New tool to guide efficient energy extraction from quantum sources

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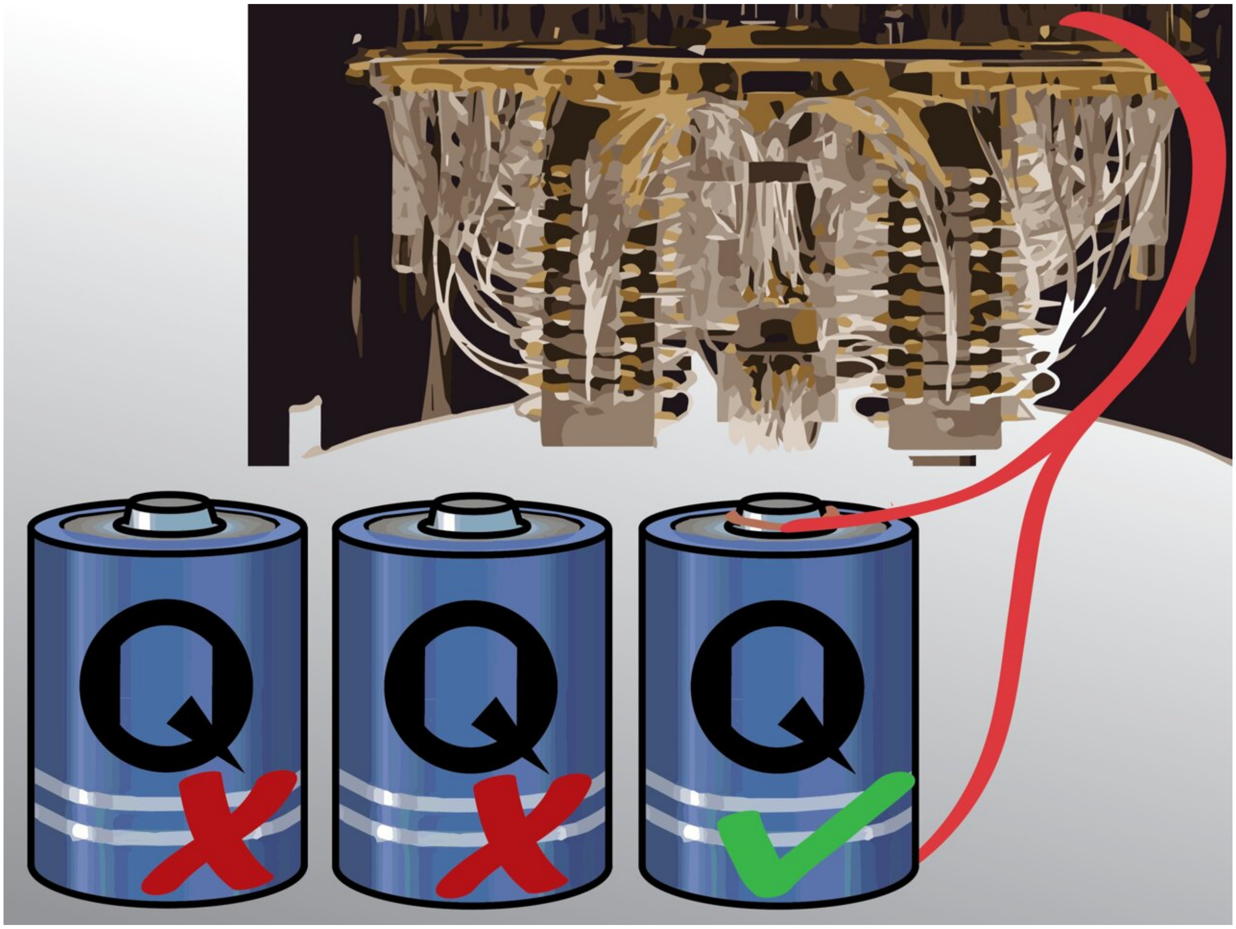

Our technological ability determines how much energy we can extract from a quantum source. This determines the current best energy source and possible best future sources if our technology surpasses a certain threshold. These can power our quantum computers, quantum sensors, quantum encryption platforms, and other quantum devices. Credit: Institute for Basic Science

The idea that energy is a fundamental driver of societal progress has led to the concept that a civilization's level of technological development can be measured by its ability to harness and use energy. Based on this, Russian astrophysicist Nikolai Kardashev devised a famous Kardashev Scale in 1964 as a way to classify civilizations based on their energy consumption. Our human civilization's current level is estimated to be around 0.73 as of today according to this scale.

Harvesting energy is one of the most critical tasks for the advancement of civilization. Early civilizations relied on manual labor and animal power for their energy needs, but it was the Industrial Revolution in the 18th and 19th centuries that marked a major shift in the way humans utilized energy. With the invention of steam power followed by the development of coal mining, humanity was able to harness the energy stored in fossil fuels on a massive scale. This allowed for the rapid increase in energy consumption and the rise of modern civilization.

While our current lifestyle is highly demanding in energy, at the same time it makes us extremely efficient. For example, a typical worker today is thought to be ten times more productive than a worker fifty years ago. Thus the unprecedented economic growth we enjoyed in the past century was largely thanks to the increase in energy consumption. Therefore, for the economy to sustain its growth and for us to ultimately attain a post-scarcity society, we need to be capable of securing ever-increasing amounts of—ideally sustainable—energy sources.

Another key ingredient is to have developed technology to use these sources effectively. This is true for any energy source: burning fossil fuels at higher temperatures release more energy, while different designs of solar cells provide different efficiency. Thus, fundamentally, the energetic output of a source depends on our ability to extract this energy and on the current technology level.

Of course, a part of the ability to extract energy is to realize there is some energy to extract. Imagine a caveperson stumbling upon a piece of coal—they would quickly learn that such a tool can be used to paint drawings inside a cave. But the fact that such a piece of coal can be burned, thus serving as an energy source, is by no means evident.

Also, there is a difference between realizing that there is some energy to extract and having the means of extraction. For instance, we are well aware that the sun combines hydrogen atoms into helium through nuclear fusion, which fuels its enormous energy output. But it is an entirely different beast to achieve this process in a lab—although recent technological progress pushes us closer to this ultimate goal.

With the recent rise in quantum technologies, the possibility of harnessing energy from quantum sources is becoming a reality. Like any technology, quantum technologies are not impervious to human limitations. Even today, quantum physicists are unsure which quantum systems can serve as an energy source and which do not. Additionally, it is unclear which can be readily available now, given our tools at hand, and which in the future.

Recently, researchers at the Center for Theoretical Physics of Complex Systems (PCS) within the Institute for Basic Science (IBS) designed a measure of extractable energy from a source—named observational ergotropy—which takes into account the exact capabilities of our current technology.

Ergotropy refers to the maximum amount of work that can be extracted from a system. Previous measures of quantum ergotropy were idealistic—assuming that experimental capabilities were ideal. This is like assuming that our fusion plant is as efficient as the sun without considering all the issues that arise when attempting to replicate the sun artificially.

In contrast with previous measures, observational ergotropy provides more realistic estimates and updates in accordance with our technological prowess, telling us which sources are the best energy sources with our current experimental capabilities.

These results can be used, for example, to determine the best platform for the experimental realization of a quantum battery—the topic in which the same IBS team has already provided fundamental theoretical achievements recently. A quantum battery can be considered any system small enough to exhibit quantum phenomena.

Imagine, for example, a line of sixteen atoms trapped by a laser or superconducting qubits from which IBM, Google, and others are building their early versions of a quantum computer. These energy-carrying platforms could power our future quantum devices, including quantum computers, quantum sensors, or devices providing quantum-encrypted, and thus completely safe, communication. In their latest study, IBS researchers showcased how the observational ergotropy discriminates which quantum battery can best power our new quantum future.

Dominik Šafránek from the PCS-IBS states, "As our technological capabilities develop, observational ergotropy can be recalculated. In the future, different sources may deemed the new ideal, replacing the previously optimal sources. We can anticipate that this measure can be used continuously across time and constitute the fundamental tool that we can use to judge potential quantum energy sources."

The article is accepted for publication in *Physical Review Letters* and is available as a pre-print on the *arXiv* server.

More information: Dominik Šafránek et al, Work extraction from unknown quantum sources, *arXiv* (2022). DOI:

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