Synthetic atoms: High energy density and a record power density.

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The weight of a battery matters. Launching a satellite battery into space costs about $20,000 per kilogram ($10,000 per pound) [1]. Satellite batteries are heavy and therefore are a significant cost factor. But on Earth the weight of batteries matters too. The weight of the battery is a large fraction of the weight of laptops, cell phones, and other mobile electronics. If we could reduce the weight of batteries we could one day fly electrically powered jumbo jets and significantly cut down on air pollution and noise.

The ratio between the maximum amount of retrievable energy and the mass of a battery measures how light weight a battery is. This quantity is called the energy density. The energy density of lead-acid car batteries is about 0.1 MJ/kg. Rechargeable Li-ion laptop batteries have an energy density of 0.7 MJ/kg and non-rechargeable flashlight Li batteries can reach 1.8MJ/kg. The energy density in electro-chemical batteries is limited by the energy density in ionic bonds to a few MJ/kg.

The energy density in covalent bonds is much higher. Therefore the energy density of chemical energy storage materials is much higher: fire wood 4 MJ/kg, sugar 17 MJ/kg, gasoline and propane 46 MJ/kg, and hydrogen 123 MJ/kg [2]. These materials release their energy as heat in a combustion reaction and these numbers do not include the mass of the oxygen gas required for the reaction. If the mass of oxygen is included, the energy density of the hydrogen – oxygen system is only 14 MJ/kg. The conversion from heat to electrical energy with a heat engine and a generator or a fuel cell is usually only 30% effective, which reduces the energy density by roughly a factor of 3 for chemical energy storage materials. The chemical reaction of the hydrogen-oxygen system is reversible and can be used to build a rechargeable battery, but for most other chemical energy storage systems the inverse reaction is too complex to build a rechargeable battery.

Capacitors in electronic circuits can be considered rechargeable batteries, but their energy density is very small: 0.000036 MJ/kg. This is surprising, because both in chemical systems and in capacitors the energy storage is due to electric forces between positive and negative charges. For instance hydrogen atoms can be considered as small spherical capacitors with a positive charge in the center and negative charge a certain distance away from the center. However in a macroscopic capacitor arcing discharges it and all energy is converted to heat, if the electric field exceeds a few MV/m, whereas in nano capacitors quantization suppresses charge recombination. Recently a nano capacitor design was suggested which combines the benefits of capacitors with...
the high energy density on chemicals with covalent bonds: synthetic atoms. A synthetic atom has the same geometry as atoms, with a positive charge in the center surrounded by a cloud of negative space charges, but is 10 – 100 times larger than atoms. Therefore the electrodes can be connected with electrical leads [3-5].

The simplest implementation of synthetic atoms is a stack of aluminum foils. Aluminum foils oxidize in air at room temperatures and have a 4nm layer of insulating aluminum oxide on both sides. A stack of three layers of ultra-thin aluminum foil creates a quantum well structure where the central flat anode is sandwiched between two double layers of aluminum oxide and two flat aluminum cathodes. The dielectric strength of aluminum oxide is typically around 1V/nm, but can be much larger, depending on the quality of the oxide layer. This means that the energy density in the oxide layers is 1 MJ/kg or larger.

In nano vacuum capacitors, the energy density is limited by the tensile strength of the central anode. For materials with strong covalent bonds such as carbon nanotubes or doped boron-nitrate nanotubes the energy density is in the hundreds of MJ/kg. This energy density is two orders of magnitude larger than in common chemical energy storage, but much less than in nuclear systems.

The energy density of nuclear systems is about one million times larger than in chemical systems. Uranium-235 releases 80 million MJ/kg of heat in fission reactions and the deuterium-tritium fusion reaction creates about 330 million MJ/kg of heat.

The energy density of synthetic atoms potentially much larger than in chemical batteries, but this is not their most significant advantage. Synthetic atoms can release the energy much faster than chemical systems. In chemical systems atoms and molecules have to be moved to release the energy, whereas in synthetic atoms only electrons move during charge and discharge processes. Electrons are 3 orders of magnitudes less massive than atoms, and therefore move much faster. For instance, in an electrochemical battery energetic molecules have to diffuse from the interior of the electrolyte to the electrodes, release their charge and energy and then diffuse away from the electrode. This is a slow process. In contrast, when a synthetic atom discharges by arcing, the electrons move almost with speed of light.

The power-to-weight ratio is a quantitative measure how light-weight a power source is. The power-to-weight ratio is equal to the ratio of the energy density and the energy release time. The energy release time for electrochemical systems is around 1 hour, therefore their power-to-weight ratio is in the hundreds of W/kg [6]. If a propane heating system burns 1kg of fuel in 1 hour, its power-to-weight ratio is about 10 kW/kg. Propane burns slowly, because it contains no oxygen and mixing of air and gas is a slow process.

TNT has a lesser energy density, 4.6 MJ/kg, because the oxygen is stored within the compound, but the combustion reaction occurs much faster. In a 1 kg lump of TNT the reaction front propagates roughly with the speed of sound, i.e. the reaction completes within about 10 microseconds. This means that the power-to-weight ratio is on the order of 10^8 kW/kg, i.e. more than 10 million times larger than that of propane. Therefore TNT is considered an explosive. If we assume, that the reaction time of nuclear reaction is similar then their power-to-weight ratio
would be around one million times larger, because their energy density is about one million times larger, i.e. the power-to-weight ratio is about $10^{14}$ kW/kg.

![Figure 1 The maximum power-to-weight ratio for chemical reactions, nuclear reactions, and synthetic atoms, such as quantum wells made of a 3 layers of thin aluminum foil.](image)

The energy density of synthetic atoms is in the range of chemical energy storage materials, but the energy release time is much shorter. For instance if the release of the electric energy in 8nm aluminum oxide layer is estimated by the time electrons need to cross the gap at a speed slightly below the speed of light, then the energy release time is 0.01 femtoseconds, and the power to weight ratio is $10^{23}$ kW/kg. Even if the electrons move only at 1% of the speed of light, the power-to-weight ratio is still a record $10^{21}$ kW/kg. Therefore it is conceivable, that even simple implementations of synthetic atoms, such as a quantum well structure, made out of a stack of 3 layers of aluminum foil, have a record power-to-weight ratio (see Fig. 1). Magee’s trend lines predict [7], that synthetic atoms and other nano capacitor systems will outperform other energy storage systems within a decade.