SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Task 42 (ECES Annex 29)

Compact Thermal Energy Storage: Material Development for System Integration

Compact Thermal Energy Storage
IEA SHC Position Paper

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Contents

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Aim of the Position Paper

This position paper explains the potential, the present status of development and the market status of compact thermal energy storages. Its aim is to inform policy makers, decision makers and opinion makers about the technologies and to discuss the technological and non-technological barriers and the actions needed to accelerate the development and market uptake of these very important technologies.

Executive Summary

About half of the world's final energy demand is used for heating and cooling purposes. Therefore, technologies that can efficiently and effectively store heat are of key importance. They assist to increase the share of sustainable heat sources and improve the efficiency of thermal systems. Recent research results and technical developments show that storage technologies will become even more important with increased use of Smart Grid developments.

Thermal energy storage technologies are needed to match the variable supply of sustainable heat and to optimize the performance of thermal systems. Innovative compact thermal energy storage technologies are based on the physical principles and properties of phase change materials (PCM) and on thermochemical materials (TCM). With these materials, heat can be stored in a more dense form and with fewer losses than conventional heat storage such as hot water storage tanks.

Some important application areas of compact thermal energy storage technologies are:

- seasonal storage of solar energy,
- "waste heat" recovery in industrial processes,
- improved efficiency in the operation of Smart Grids, district heating- and low-temperature distribution networks using (micro)cogeneration plants, solar thermal collector systems and heat pumps, and
- assist in the heat management of energy systems for hybrid and electric vehicles and transport systems.

The technology of compact heat storage systems is still under development. PCM products are already on the market for a number of niche applications. PCM is applied for temperature control in buildings and for transportation of vulnerable goods, such as medical items, food, etc. Although a number of TCMs exist (zeolites, salt hydrates and composite materials), their application in storage systems still needs more R&D work, especially with regard to process engineering.

The potential for thermal storage systems based on PCM and TCM technologies is huge. For example it is estimated that about 800 GWh_{th} (or 18 million cubic meters of water) is the capacity of installed solar water storages for households in the year 2012.

The potential of new compact thermal storage systems for non-solar applications is considerably higher because stored energy can replace heat and cold produced using fossil fuels. Storage technology therefore also reduces CO_2 emissions. Stored thermal energy can reduce the need for expensive peak power installations, which operate occasionally and therefore high energy costs result.

The potential of thermal energy storage technologies becomes even higher when current "Smart Grid" developments and the integration of fluctuating renewable energies into the electricity (and thermal) grids are taken into account.

The technical barriers to exploit the potential are related to the fact that the technology needs further progress on three levels 1) material level, 2) component level, 3) system level. The systems must operate in highly fluctuating environmental and meteorological conditions. Compact thermal energy storage systems in their present development stage still require complex control, which causes high investment costs in the development of prototype systems.

Further research and development is needed to overcome economic barriers. The cost of a stored kWh of thermal energy in most applications is still too high to compete with burning oil and gas, especially as negative environmental effects of the current technology – for example CO_2 emissions – are not adequately considered in common economic evaluations.

Consequently, strong support of R&D work by governmental and international research programs is needed. IEA SHC Task 42 carried out in conjunction with Annex 29 of the IEA ECES Programme is a good example of the type of activities needed to accelerate technical and economic progress.

Introduction and Relevance

About half of the worldwide final energy demand is for heating and cooling purposes. Therefore, technologies that can efficiently and effectively store heat are of key importance. They assist to increase the share of sustainable heat sources and improve the efficiency of thermal systems. Recent research results and technical developments show that storage technologies will become even more important with increased use of Smart Grid developments.

Thermal energy storage technologies are needed to match the variable supply of sustainable heat and to optimize the performance of thermal systems. Current thermal energy storage technologies, mainly based on water tanks, perform well for short-term storage. Due to heat losses, long term thermal storage with water is not efficient for small and medium sized systems. For very large water storage systems, mostly connected to district heating networks, the long-term storage efficiency is good.

Long term storage and seasonal storage of heat is especially important for the further development and application of solar energy techniques in the future energy supply systems. Conventional storage systems based on hot water tanks can also be improved in certain details, but in order to enable a real breakthrough in thermal energy storage new materials and system technologies are needed.

Innovative compact thermal energy storage technologies are based on the physical principles and properties of phase change materials (PCM) and on thermochemical materials (TCM). With these materials, heat can be stored in a more dense form and with fewer losses than with hot water storage tanks.

PCM – Phase Change Materials
In PCM materials, the heat is stored when the material changes its state from solid to liquid or from liquid to vapor. Two main characteristics for this storage principle are the high amount of heat that can be stored and the fact that the storage takes place within a small temperature range, either the melting temperature or the evaporation temperature. The latter characteristic is also a limitation for the application of this storage method; only when heat should be stored in a limited temperature range the method has advantages over "normal" sensible heat storage. Examples of these applications, which are already on the market, are the control of room temperature by adding PCM materials into the walls of rooms. Another example is the storage of heat for operating a heat pump system by using an ice water storage tank as the low temperature heat source. During the ice formation, the heat pump is provided with a very large amount of heat at a constant (0 °C) temperature, leading to a higher performance of the heat pump.

TCM – Thermochemical Materials
With this heat storage method, the heat is stored through the separation of two different substances, in practical applications either two liquids or a solid and a vapor. The binding of the two substances can be caused by a number of physical principles or binding forces. The stronger the force, the higher the temperature needed to separate the two working materials and thus to store the heat. The range is from physical sorption caused by surface forces with storage temperatures starting at 30 °C, through chemical sorption caused by covalent attraction with temperatures above 100 °C, to chemical reactions caused by ionic forces with temperatures above 200 °C. In general, the storage density also increases with increasing temperature. There exist a large number of potential thermochemical materials, each with different properties regarding, for instance, mechanical stability, vulnerability for impurities, side reactions, vulnerability to unwanted morphological change, etc.

Application Areas
Compact thermal energy storage technologies still need further development and have a number of important application areas. Some very important ones are:

- Seasonal thermal storage of solar energy, with which the abundant energy supply in summer can be used in winter, for example for room heating purposes and heating of domestic hot water.
- Storage and transport of industrial "waste heat" from one industrial process to a place of another industrial process or to a residential area where this rejected heat can be utilized.
- Compact thermal energy storage technologies for Smart Grids to provide novel switchable supply or demand of energy in future intelligent electricity

and heating networks (Smart Grids) by coupling compact thermal storages to (micro)cogeneration or heat pumps or other sources (and sinks) of energy grids.
- Application of innovative compact thermal energy storages in hybrid or electric vehicles or other electric transportation modes to assist in the management of heat.

Compactness
The higher the amount of heat stored per cubic meter of volume, the more compact the storage technology. There is no absolute way for calculating the compactness or storage density of a certain storage technology, as this is dependent on the operational conditions of the heat storage application. The conditions that are most important are the temperatures for charging and discharging the storage and the additional space needed for the thermal insulation and the auxiliary components, such as heat exchangers, pumps, valves, vessels, and pipes. The only valid comparison of the storage densities of different technologies is for a well-defined application. On international level, first descriptions of the calculation of a key performance index on storage density are being discussed now.

Status of the Technology

PCM products are already on the market for a number of (niche) applications: for control of temperature for transportation of vulnerable goods, such as medical items, food, et cetera.

PCMs are also used in a number of building products to enable a better temperature control in buildings, especially for prevention of overheating in summer.

The demonstration of the application of PCM for transportation of heat is ongoing, while R&D is performed into novel Phase Change Materials for medium and high temperature applications, such as for industry and for Concentrating Solar Power (CSP) thermal power plants.

TCM is still in the R&D phase. A number of already existing materials (zeolites, salt hydrates and composite materials) are being applied in new system concepts for seasonal thermal storage of solar energy. First systems will be tested in the laboratory in 2015 and 2016. Field tests with these systems are expected in the years to follow. Only a few targeted programs or projects exist that work on developing improved or new TCM and the necessary engineering technology for the design storage devices. A long term target is to arrive at storage technologies that have a considerably higher storage capacity in relevant applications compared to hot water storage tanks. It is an additional and very challenging task for process-engineers to develop storage devices that operate efficiently and reliably and can be integrated easily into existing energy-management systems.

Potential

The potential for thermal storage systems based on PCM and TCM technologies is huge. But it is very difficult to quantify or even estimate it because the possible areas of application are so broad and diversified.

With respect to solar energy alone, it is estimated that the capacity of installed solar water storages for household applications alone is about 800 GWh_{th}. (in the year 2012). This is a total water storage volume of approximately 18 million cubic meters.

The potential of new compact thermal storage systems for non-solar applications is considerably higher because stored energy can replace heat and cold produced using fossil fuels. Storage technology therefore also reduces CO_2 emissions. Stored thermal energy can reduce the need for expensive peak power installations, which operate occasionally and therefore high energy costs result.

Thermal energy storage reduces CO_2 emissions by replacing the burning of oil and gas. For an example, it has been estimated that about 1.4 million GWh per year could be saved in Europe by more extensive use of thermal energy storage. This summarizes the potential in buildings for heating and domestic hot water but also in the commercial and industrial sector for more energy efficient processes by storing heat and cold.

The potential of thermal energy storage technologies becomes even higher when current developments regarding the integration of fluctuating renewable energies into the electricity grids are taken into account. This concerns especially the integration of wind power and electricity from photovoltaics into the electricity distribution system together with an increasing number of heat pump and cogeneration systems. Research on the possibilities of thermal energy storage under these new framing conditions in the electricity sector have only recently been started and are considered to be of increasing importance for the future development of efficient energy systems. "Smart Grids" need storage technologies and they become more and more important.

Current Barriers

The development of Compact Thermal Energy Storage systems based on phase-change and thermo-chemical materials is still very much in its R&D phase. It therefore still faces strong technical, financial and non-financial challenges.

The technical barriers are related to the fact that the technology needs further progress on three levels: 1) materials, 2) components, and 3) systems. The physical phenomena, which may be phase change processes, sorption processes or thermo-chemical reactions, take place on the molecular level. Basic and applied research is still necessary to fully understand the physics and chemistry involved in order to improve and synthesize storage materials. Modeling materials and the simulation of reactions and processes on the molecular scale will also contribute to this.
While the reactions take place on the molecular scale, the energy to be stored or

released is transported on a macroscopic scale. That means that process engineers need to be able to calculate and deal with the flow of liquids, gases or vapor.

Moreover, very often components have to be designed to operate in vacuum conditions. In thermochemical reactions it is necessary to deal with heat and mass transfer, which leads to components that have to be controlled with respect to several different operational parameters in order to achieve a high energy storage performance.

This results in complex system operational conditions. They often include highly fluctuating environmental and meteorological conditions. Therefore, the systems under development still require highly complex control, which leads to high investment costs in developing prototype systems.

Consequently, if we are to realize the huge potential of compact thermal energy storage systems based on PCMs and TCMS more R&D work is needed to address these technical barriers.

Further research and development is needed to overcome economic barriers. The cost of a stored kWh of thermal energy in most applications is still too high to compete with burning oil and gas, especially for long-term storage in which only a small number of storage cycles occur during the life time of the storage. The more often a storage is loaded and unloaded (high cycle numbers) the lower becomes the cost of the stored energy. Long term storage competes against burning oil and gas, which is stored chemical energy. Negative environmental effects of burning oil and gas – for example CO_2 emissions – are not adequately considered in common economic evaluations.

The cost uncertainty of thermal energy storage technologies is a major barrier for their further development. A group of experts in the IEA-SHC Task 42 is therefore carrying out a study to evaluate storage costs in a "top-down" and in a "bottom-up approach": The top-down approach assumes that the cost of energy storage should not exceed the cost of substituted energy generation. The maximum acceptable cost is calculated from the discount rate of storage capital, the payback period of the investment, the number of storage cycles, and the cost of substituted energy. To simplify the evaluation, this analysis neglects operating costs and changes in the cost of energy production over time. On the other hand, the bottom-up approach focuses on the actual costs of real storage systems. To investigate particular storages, a questionnaire was developed which inquires among other technical parameters the costs of the storage divided into investment costs (storage material, storage tank or reactor, charging/discharging unit), operating costs, and additional costs, e.g. maintenance or installation costs. The bottom-up approach has been applied to analyze the costs of 20 thermal energy storages so far. For the most part, these innovative storages are subject of ongoing R&D work. The study is on-going. One result from the top-down approach is that the maximum acceptable storage capacity costs are in the range of 2 to 4 Euro/kWh_{cap} for the case of seasonal storage, 25 years life time and low interest rates (1%). Estimated "bottom-up" costs of compact thermal energy storage technologies under development are in the range of 2 to 15 Euro/kWh_{cap}.

Similar to the economic situation of all renewable energy technologies, initial investment costs to implement storage technologies in energy systems are often still a very strong barrier. Adequate long-term financing innovations for initial investment costs in renewable energy system applications developed by the banks and the financial sector may assist to overcome these barriers.

Given the situation as described, it follows that an important barrier is the need for broad and well-coordinated, multinational R&D work within long-term international research programs. IEA SHC Task 42 carried out in conjunction with Annex 29 of the IEA ECES Programme is a good example and starting point for the activities needed. It is also important to establish more national and international research projects in order to achieve the necessary results in the different crosscutting scientific and engineering fields of expertise addressed by compact thermal energy storage systems based on phase-change material and thermo-chemical material technologies.

Actions Needed

What kind of actions would it take to really drive market deployment?

1. Strong support of R&D work by governmental and international research programs as described above. Compact thermal energy storage systems based on phase-change and thermo-chemical material technologies are to a large extent still in their development stage. The challenges cannot be addressed by single research groups and singularly achieved research results, but need a broad and internationally collaborative approach.

2. The companies involved in the development of compact thermal storage systems are often relatively small and highly innovative. They need strong support by governments to be able to apply their technology in the building and industrial processes sectors, in spite of the economic disadvantage they still may have.

3. Strong support of a growing number of demonstration projects is needed in order to gather operational experiences, to monitor and evaluate performance and to improve the performance of systems step-by-step. A much better basis for the further development and deployment of the huge potential of compact thermal energy storage systems will be established if these actions are taken.

Acknowledgement

The content of this paper builds upon the concepts developed in the context of the joint IEA (International Energy Agency) SHC (Solar Heating and Cooling Programme) Task 42/ECES (Energy Conservation through Energy Storage Programme) Annex 29: Compact Thermal Energy Storage: Material Development for System Integration (http://task42.iea-shc.org/).

IEA Solar Heating and Cooling Programme

The IEA Solar Heating and Cooling Programme members have been collaborating since 1977 to advance active solar and passive solar and their application in buildings and other areas, such as agriculture and industry. Under the management of an Executive Committee representing the members, the Programme carries out a strategy to enhance collective knowledge and application of solar heating and cooling through international collaboration.

More information can be found on the websites of the IEA Solar Heating and Cooling Programme, www.iea-shc.org and the IEA Energy Conservation through Energy Storage, www.iea-eces.org.