Ultra high temperature latent heat energy storage and thermophotovoltaic energy conversion

Alejandro Datas*, Alba Ramos, Antonio Martí, Carlos del Cañizo, Antonio Luque

Instituto de Energía Solar – Universidad Politécnica de Madrid, Madrid, 28040, Spain

A R T I C L E   I N F O

Article history:
Received 4 September 2015
Received in revised form 6 April 2016
Accepted 11 April 2016

Keywords:
LHTES (Latent heat thermal energy storage)
High temperature
Thermophotovoltaics
Silicon
Boron
PCM (Phase change materials)
CSP (Concentrated Solar Power)

A B S T R A C T

A conceptual energy storage system design that utilizes ultra high temperature phase change materials is
presented. In this system, the energy is stored in the form of latent heat and converted to electricity upon
demand by TPV (thermophotovoltaic) cells. Silicon is considered in this study as PCM (phase change
material) due to its extremely high latent heat (1800 J/g or 500 Wh/kg), melting point (1410 °C), thermal
conductivity (~25 W/mK), low cost (less than $2/kg or $4/kWh) and abundance on earth. The proposed
system enables an enormous thermal energy storage density of ~1 MWh/m³, which is 10−20 times
higher than that of lead-acid batteries, 2−6 times than that of Li-ion batteries and 5−10 times than that
of the current state of the art LHTES systems utilized in CSP (concentrated solar power) applications. The
discharge efficiency of the system is ultimately determined by the TPV converter, which theoretically can
exceed 50%. However, realistic discharge efficiencies utilizing single junction TPV cells are in the range of
20−45%, depending on the semiconductor bandgap and quality, and the photon recycling efficiency. This
concept has the potential to achieve output electric energy densities in the range of 200−450 kWh/m³,
which is comparable to the best performing state of the art Lithium-ion batteries.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

LHTES (Latent heat thermal energy storage) employs energy to
cause the phase change transition in a material that subsequently
stores energy in the form of latent heat. That material is referred to
as PCM (phase change material) and is the key element deter-
mining the overall performance of the storage system. PCMs
promises one of the highest energy densities and lowest costs of
existing LHTES materials [1,2]. However, current LHTES solutions
are subject to a very low heat extraction rate from the storage
medium, which is attributed to the low solid-phase thermal con-
ductivity and moderate latent heat of PCMs. Current research ef-
forts focus on developing relatively sophisticated PCM
encapsulation so that thermal conductivity is notably enhanced
[1.3−6]. However, these strategies inherently have a lower energy
density potential, since part of the volume is dedicated to the PCM
host.

An alternative solution consists of directly using PCMs with
higher thermal conductivity and latent heat. As a general rule, the
heat of fusion of materials increases with melting temperature
[1,7]; thus, there is an interest on moving towards higher melting
point PCMs. However, in LHTES for power generation there is a
maximum temperature imposed by the HTF (heat transfer fluid)
that is used to carry the heat from the PCM to the heat engine,
which degrades at high temperatures. Maximum temperatures are
typically below 500 °C [8]. Other technological options exist
though; such as TPV (thermophotovoltaics) [9,10], thermionic [11]
or hybrid thermionic-photovoltaic [12] devices that do not
require HTFs and consequently have the potential to operate at
extraordinary high temperatures.

Previous works have proposed conceptual system designs for
solar thermal energy storage based on very high melting point
PCMs, such as pure silicon and boron (melting points of 1410 °C
and 2076 °C, respectively) and TPV converters [13−19]. The first
experiments on molten silicon for LHTES applications have been
recently carried out at the University of South California with the
aim of developing a solar thermal propulsion system for micro-
satellites [20]. The container damage due to freezing expansion
of pure silicon was the most relevant engineering concern. Besides, a
highly asymmetric freezing profile was observed due to the use of
non-adiabatic container walls, which produced regions of molten
silicon encased in solid silicon that ultimately resulted in high
stressed and container damage. It is worth noting that these issues could be solved in future designs by several means, such as using quasi-adiabatic container walls, i.e. improved container thermal insulation, or reducing the container fill factor [20]. In the opinion of the authors, an especially interesting solution consists of using silicon alloys instead of pure silicon, in order to reduce the freezing expansion coefficient of the PCM. We believe that, among all the possibilities, the silicon-boron system is particularly interesting due to the extremely high latent heat of boron (4650 J/g) and the moderately low melting temperature (1385 °C) for the eutectic Si0.52B0.08 [21,22]. Besides, the silicon lattice parameter contracts upon alloying with boron [21], which suggests that freezing expansion issues could be eliminated. Other practical concern is the thermo-chemical compatibility between the container and the PCM at those high temperatures. A variety of refractory materials have been extensively used for casting solidification of all kinds of metals at high temperatures, including silicon and boron. Some examples are BN (used in Ref. [20]) SiC and Si3N4. In these cases, important selection criteria are the wetability, solubility and reactivity of the container with the PCM, along with evaporation and oxidation of the PCM in oxygen-rich atmospheres. Thus, it is still needed an extensive research on the compatibility of these materials for the particular application of LHTES, especially concerning cycling and long term reliability.

In this work we present a conceptual LHTES system design for both S2H2P (solar-to-heat-to-power), commonly referred to as CSP (concentrated solar power), and P2H2P (power-to-heat-to-power) applications. Notice that other P2H2P concepts have been previously proposed to store the excess of electricity in the grid and co-generate heat and electricity [23]. The concept presented in this paper is based on the same operation principles than previously proposed systems in Refs. [13–19], i.e. high temperature PCM and TPV energy conversion. The proposed system differentiates from the previous designs in its geometrical configuration, which facilitates the thermal insulation of the PCM and the integration of an independent (mobile) TPV generator, providing a tunable power discharge rate (from zero to full-discharge mode). We assess this concept theoretically to predict its performance under several assumptions, which range from idealistic (to provide the upper bounds of this concept) to more realistic, to provide its actual short-term potential.

2. System description

Fig. 1 shows two possible configurations of the LHTES system presented in this paper for P2H2P [24] (left-hand side) and S2H2P or CSP (right-hand side) applications. In the P2H2P case, an electric heating system is used for melting the PCM. Among all the possible options, an inductive electric heater could be used if the PCM is magnetic or electrically conductive (e.g. iron or metallurgical silicon). Other options include resistive or microwave heating. In any case, electrical energy is stored in the form of the latent heat within the PCM. In the S2H2P case (right-hand side in Fig. 1); concentrated solar power heats the inner walls of the vessel containing the PCM. If the sunlight concentration factor is high enough [13,14], (above 1000 suns) the solar heat will produce the melting of the PCM and consequently, solar energy will be stored in the form of latent heat. Other arrangements not illustrated in this paper may use the waste heat from high temperature industrial processes or other kinds of electric heating.

In both cases of Fig. 1 the stored heat is released in the form of electricity by using a TPV converter, which comprises a number of infrared sensitive photovoltaic cells that directly produce electricity from radiant heat. In contrast to conventional heat engines, the contact-less nature of TPV converters enable extremely high temperature operation, which is essential for this kind of systems. Besides, TPV can provide extremely high power densities (power-to-weight and power-to-volume ratio) at low maintenance costs (neither moving parts nor working fluids within the converter) along with silent operation, which is important for decentralized applications. Furthermore, the TPV conversion efficiency is very high, potentially exceeding 50% due to the possibility of sub-bandgap photon recycling, which can be accomplished, for instance, by using reflectors in the back side of the TPV cells [25].

When electricity is demanded from the LHTES system, the TPV generator is moved in the cylindrical cavity formed by the inner walls of the vessel, from now-on referred to as emitter (Fig. 1). Then, the TPV converter is irradiated by the emitter, which is in direct contact with the molten PCM, and produces electricity. During this process, the PCM progressively solidifies creating a crust of solid around the emitter. This crust difficulpts the flow of heat from the liquid PCM to the emitter. In this concern, the higher solid-phase thermal conductivity of silicon PCM
enormously mitigates the impact of this effect on the output system power. Notice that these systems have the possibility of delivering not only electricity, but also heat from the TPV cells cooling, which might be beneficial in some particular applications such as in domestic heating, where the output coolant temperatures of 40–70 °C match perfectly with the heating temperature requirements.

From the previous description, it is evident that the energy density (stored energy per unit of volume) and the specific energy (stored energy per unit of weight) of these systems relies on the latent heat of the PCM. Besides, the PCM melting temperature determines the attainable TPV conversion efficiency and power density (W/cm²). Thus, high melting point and latent heat are desirable. As explained above, among all the possible candidates, silicon and boron stand out as particularly interesting materials due to their extremely high latent heats (1800 J/g and 4650 J/g, respectively, see Fig. 2). Silicon is advantageous from the practical point of view due to its higher thermal conductivity (25–130 W/mK) and moderate melting point (1410 °C) if compared with boron (thermal conductivity below 30 W/mK and melting point of 2076 °C) [13,26,27]. Besides, silicon is abundant (second most abundant element on earth) and has low cost (~1.7 $/kg). As described above, silicon-boron alloys are particularly interesting due to their potential to achieve extremely high latent heat, moderate melting temperature and lower freezing expansion coefficient than pure silicon. However, for the sake of concreteness in this paper we will use the latent heat and thermal conductivity values of pure silicon. The analysis of other promising PCMs will be considered in future works.

3. System model

In order to describe the transient performance of the LHTES system, we assume a quasi-1D analytical model in which the solid–liquid interface is a moving cylinder at a distance \( r_m(t) \) from the axial center of the system (Fig. 3). To solve the problem we follow the quasi-stationary approach used in Ref. [15] assuming an adiabatic (loss-less) container and neglecting natural convection in the liquid. Natural convection in the liquid can be disregarded, as we will see later, due to the very low temperature gradient in the liquid silicon, which leads to a very small variation of the silicon density. Due to the later assumption the 1D-Fourier conduction law applies to describe the heat flow in both liquid and solid phases:

\[
Q_s = 2\pi r L k_s \frac{dT}{dr}
\]

By integrating (1) in the solid and liquid we obtain the following expressions for the temperatures \( T_1 (r = R_1) \) and \( T_2 (r = R_2) \) as a function of the melting temperature \( T_m \).

\[
T_1 = T_m - \frac{Q_s}{2\pi L k_s} \ln \left| \frac{r_m(t)}{R_1} \right|
\]

![Fig. 1. Electric-TES (left) and solar-TES (right) systems utilizing high melting point PCM and thermophotovoltaic (TPV) cells for electricity production [24].](image1)

![Fig. 2. Latent heat of fusion of different materials as a function of the melting temperature [3,4,33].](image2)
(34) In vacuum, in the spectral interval \((\text{liquid to the solid equals the energy employed in performing the phase change of a the PCM contained in between liquid PCM, respectively. Due to the assumption of adiabatic cross-sectional view of the LHTES system illustrating the heat transfer from the emitter and the cells and a reflector of reflectivity \(\beta_{\text{BR}}\) located on the back side of the TPV cells.)

Finally, due to adiabatic container the total energy stored in the PCM is delivered only by heat radiation through the emitter surface, which leads to

\[
E_{\text{tot}}(t + \Delta t) = E_{\text{tot}}(t) - Q_t \Delta t
\]  

(7)

where \(E_{\text{tot}}\) is the total thermal energy stored in the PCM including both specific and latent heat:

\[
E_{\text{tot}}/(2\pi L) = \rho_c c_p \int_{r_n}^{r_m} r T_s(r) dr + \rho c_p \int_{r_m}^{r_s} r T_f(r) dr + \rho c_p (R_s^2 - R_m^2)
\]

\[
\times /2
\]

(8)

Integrals in (8) can be analytically solved by introducing the expressions for \(T_s(r)\) and \(T_f(r)\) obtained from the integration in (1):

\[
\int_{r_n}^{r_m} r T_s(r) dr = \frac{1}{2} \left[ \frac{\pi^2}{4} T_m^2 - \frac{\pi^2}{4} T_1^2 - \frac{Q_t}{4\pi L} \left( R_m^2 - R_s^2 \right) \right]
\]

(9)

\[
\int_{r_m}^{r_s} r T_f(r) dr = \frac{1}{2} \left[ \frac{R_s^2}{2} T_2 - \frac{R_m^2}{2} T_m - \frac{Q_t}{2\pi L} \left( R_m^2 - R_s^2 \right) \cdot (2 \ln |r_m| - 0.5) \right]
\]

(10)

The Equations (2)–(5) and (7) can be solved numerically to obtain \(T_1, T_2, Q_t, Q_s\) and \(r_m(t + \Delta t)\). Finally, the output power from the TPV converter is given by Ref. [25].

\[
P_{el} = \pi A_e q V \times \left\{ N(\epsilon_G, \infty, T_e, 0) - [1 + 2n_i^2 \left( 1 - \frac{\beta_{BR}}{2} - \frac{1 - \eta_{\text{int}}}{\eta_{\text{int}}} \right) \right]
\]

\[
\times \left\{ N(\epsilon_G, \infty, T_e, q V) \right\}
\]

(11)

where

\[
N(\epsilon_1, \epsilon_2, T, \mu) = \frac{2}{h^2 c^2} \int_{\epsilon_1}^{\epsilon_2} \frac{\epsilon^3 d\epsilon}{\exp[(\epsilon - \mu)/kT] - 1}
\]

(12)

has the same meaning than \(E\) but for the photon flux instead of the energy flux, \(n_i\) is the refraction index of the semiconductor and \(\eta_{\text{int}}\) is the internal luminescence efficiency, i.e. the fraction of electron–hole pairs that recombine radiatively within the semiconductor. In a first approximation, the external luminescence efficiency, i.e. the fraction of electron–hole pairs that recombine radiatively to yield a photon that ultimately escapes the TPV cell, can be obtained as a function of \(\eta_{\text{int}}, n_i\) and \(\beta_{BR}\) by:

\[
\eta_{\text{ext}} = \frac{1}{1 - n_i^2 (1 + \beta_{BR} - 2/\eta_{\text{int})}}
\]

(13)

4. System performance with ideal TPV cells

In this section, the TPV cells are assumed to be ideal (i.e. \(\eta_{\text{int}} = 1\)) with a bandgap of 0.5 eV, which could be manufactured for instance using InGaAsSb alloys on GaSb substrates. Under this
assumption, Equations (2)–(5) and (7) are solved for the silicon parameters listed in Table 1 and Table 2.

Table 3 shows the model results for the discharge of the LHTES system with different geometries and for two values of $\rho_{BR}$ (the ideal case of $\rho_{BR} = 1$ and a more realistic one of $\rho_{BR} = 0.8$). Initial condition is that emitter temperature equals the silicon's melting point, so that energy is released from the system during the silicon solidification. The system is considered discharged when all silicon is solidified. Notice that the values in Table 3 refer to the full-power discharge mode, i.e. when the TPV converter is entirely introduced in the cavity from the beginning, which provides the highest power-to-discharge time ratio.

Notice that these results, calculated under the assumption of adiabatic container, are valid for container walls of 10 cm and thermal conductivities below 0.01 W/m-K (small systems) and adiabatic container, are valid for container walls of 10 cm and power-to-discharge time ratio.

in the cavity from the beginning, which provides the highest discharge mode, i.e. when the TPV converter is entirely introduced

Table 1
Silicon thermal properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>sym</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latent heat of fusion</td>
<td>$L_f$</td>
<td>1800 J/g</td>
</tr>
<tr>
<td>Thermal conductivity (solid)</td>
<td>$k_s$</td>
<td>25 W/m-K</td>
</tr>
<tr>
<td>Thermal conductivity (liquid)</td>
<td>$k_l$</td>
<td>50 W/m-K</td>
</tr>
<tr>
<td>Density (solid &amp; liquid)</td>
<td>$\rho_s - \rho_l$</td>
<td>2520 kg/m$^3$</td>
</tr>
<tr>
<td>Heat capacity (solid &amp; liquid)</td>
<td>$c_p = c_p$</td>
<td>1040 J/kg-K</td>
</tr>
<tr>
<td>Melting point</td>
<td>$T_m$</td>
<td>1680 K</td>
</tr>
</tbody>
</table>

Table 2
Other system parameters.

<table>
<thead>
<tr>
<th>Property</th>
<th>sym</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPV cell bandgap</td>
<td>$c_{ll}$</td>
<td>sweep param</td>
</tr>
<tr>
<td>TPV cell BSR reflectivity</td>
<td>$\eta_{BR}$</td>
<td>sweep param</td>
</tr>
<tr>
<td>TPV cell internal photoluminescent efficiency</td>
<td>$\eta_{int}$</td>
<td>sweep param</td>
</tr>
<tr>
<td>TPV cell temperature</td>
<td>$T_c$</td>
<td>300 K</td>
</tr>
<tr>
<td>TPV cell voltage</td>
<td>$V$</td>
<td>optimized</td>
</tr>
<tr>
<td>PCM length</td>
<td>$L$</td>
<td>sweep param</td>
</tr>
<tr>
<td>PCM inner radius</td>
<td>$R_1$</td>
<td>sweep param</td>
</tr>
<tr>
<td>PCM outer radius</td>
<td>$R_2$</td>
<td>sweep param</td>
</tr>
</tbody>
</table>

From Table 3 we conclude that total energy densities (heat plus electricity) of ~1 MW/m$^3$ and electric energy densities of 200–600 kWh/m$^3$ are attainable in principle, which is comparable to that of best performing state of the art Li-ion batteries (Fig. 4) [28,29].

Fig. 5 shows the output power as a function of time for the case of a LHTES system with $\rho_{BR} = 1$, $L = 1$ m, $R_1 = 0.2$ m and $R_2 = 0.5$ m. This particular arrangement delivers 916 kWh of energy, from which 497 kWh is electricity and 419 kWh is heat. This amount of energy (heat plus electricity) is enough to power 32 Spanish dwellings (average consumption of 10,500 kWh/home/year [30]) during 24 h. Smaller systems (microwave oven size) could be scaled to power one single dwelling during one full day (see Table 3).

Another interesting feature of these systems is the very high power peak at the start of the discharge (Fig. 5) in the full-power discharge mode. This peak can be used for power quality applications, such as in UPS (uninterruptible power systems), where high power is required during short periods of time.

Finally, Fig. 6 shows the temperature profile through the PCM (in the radial direction) for the same LHTES system configuration than that of Fig. 5. Notice that the very low temperature gradient in the liquid (that allows us to disregard the natural convection

Fig. 4. Specific energy and energy density of several energy storage systems (taken from Refs. [28,29]). Silicon-LHTES refers to the system analyzed in this work.
phenomenon) is attributed partially to the fact that most of $Q_s$ comes from the released latent heat at the solid–liquid interface, which makes $Q_l$ notably smaller than $Q_s$. A fast decrease in the emitter temperature (at $r = R_1 = 0.2$ m) is observed during the first instants of operation. This is related to the sharp initial drop in the electrical power shown in Fig. 5. This strong drop in the emitter temperature is attributed to the decreasing area in the direction of the heat flow and to the lower thermal conductivity of the silicon’s solid-phase. The lower emitter temperature, which definitively affects the output electric power, does not necessarily affect the conversion efficiency. This is true at least for TPV converters with $\rho_{BR} \rightarrow 1$, for which most of sub-bandgap radiation is reflected back to the emitter. In this case, the lower emitter temperature implies a longer discharging time (due to lower radiative power) instead of lower conversion efficiency.

5. System performance with realistic TPV cells

Realistic TPV cells are modeled in this work by introducing the internal and external photoluminescent efficiency, $\eta_{int}$ and $\eta_{ext}$ respectively, which account for non-radiative recombination. The best performing III-V semiconductor based PV cells have demonstrated $\eta_{int}$ and $\eta_{ext}$ values above 95% and 35%, respectively [31]. However, semiconductors with non-direct transitions between valence band and conduction band, such as silicon, have much lower efficiencies, in the order of $\eta_{ext} \sim 0.1-1%$ [32]. Fig. 7 shows the equivalency between $\eta_{ext}$ and $\eta_{int}$ for several values of $\rho_{BR}$ according to the model used in this work. From this figure we see, for instance, that $\eta_{ext} = 0.01$ (optimistic case for silicon) corresponds to $\eta_{int} = 0.2$.

Fig. 8 shows the average conversion efficiency during the full-discharge of the system as a function of the TPV cell bandgap ($\varepsilon_G$) for different values of $\eta_{int}$ and $\rho_{BR}$. For ideal BSR ($\rho_{BR} \rightarrow 1$), the conversion efficiency increases monotonically with the semiconductor’s bandgap, independently of the internal luminescent efficiency. This is because most of the sub-bandgap radiation is effectively reflected back to the emitter by the BSR and do not represent a loss of energy. On the other hand, for realistic values of $\rho_{BR}$, there exist an optimum bandgap which depends on both $\rho_{BR}$ and $\eta_{int}$.
It is evident that high quality BSR is important for achieving high conversion efficiency. However, even for relatively low values of ρBR ~ 0.8 we can achieve decent conversion efficiencies by utilizing high quality (i.e. ηint > 0.95) low bandgap (below 0.75 eV) semiconductors. For instance, by utilizing semiconductors with bandgaps in the range of 0.7—0.75 eV such as GaSb or InGaAs lattice matched to InP substrates, efficiencies in the range of 25—45% are achievable for BSR reflectivities in the range of 80—95%. On the other hand, semiconductors with bandgaps as low as 0.5 eV (e.g. InGaAsSb on GaSb substrates) are less sensitive to the BSR quality, with achievable efficiencies in the range of 30—45% for the same values of ρBR. Notice that the impact of ηint on the conversion efficiency is more relevant for low bandgap semiconductor, in which case having high quality material is especially relevant. However, even for “low quality” and low bandgap semiconductors such as germanium (0.67 eV and assuming ηint = 0.2) we could obtain decent efficiencies in the range of 20—35%. The lower efficiencies in this case are greatly compensated by the lower cost of germanium substrates if compared with other III-V substrates such as InP or GaSb (about six times cheaper).

Lastly, another possible strategy consists of using high bandgap semiconductors, in which case the impact of ηint is less important and the conversion efficiency depends mostly on the BSR reflectivity. Therefore, in this case it makes more sense to use relatively “low quality” and “low cost” semiconductors such as silicon (bandgap of 1.12 eV and ηint = 0.2) including a very high quality BSR, in which case efficiencies in the range of 8—25% are attainable for ρBR in the range of 0.8—0.95. As in the case of germanium, the low efficiency is compensated by the much lower cost of the silicon devices.

In general, the use of higher bandgap semiconductors is accompanied by a decrease in the output electrical power (Fig. 9), which is attributed to the poor match between the radiative spectrum and the TPV cell spectral response. For high TPV conversion efficiencies (corresponding to high BSR reflectivity) the lower power density results in a dramatic increment of the discharge time, as shown in Fig. 10. This is because most of the radiative power is reabsorbed by the emitter, drastically reducing the power discharge rate.

![Fig. 9. Average output electric power as a function of the TPV cell bandgap, the BSR reflectivity and the internal photoluminescent efficiency. The LHTES system has the following configuration parameters: L = 1 m, R1 = 0.2 m, R2 = 0.5 m. The average electric power density, in kW per m² of TPV cell area, is obtained dividing the data of this Figure (in kW) by the total TPV cell area of 2πrL = 1.26 m². For instance, an average output power of 25 kW corresponds to an average output power density of ~2 W/cm².](image)

Notice that in germanium and silicon TPV cells, the use of BSR could be challenging due to their low absorption coefficient and the consequent requirement of a thick semiconductor layer to absorb the entire incident light. This could bring too high free-electron absorption losses which drastically deteriorate the effectiveness of the BSR. In this case, an alternative solution is to use front surface filters instead of (or in combination with) a BSR.

It is worth noting that, although not considered in this paper, the use of multijunction TPV cells could represent a means of achieving higher efficiencies and power densities without the necessity of highly efficient BSR [25].

6. Conclusions

A conceptual LHTES system utilizing high temperature silicon PCM and thermophotovoltaic cells has been presented. The proposed LHTES system is fully scalable in terms of power (from kW to MW), energy (from tens of kWh to tens of MWh) and discharge time (hours to days) and enables an ultra high thermal energy storage density of up to ~1 MWh/m². The attractiveness of this concept, besides the extreme energy density, is the possibility of using silicon as PCM, the second most abundant element on earth crust.

A theoretical analysis describing the transient response of the system has been presented. A few different configurations have been studied in order to illustrate the system performance. This analysis has been extended to both ideal and realistic TPV cells with non-radiative recombination to provide the actual short-term potential of the concept. According to the model results, discharge efficiencies in the range of 20—45% are practically attainable depending on the TPV cell bandgap, semiconductor quality and photon recycling efficiency. This leads to electric energy densities in the range of 200—450 kWh/m³, which is comparable to the best performing state of the art Li-ion batteries.

Acknowledgment

Authors acknowledge the financial support of the Comunidad de Madrid through the Programme MADRID-PV (Grant number S2013/MAY-2780) and from the Spanish Ministerio de Economía y
Competitividad through the Project PROMESA (grant N. ENE2012-37804-C02-01).

References


