoring and control through advanced networking and information collection, which optimize costs and energy. That coordination among multiple energy types involves using smart detectors to both obtain real-time monitoring and collect data on the status of each source and then prioritize accordingly.

Self-sustainability through dynamic sensing

For a living system to remain self-sustaining, it must be able

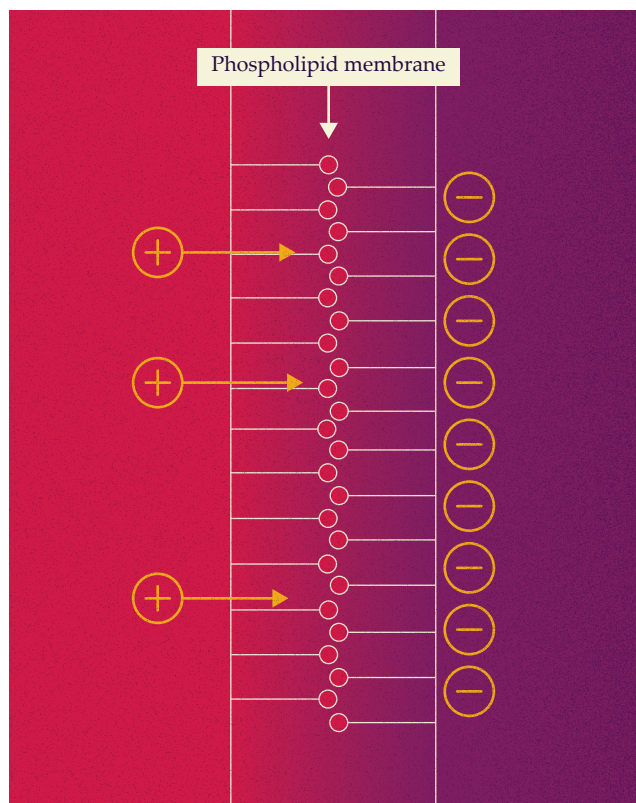


FIGURE 3. CELLULAR CONCENTRATION GRADIENT. A cell wall includes a phospholipid membrane, across which there is an ion gradient. Inside the cell are negative ions. Positive ions from outside the cell will move across the membrane to achieve equilibrium. New batteries for future electrical power grids are designed similarly and will be improved as electrical systems are better able to imitate the biological version. (Adapted by Jason Keisling.)

to manage excess energy. Living systems have evolved to meet that challenge. For example, some fat tissues store unused energy in the form of triacylglycerols (TAGs). A human body contains, on average, one month's worth of energy in TAG storage.

Yet with a constant stream of new nutrients from getting regular meals, the body usually has little need to actively ration and use those reserves. It is able to dynamically recognize the availability of energy sources and balance the supply with the demand of what cells need to function. When the amount of incoming energy dwindles, however, the pathways that govern TAG storage and metabolism slow down. A decrease in food consumption causes two major metabolic effects with respect to TAG: The body begins rationing the use of stored energy by breaking down TAGs, and it halts energy storage by suppressing the creation of TAGs.¹² Dynamic modulation of stored energy in response to changing energy accumulation is a major success of biological systems.

The need to maintain dynamic sensing in an engineered grid is highlighted by the unexpected shutdown of many northern Spain wind turbines in 2009, when power-grid resilience was aided by energy storage. While wind power production had been projected to supply 45% of total energy demand,

the shutdown caused production to fall to a mere 16%. In response, Spain's energy control center immediately increased hydroelectric power and drew on pumped-storage hydro-power (PSH) while also starting coal and gas power stations to make up for the sudden drop in supply. Within hours, electricity supply and demand had reached equilibrium again.¹³ No outages were reported throughout the duration of the incident, even though the grid experienced a sudden loss of its active power generation.

Note what made that possible—enough stored power in an easily accessible form that could immediately fill power demand when the wind turbines were shut down and multiple ways of generating electricity through human-controllable, dispatchable means. As power-grid systems shift to incorporate decentralized controls and renewable sources, larger portions of power generation will be susceptible to unpredictable external events. To remain self-sufficient, modern grids will need to have a reliable power supply with great energy autonomy, be able to share excess energy with stations experiencing a deficit, and improve energy storage capabilities.

Various forms of stored energy exist in biological systems. They can be immediately converted to ATP or can be kept unused for extended periods of time. Control and feedback mechanisms help in determining what type of energy is stored, how it is stored, and how it is broken down. One of the main forms of energy storage in biological systems is glycogen—a branched molecule of glucose that can be rapidly broken down and converted to energy. Glycogen is mainly formed when living systems do not need to use energy immediately. In addition to glycogen, fats are stored forms of energy that can be converted to usable ATP over the longer term. While glycogen is mainly stored in the liver, fats can be stored throughout the body, creating built-in redundancies.

Energy from gradients

Modern smart grids also have decentralized energy storage for emergencies. The current US power-grid system uses several electrical energy storage systems, such as PSH and advanced battery energy storage. Looking globally, more than 90% of energy storage is via PSH. That type of system uses energy to pump water uphill to higher reservoirs in times when excess energy is available. Then, when electricity is needed, water is released from the higher reservoir through a hydroelectric turbine that produces electricity from kinetic energy.

The PSH method of energy storage uses a topographical gradient to drive energy generation. For large-scale energy storage, it doesn't use traditional batteries, which often incorporate rare and toxic materials.¹⁴ Although it is a promising way of incorporating renewable resources for energy storage, PSH does have its limitations. Namely, it requires specific geographical conditions. Thus, taking advantage of hydropower with the addition of an electrochemical gradient—eliminating the need for specific topographic requirements—can be a worthwhile area of future research. Fortunately, inspiration can be derived from biological systems that employ concentration gradients.

Previous work has investigated batteries that store energy through electrodialysis (ED) and reverse electrodialy-

sis (RED). Both methods utilize the chemical potential difference between two solutions of different salt concentrations.¹⁵ As seen in figure 2, ED separates fluids by their salt concentration to store energy, and RED reverses the process: When the solutions are mixed, charged ions pass through a membrane and their movement generates an electrical current. Previously, RED was mostly used to harness free energy. But recent models have successfully used the chemical phenomenon to create an energy storage system that takes advantage of the chemical potential energy and converts it into electrical energy.

The first installation of an RED-based power plant was in the Netherlands in 2014. Following suit, another was installed in southern Italy, where experimental data on the efficiency of the system was recorded for the first time. The RED prototype, which was tested over a five-month period, was able to endure changes in environmental conditions without experiencing a significant loss in performance.¹⁶

Looking to the future, improvements in membrane technology will pave the way toward increasing the cost-efficiency of sustainable, RED-based power plants. The principles used in the concentration-gradient flow battery are based on biological systems. As seen in figure 3, cells also use membrane potential and the concentration gradient.

We propose that researchers can continue to enhance electrical power grids by drawing inspiration from biological systems. Improvements such as increasing resilience and flexibility in response to stochasticity, exploring innovative methods of energy storage, and strengthening intercommunication between energy distribution systems are within our reach.

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