The Photon Battery
- a new concept for low cost, large scale or high energy density electricity storage

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Abstract

In this report a photon battery is presented as a new type of electrical energy storage. The battery charging is based on conversion of electricity into photons and these photons are absorbed by an energy storage material, which is therefore heated to high temperatures. To extract electricity when needed, photons emitted from the hot energy storage material can be converted back to electricity by photovoltaics. The basic principles of the energy cycle are presented and the efficiency of the photon battery is discussed. The maximum energy density for different types of materials are estimated and examples of application of photon batteries for low cost and large scale electricity storage is suggested, and higher energy density applications are also discussed.
Background

Due to the problems with fossil-based energy sources, such as global warming and emission of toxic particles, renewable energy sources may be increasingly important in the future energy systems. However, renewable energy sources such as solar cells and wind power are intermittent and the power depend on the weather conditions. Since solar electricity production only is generated during daytime, electrical energy storage for at least a few hours is needed for electricity grids with a large electricity contribution from solar cells. Therefore, to be able to include a large fraction of these energy sources in the electricity grid, storage of electrical energy at least for some hours will be needed to balance the variation in energy production and consumption. Also, local electrical energy storage is of great interest when the number of houses with roof-top solar cells increases, to be able to locally store electrical energy during daytime, for later use in evenings and mornings. In addition to these stationary electricity storage systems, a growing amount of electrical vehicles need to have batteries, which should be low cost but in this case also with high energy density.

Lithium ion batteries [1-3] or sodium ion batteries [1-4] may be used for electrical energy storage in many of these applications and other technologies such as flow batteries [1-5], fly-wheels [1-3,6], or energy storage in pumped water [1-3], or compressed air storage [1-3], can also be used in some locations. Another interesting technology for large scale energy storage is based on melting silicon during peak electricity production [7]. To extract energy, the melted silicon is pumped to a container where photovoltaic cells can be introduced, which converts the light emitted from the hot silicon to electricity [7]. This type of energy storage may have a low cost, and can also be large scale. However, this type of storage requires very heat resistant pumping of the melted silicon to the photovoltaic cells, which may be a technological challenge. Also, rather much energy may be lost due to heat leakage by pumping the melted silicon to the container with photovoltaic cells.

Additional new electrical energy storage techniques that complement the techniques mentioned above can also be of great importance. The next decades an increasing amount of electrical energy storage will be needed, and additional new technologies may be necessary to fill the increasing need. Especially low-cost and large scale energy storage and other techniques for high energy density electrical storage can be very useful for a quicker change towards electricity systems based on renewable energy.

In this report a concept of a photon battery for electrical energy storage is presented. In this type of battery the electrical energy is converted to photons, and then energy is stored as photons and heat and then the photons are converted back to electricity. The advantages and disadvantages of this type of battery are discussed, and different materials for use for the different parts within the battery are proposed.

Concept of the photon battery

In figure 1 the basic principles of the photon battery are described. Figure 1A describes the charging process of the photon battery. During charging electricity runs through a heating element that is heated due to electrical resistivity and it heats up to high temperatures and therefore emits photons, similar to in a light bulb. The photons emitted from the heating element is absorbed by an energy storage material, which therefore also becomes hot. During charging the energy storage material therefore heats up to high temperatures.
Figure 1: Schematic description of a photon battery. A) shows the charging process of the photon battery, where electricity is introduced to a heating element emitting photons which are absorbed by an energy storage material, which therefore is heated. B) shows the charged photon battery, which has energy stored in the hot energy storage material, which therefore glows. C) shows the electricity generation by using a photovoltaic device, which absorbs photons emitted by the hot energy storage material.

Figure 1B describes when energy is stored in the photon battery. When the energy storage material is hot, it emits photons and the emitted photons are kept within the chamber surrounding the energy storage material and photon recycling occurs. In the photon recycling process photons are re-absorbed by the energy storage material, and energy remains in the system. Heat insulation materials are used around the chamber with the energy storage material to reduce cooling by the surroundings, and the energy is therefore stored in the system.

Figure 1C describes the electricity extraction from the photon battery. When electricity is needed, part of the heat insulation material can be moved and photons emitted from the energy storage material can be absorbed by photovoltaic cells and electricity is generated.

**Heating element for photon emission**

When the battery is charged, electricity run through a heating element, which is heated by joule heating due to electrical resistivity. The heating element emits radiation due to the high temperature and the emitted radiation can be absorbed by the energy storage material. This type of heating element is commonly used in ovens for high temperatures and the materials used in the heating element need to have a high melting point to be able to operate at high temperatures. Depending on the atmosphere surrounding the heating element, it also needs to be resistant to reactions with the surrounding atmosphere. If air is used in the chamber surrounding the heating element, the material especially needs to be resistant to oxidation. Examples of materials that are used in high temperature ovens in air, is molybdenumdisilicide or siliconcarbide. Using these materials, temperatures of the heating element can be above 1500 °C in air for long time. This is especially useful for large and low cost energy storage systems without using inert atmosphere around the heating elements. To reach higher temperatures of the heating elements, inert atmospheres such as argon can be used around the heating element. In that case tungsten, which has a very high melting point, can be used as heating element. Tungsten heating elements can be used to reach above 3000°C, and the heating element then works with similar principles as a light bulb.
Energy storage material

The photons emitted by the heating element is absorbed by the energy storage material. The energy stored is therefore ideally equal to the energy emitted by the heating element. Using heat insulation materials around the chamber with the energy storage material, losses of heat to the surrounding can be decreased and energy can be stored for long times.

The amount of energy stored in the material depends on the increase in temperature and the heat capacity of the material. A higher heat capacity gives a higher possible energy storage for a specific temperature change. The temperature change of the energy storage material during charging may be as high as 1000-2000°C, depending on the choice of materials and systems. This will result in a considerable amount of energy stored. For example a material with the heat capacity around 1 J/K/g (which many materials have), can store approximately 1 MJ/K/ton and 1 GJ/ton when heated to 1000°C during charging, which is equal to around 277 kWh/ton.

If there is a phase change in the heating temperature range this can also affect the energy storage capacity of the material. However, phase changes usually introduce volume changes of the energy storage material, which need to be considered in the construction of the device.

The choice of energy storage materials may depend on many factors, for example if the energy storage should be low-cost, or high energy density, or low weight etc. Important properties of the energy storage material to consider for a functional device are also for example the melting point, reactivity with the atmosphere, phase change temperatures, the heat expansion and the boiling point. The chemical stability at high temperatures is specifically important, and also the reactivity with oxygen, if the energy storage material is in air. To avoid reactions with air at high temperature it can be necessary to use inert atmosphere, such as Ar, surrounding the energy storage material, similar to the heating element above. There are however materials that also can be used in air at high temperatures, such as many oxides, that don’t react with air. For example aluminum oxide, silicon oxide, magnesium oxide and many other oxides or mixes of oxides are stable at temperatures higher than 1000°C in air, and may therefore be used as energy storage materials.

Depending on the temperature of the energy storage material it emits photons with different energies. The light emission spectrum may be estimated by black-body radiation. The black-body radiation spectrum can be determined from Planck’s law:

\[ B(\nu, T) = \frac{2h\nu^3}{c^2 e^{\frac{h\nu}{kT}} - 1} \]  \hspace{1cm} (eq.1)

Where \( B \) is the spectral radiance density, \( h \) is Planck’s constant \( c \) is the speed of light, \( T \) is the absolute temperature of the black-body, \( k \) is Boltzmann constant, and \( \nu \) is the frequency of the light.

The maximum of the light emission spectrum of a black-body is given by Wiens displacement law:

\[ \lambda_{\text{max}} = \frac{b}{T} \]  \hspace{1cm} (eq.2)

Where \( \lambda_{\text{max}} \) is the wavelength of the maximum in the light emission spectrum, \( b \) is Wien’s displacement constant and \( T \) is the absolute temperature.

The integrated radiance from the black-body is given by Stefan-Boltzmann law:

\[ j = \sigma \cdot T^4 \]  \hspace{1cm} (eq.3)

Where \( \sigma \) is the Stefan-Boltzmann constant and \( T \) is the temperature.
To specifically direct the photons emitted to the photovoltaic device, it is possible to use highly light emitting materials on the surface of the energy storage material facing the photovoltaic device and low emitting materials at the other surfaces of the energy storage material. It is also possible to use materials with increased light emission in the visible region and reduced infrared light emission at high temperatures at the surface facing the photovoltaic device.

**Conversion of emitted photons from the energy storage material to electricity**

In general the light emission spectrum from hot materials extends from far infrared radiation to visible light, and the light emission spectrum from a black-body can be described by eq.1 above. As given by eq.2 the light emission peak wavelength also depends on the temperature of the hot material. At low temperatures, the material mainly emits photons in the infrared region and at high temperatures the light emission is more in the visible region.

In the photon battery, the temperature of the energy storage material will vary from rather low temperatures (when the battery is not charged) to very high temperatures (when the battery is fully charged). The spectrum of the light emitted from the energy storage material will therefore be very different depending on the level of charging of the battery. When the battery is fully charged the energy storage material will emit light in the visible region and close infrared region, and when the battery is less charged the energy storage material will emit light more in the infrared region. To be able to extract electricity from the battery, the photovoltaic device therefore needs to be able to convert both visible light and infrared light to electricity.

The photovoltaic device can for example consist of a silicon photovoltaic cell, which convert photons both in the visible region and in the near infrared region up to a wavelength of around 1100 nm to electricity. Photons with longer wavelength (lower energy than the bandgap) will be transmitted through the silicon photovoltaic cell, and by using a reflector on the backside of the silicon photovoltaic cell, the light can be reflected back to the energy storage material. It is therefore possible to recycle these low energy photons to the energy storage material, to reduce losses in the battery.

One loss in the conversion from photons to electricity is the energy loss for high energy photons in the photovoltaic device. The excess energy of the photon, compared to the bandgap energy of the photovoltaic material, will be lost as thermal heat in the photovoltaic device and therefore result in losses in the photon battery. To increase the efficiency of the conversion of photons to electricity a stack of several photovoltaic cells can be used, which is further discussed below.

**Energy efficiency of a photon battery**

The energy efficiency of a photon battery depends on a number of factors. The electricity introduced in the battery is converted to light and heat within the chamber including the heating element and the energy storage material. Some losses may occur in the cables connected to the heating element, but most of the photons and heat should be produced and kept within this chamber. The losses during charging are therefore expected to be small. The photons emitted from the heating element is absorbed by the energy storage material and the energy stored in the battery is therefore mainly stored within the heated energy storage material. Depending on the heat insulation of the chamber including the heating element and the energy storage material, the energy will be preserved in this chamber for a certain time. However, due to heat losses to the surrounding, the energy will slowly leak out from the chamber, and the rate of the energy loss to the surrounding will be limited by the
efficiency of the heat insulation material. In figure 1, the heat insulation material surrounds the chamber with the energy storage material completely, and only when electricity is needed, part of the heat insulation will be moved, so that photons can reach the photovoltaic device. To avoid large heat losses during the electricity extraction, one or several transparent glass windows can be placed between the energy storage material and the photovoltaic device. The photons transmitted through the glass windows then reach the photovoltaic device, where the photons are converted to electricity. In the section above it was described that one photovoltaic cell or several photovoltaic cells in a stack can be used to convert the light to electricity. By using several photovoltaic cells in a stack, similar to what is used in a tandem solar cell, photons with different energy can more efficiently be converted into electricity, increasing the total efficiency of the photon battery. Presently there is a strong development in this area, with increasing efficiency of the light to electricity conversion. Photons with very low energy (infrared radiation with long wavelength) are not absorbed by the photovoltaic cells and are therefore transmitted through the photovoltaic device. In order to not lose the energy from these low energy photons a reflector can be placed behind the photovoltaic device to reflect these photons back to the energy storage material. By this photon-recycling, the losses for the conversion from photons to electricity is rather low.

Energy storage at large scale or high energy density

The photon battery is probably most advantageous for large scale electricity energy storage, because of the reduced heat losses at large volume energy storage (since volume increases more than the surface area when scaling up to large size energy storage materials). Also, many different materials can be used for energy storage and therefore low cost and abundant materials can be used. For example mixes of oxides, which can be heated to high temperatures without degradation are suitable, such as silicon oxides mixed with aluminum oxide, magnesium oxide etc. These oxides also have rather high melting points, which makes the energy storage material solid and easy to handle, for example as bricks. It is also possible to use other materials with lower melting points for the energy storage material and instead use a container made of a material with high melting point to keep the energy storage material in place. In this case the energy change at melting can be used to reach higher energy densities in the battery.

Since the energy stored in the system depends on the temperature of the energy storage material, very high temperatures can result in very high energy densities. However, at very high temperatures reactions with the surrounding air can occur. To avoid these reactions it may be preferable to use inert atmosphere as argon in the chamber surrounding the energy storage material, as discussed above. In this case temperatures up to around 2000°C or even higher may be possible. This will then give higher energy density of the battery and possibilities to reach over 500 kWh/ton (500 Wh/kg) for the energy storage material. However, it should be considered that the chamber surrounding the energy storage material, the heat insulation, the heating elements and the photovoltaic cells also will contribute to extra weight, and a practical energy density is probably significantly lower.

It is also interesting to consider the volume for a certain amount of energy of the photon battery. Assuming a metal oxide as energy storage material, the density is somewhere between 2000-4000 kg/m³ and the energy stored in one cubic meter is then around 1-2 MWh (1-2 kWh/liter). But again the surrounding chamber, insulation, heating elements and photovoltaic cells should also be considered, which increase the volume, and reduce the energy per volume in practical devices. However, it is interesting to see the possible theoretical potential of this technology, and the numbers that may be reached in future devices.
Possible future applications of photon batteries

Due to the advantages with low heat losses for energy storage in large volume with small surface, the most probable application for photon batteries is for large scale electricity storage (MWh-GWh scale). Due to the increased use of solar cells and wind power, photon batteries may be a very good option for balancing these intermittent energy sources. Especially to balance the electricity production and usage over the day and night can be a good working area for the photon batteries, since in this case rather quick use of the energy is done, which reduce the long term heat losses. Medium sized batteries (MWh) can also be used to locally support the electricity grid in different areas where the energy production or energy usage varies to a large extent, for example close to wind power farms, solar cell power plants or charging stations for vehicles. In addition to these large scale energy storages, it may also be possible to use smaller scale (10-100 kWh) photon batteries in houses with photovoltaics for balancing the local electricity system within one building. In this case efficient heat insulation is needed to prevent leakage of energy to the surrounding, from these smaller batteries. It may even be possible to include the photon batteries in vehicles, since a high energy density can be achieved with high temperature energy storage materials. For large vehicles such as ships, trains and heavy trucks, this could be an interesting option if high energy densities can be reached, efficient heat insulation and efficient photovoltaic cells can be used in the photon batteries.

Summary

In this report a concept of a photon battery is introduced. The basic working principles are described and possible constructions and materials for photon batteries are discussed. Based on these materials, the theoretical energy densities of photon batteries are estimated, and finally possible applications of the photon battery are discussed. From this discussion it is concluded that the photon battery can be of specific interest for large scale energy storage for example in electricity grids, but if high energy density can be reached, for high temperatures of the energy storage material, applications in vehicles could be another interesting future possibility. An interesting advantage with this type of battery compared to many other batteries, is the possibility to use a large variety of materials for the energy storage material. Specifically abundant, low-cost and low-toxic materials can therefore be considered for the construction of the photon batteries, which is important and necessary for a future large scale production.

References