Compact Thermal Energy Storage for Potential Canadian Market Applications

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Bill Wong[1], Wim van Helden[2] and Marc A. Rosen[3]
[1]Science Applications International Corporation, Ontario, Canada
[2]Renewable Heat, The Netherlands
[3]University of Ontario Institute of Technology, Ontario, Canada

Abstract

Canada has an ideal climate for the application of seasonal thermal energy storage technologies. The potential positive impact on the ability to store summer heat for winter heating use is significant. Research efforts in Europe on compact thermal storage solutions are showing some signs of promise however, many technical challenges are still present and commercialization requires more work. The solution would have to be appropriately scaled to integrate easily into the existing heating systems of Canadian homes and to meet a number of other market requirements. This review paper highlights some of the recent advances and discusses some of the challenges.

Keywords: thermal energy storage, thermochemical materials, solar seasonal energy storage

Résumé

Le climat canadien convient parfaitement à la mise en œuvre des technologies de stockage saisonnier d'énergie thermique. L'incidence positive potentielle sur la capacité à stocker la chaleur recueillie l'été en vue du chauffage en hiver est notable. La recherche effectuée en Europe sur les solutions de stockage thermique compactes est quelque peu prometteuse; il reste cependant plusieurs difficultés techniques à surmonter et la commercialisation nécessite des études supplémentaires. La solution doit être adéquatement mise en application pour en faciliter l'intégration aux systèmes de chauffage existants des maisons canadiennes et satisfaire à un certain nombre d'exigences du marché. Cet article de synthèse met en relief quelques-uns des progrès récents ainsi qu'un certain nombre de défis.

Mots-clés : stockage d'énergie thermique, matériaux thermochimiques, stockage saisonnier d'énergie solaire

1. Introduction

Most population centres in Canada receive a significant amount of solar radiation – more, in fact, than some countries such as Germany, Denmark and Japan, where use of solar energy is becoming common. This relatively high availability of solar energy has recently led to high annual growth in sales of solar energy equipment in some regions of Canada – although only a small portion of this equipment is used for space heating. It can be shown that the amount of solar radiation incident on a well designed and unobstructed roof of a typical home exceeds its energy consumption over a year. However, for Canada, the bulk of the solar radiation is received in the summer months; relatively little solar energy is available during the winter months, when the demand for space heating reaches its peak. The ability to effectively store thermal energy for a period of months provides an opportunity to substantially increase the use of solar energy.

Seasonal thermal energy storage has been successfully demonstrated around the world, including at the Drake Landing Solar Community (DLSC) in Okotoks, Alberta (www.dlsc.ca). The DLSC project was designed to achieve a 90% solar fraction on the space heating requirement for an average year in this community of 52 R-2000 homes. In the 2011/12 heating season, an unprecedented 97% solar fraction was demonstrated. Although successful, to date these demonstration projects based on underground thermal energy storage (UTES) technologies were designed for new construction communities. It would appear that the large scale solar UTES concept would have limited wide-scale application in the retrofit market in Canada due to the high cost for retrofitting district energy in an urban environment. Different solutions are needed to address the challenges of space heating in this country, particularly for the vast majority of Canadians that live and work in existing buildings.

The challenges for building space heating in the winter will become more serious should fossil fuel prices rise significantly in the future. Research efforts in Europe on compact thermal storage solutions are showing some signs of promise. However, many technical challenges are still present and commercialization is still some time in the future. The solution would have to be appropriately scaled to integrate easily into the existing heating systems of our buildings and to meet a number of other market requirements.

Canada has an ideal climate for the application of seasonal thermal energy storage technologies. Significant research and development has been carried out on compact thermal energy storage technologies in Europe with the aim of eventually developing a product that could be installed in the retrofit market and that would be able to store summer heat and retrieve it for winter use. If successfully commercialized, compact thermal energy storage could make a significant contribution towards Canada's greenhouse emissions reduction goal by displacing the traditional fossil fuels used for space heating in the existing built environment.

This paper highlights recent major advances in compact thermal energy storage research and identifies some of the challenges that need to be addressed and that require resources and research. As the climate in Canada is very well suited for seasonal thermal energy storage the potential for this technology to make a significant positive contribution to our environment should not be ignored.

2. Technology concept overview

Thermal storage technologies can be subdivided into three categories: sensible heat, latent heat, and sorption and thermochemical heat. Each is described below.

Sensible Heat - The first category of thermal energy storage is the storage through sensible heat. Here energy is stored in a material using its specific heat. This is the oldest and most used technology for storing heat. For temperatures below 100°C water is commonly used as the storage medium. Water is a very suitable storage material as it has a high specific heat, is abundantly available and is non-toxic and inexpensive. Water-based heat storage applications can range from very small (i.e. domestic boilers) to very large (i.e. aquifer thermal energy storage systems) in physical size. For temperatures higher than 100°C pressure devices or steam vessels are needed for water which are relatively more expensive. Therefore, materials other than water are preferred at these higher temperatures. For intermediate temperatures up to 400°C heat is commonly stored in ceramic materials or natural or synthetic oils. At even higher temperatures heat is mostly stored in concrete, ceramics or molten salts.

Latent Heat - The second category is latent heat storage. Here heat is stored via the phase change property of a material, either from solid to liquid or from liquid to gas. The solid to liquid phase transfer is mostly used. The typical property of latent heat storage is that heat is stored in a very narrow temperature range. Consequently, this technology has specific advantages in applications that could use heat with only small temperature differences in the heating process.

Sorption and Thermochemical Heat – Sorption materials have a tendency to take up vapour of certain other materials, for instance water vapour. When taking up the vapour the bonding energy of the vapour molecules to the material structure of the sorption material is released in the form of heat. The temperature at which this heat is released is proportional to the strength of the bond. When the sorption material does not change in structure due to the sorption process, it is called **ad**sorption, when the structure changes it is called **ab**sorption. Examples of adsorption materials are silica gel and zeolites, while lithium bromide and ammonia are often used as absorption materials.

In a chemical reaction, two materials react to form a third new material (see Figure 1). In most formation reactions, heat is released via exothermic reactions. The heat is released at a certain temperature, depending on the strength of the molecular bonds in the compound. In principle, the reaction can be reversed. When the compound is heated above the equilibrium temperature, it is split into the original reaction materials/components. In fact, the forward and backward reactions occur simultaneously and the equilibrium can only be shifted towards the forward reaction if one of the components is taken out of the reaction volume. For example, if one of the original components is a vapour: it vapourises and pushes the reaction equilibrium forward.

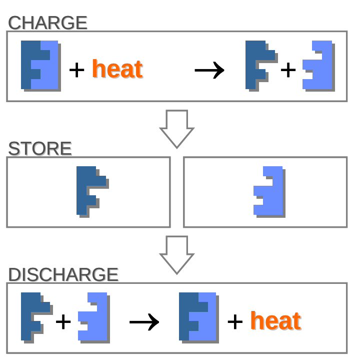

Figure 1: Schematic of Thermochemical Energy Storage. [Source: ECN]

The temperature levels during the load/unload cycle depend on the materials, i.e. the nature of the chemical bonds that are involved in the reactions. In general, lower temperature levels bring about lower reaction enthalpies. The amount of energy that can be stored depends on temperature and chemical and physical properties such as number of bonds per volume, mass density, etc. Examples of thermochemical materials are salt hydrates that react with water vapour, for instance magnesium sulphate, or oxides of metals, that react with water to form the hydroxide of the metal, for instance magnesium oxide/hydroxide.

This paper focuses on the sorption and thermochemical energy storage materials.

3. International R&D programs

The International Energy Agency (IEA) has two programs that have activities on thermal energy storage. These are the Solar Heating and Cooling (SHC) program and the Energy Conservation through Energy Storage (ECES) program. These two programs started a joint activity, Task 42/24 on “Compact Thermal Energy Storage: Material Development for System Integration”.

Task 42/24 is a worldwide cooperation of institutes, universities and industries (from over 15 countries including the US, Japan and many European countries) which aims to research and develop new materials, methods and tools, material test standards and applications for compact thermal energy storage technologies. The project time frame is 2009 to 2013 (task42.iea-shc.org).

Thermal energy storage is an important technology for renewable energy systems and for solar thermal systems in particular. In order to reach high solar fractions, it is necessary to store heat or cold efficiently for longer periods of time. Until now, no cost-effective compact storage technologies have been available to do this, and it was concluded in several previous IEA Tasks that a lack of suitable storage materials was the main bottleneck in thermal energy storage research.

Research work has started in the IEA Task 42/24 to develop new storage materials and develop methods for an effective integration of these materials in storage systems. The objective of this Task is to develop advanced materials for compact storage systems, suitable not only for solar thermal systems, but also for other renewable heating and cooling applications such as solar cooling, micro-cogeneration, biomass, or heat pumps. The Task is structured in materials-related and application-related working groups, and has one working group dedicated to the theoretical limits of compact thermal energy storage.

From the start of Task42/24, there has been considerable interest from research groups around the world and there are more than 60 experts from over 40 organisations contributing to the collaborative work in the Task. As is usual with IEA Tasks, the collaborators both bring in their own work and collaborate on common Task activities.

4. State of the art in thermochemical material research

The range of possible applications for heat storage using thermochemical reactions is very wide. Starting from temperatures of around 70°C (salt-hydrates and -solutions), to typical dissociation processes of hydroxides at around 200-350°C, ammonia dissociation at 400-700°C, until around 2000°C for solar thermal processes in tower plants (i.e. for the production of solar fuels). The focus of this review is for the lower temperature range for space heating and domestic hot water production. Significant advances have been made over the past decade [1] on compact thermal energy storage with promising results shown in laboratory tests involving salt hydrates [2] [3]. The research has covered a wide range of topics, including power and temperature during discharge, open versus closed systems, system design concepts, various reactor designs (liquid and solid) and the temperature range of typical thermochemical storage applications [4]. It is not feasible to include a detailed discussion on all the research topics in this paper; rather the authors focus on the following three areas: thermochemical material (TCM) storage densities; TCM materials; and material-related challenges.

4.1 Thermochemical material storage densities

The amount of stored energy per unit volume is one key indicator for the quality of heat storage. The energy density of sensible heat storage is limited by the maximum applicable temperature and the specific heat capacity of the storage material. Water, for example, is able to absorb about 210 kJ per litre or 58 kWh/m^3 while being heated from 40 to 90°C. Water in a tank can store heat when the tank is thermally insulated, and taking into account the space for insulation realistic energy densities are in the range of 30-40 kWh/m^3. For example a common buffer-tank with a volume of 1000 litres and 10 cm of thermal insulation can store 58 kWh and has an effective volume of 1.6 m^3 and an energy density of 36 kWh/m^3.

If thermochemical storage (TCS) is compared to water stores, the effective energy density has to take into account the space for the apparatus, storage for charged and discharged material, and all other components. Nevertheless TCS systems have not been realized yet, and practical data is therefore rare. Actual development projects report experimental data of laboratory scale systems with energy densities that are three times the storage density of water.

There is a distinct upper limit to the storage density given by the physical constant of the reaction enthalpy. The reaction enthalpy is the maximum energy that can be transferred during the reaction. In reality the reaction performance is described by the so called free enthalpy which is a constant that is always less than the reaction enthalpy and controlled by temperature and entropy transfer (i.e. the reaction conditions). Further reduction of usable energy amounts happens due to losses of sensible heat to the ambient and heat exchanger losses between source and sink. In general, low efficiency during charging is somewhat acceptable since charging happens in (summer) periods with excessive (solar) thermal energy. Energy efficiency and temperature development during discharge is the main criteria for the applicability of storage systems.

The lower limit of TCS storage densities in practice is given by heat storage with other (cheaper) technologies. It was generally accepted by the Task 42/24 workshop participants that in order to ensure the competitiveness of TCS concepts the TCS storage densities need to be in the range of 4-8 times higher than the energy density of water.

4.2 TCM materials

The selection of a TCM for a certain application depends on the regeneration temperature levels needed, desired temperature levels of usage, technical requirements like energy demand, power, number of load cycles during lifetime, technical infrastructure and costs of the storage materials. Salt solutions, salt hydrates, ammonia, hydroxides, carbonates and metals are promising candidates for future thermochemical storage applications. Some materials are subject to intensive research for the purpose of heat storage applications temperature levels [5]. Examples of experimental data are given in **Error! Reference source not found.**. The numbers for energy density are theoretical values for pure materials under ideal reaction conditions (thermodynamic equilibrium). Practical values for the energy density have to take into account the limited efficiency of every sub-process and the additional demand of space for the storage apparatus and technical infrastructure.

Material	Dissociation reaction	Storage density (kWh/m³)	Turnover temperature (°C)
Calcium sulphate	$CaSO_4.2H_2O \Leftrightarrow CaSO_4 + H_2O$	400	90 [6]
Iron hydroxide	$Fe(OH)_2 \Leftrightarrow FeO + H_2O$	630	150 [6]
Magnesium sulphate	$MgSO_4.7H_2O \Leftrightarrow MgSO_4 + 7H_2O$	633	122 [6]

Iron carbonate	$FeCO_3 \Leftrightarrow FeO + H_2O$	743	180 [6]
Ammonia	$2NH_3 \Leftrightarrow N_2 + 3H_2$	800	400-500 [7]
Magnesium hydroxide	$Mg(OH)_2 \Leftrightarrow MgO + H_2O$	943	250-400 [8]
Calcium hydroxide	$Ca(OH)_2 \Leftrightarrow CaO + H_2O$	1260	550 [9]
Zinc oxide	$ZnO + C \Leftrightarrow Zn(g) + CO$	4571	1400 [10]

Table1: Examples of thermochemical reactions with their storage densities

Salt hydrates in general are promising candidates for heat storage in the low temperature range because of the relatively low bonding force of the associated water molecules and subsequently low dehydration temperatures. Additionally the physical process mechanisms of salt hydration are very similar to desorption processes in molecular sieves and therefore combined materials like zeolite-salt composites can be developed.

The hydration reactions of different types of dehydrated salts ($MgSO_4$, $CuSO_4$, $Al(SO_4)_2$) have been investigated. Magnesium-sulphate-monohydrate ($MgSO_4$*H_2O) for example, has a high potential as a chemical storage material [11]; with the involved condensation heat of water vapour, a theoretical storage density 633 kWh/m³ can be obtained. This is about 11 times higher than the storage density of a water store with the same volume (at $\Delta T = 50$ K). In practical applications, limitations have to be accepted. A material developed on the basis of the mentioned salt hydrate $MgSO_4$ together with zeolite as a mechanical frame show the capability to store 166 kWh/m³ and perform a 25 K temperature lift while hydrated [12].

4.3 Material-related challenges

Although recent research has brought attention to salt hydrates with promising laboratory results, their utilization for heat storage exhibits several material-related problems:

- Structural changes: Solid absorption materials undergo structural changes during absorption (changes in volume, rheological behaviour). This can result in degradation and failure of the storage material.
- Phase change: During desorption (heating) the salt can solute in leaking crystal water (incongruent melting). Salt solutions can cause corrosion and mechanical damage to the system.
- Dissociation: Low stability under hydrothermal conditions can lead to decomposition of the salts and formation of strong acids (for example, HCl in chloride salts) and related pollution and corrosion problems.
- Reaction kinetics: The hydration of salts is a sequence of reactions forming successively higher grades of salt hydrates. Kinetic hindrance and thermodynamically stable intermediates can significantly reduce the reaction dynamics and output power of the overall process (e.g. the limited power of the $MgSO_4$-process).
- Temperature lift: The reaction temperature during adsorption strongly depends on the vapour pressure (evaporator temperature). For seasonal storage, for example, the minimum reaction temperature of 40-60°C has to be reached with water evaporation temperatures around 0-10°C (target working process for input flow in winter).
- Corrosion: Suitable materials are needed for construction and practical reliability over long periods (for lifetimes of 20-30 years).

5. Canadian market overview and opportunities

5.1 Potential Canadian market

As an indicative estimate, Canada has over 13 million homes and over 130,000 commercial and institutional buildings as the existing building stock. The market for new home and building construction is strong in Canada but the new construction is only a very small fraction (in the order of 1-2% per year) of the existing buildings. In most regions of Canada the existing building stock is based mainly on fossil fuel energy source for space heating. This represents a very large potential for innovative product commercialization utilizing compact thermal energy storage technologies.

The energy requirement for space heating for an average Canadian home is in the order of 60% of the total home energy usage (see Figure 2). This will present a major challenge for Canadian homeowners as the cost of fuel increases in the future. For a number of remote regions using heating oil or diesel-generated electricity as the main heat source, the cost of heating oil is already very high. This is starting to cause financial pressures on some families, especially those with low and/or fixed incomes. A number of observations regarding the potential Canadian market for compact thermal energy storage could be made through reviewing the Canadian housing and heating system data provided by Natural Resources Canada's Energy End-use handbook [13].

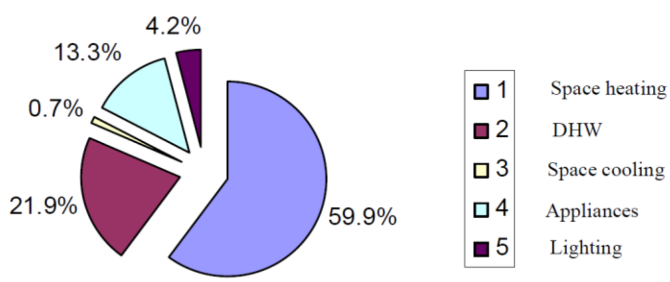

Figure 2: Breakdown of Canadian Home Average Energy Use. (NRCan 2010)

As can be seen in Figure 3, over 65% of Canadian homes are heated by furnaces or boilers using a forced-air or hydronic system. Upon further analysis, one can see that forced-air or hydronic heating systems powered by furnaces or boilers are mainly used in the province of Ontario and the Prairie provinces.

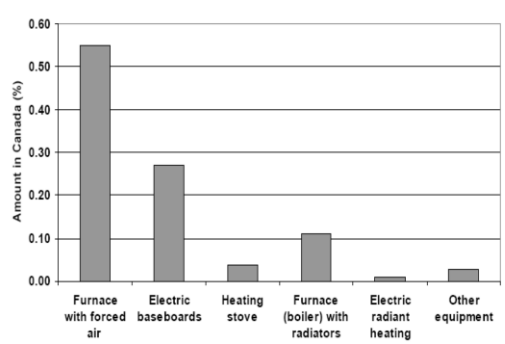

Figure 3: Breakdown of Type of Heating Systems for Canadian Homes. (NRCan 2010)

The review on compact thermal energy storage technologies reported in earlier sections shows a preference for technology integration with forced-air or hydronic building heating systems. This points to the province of Ontario and the Prairie provinces as the primary markets for potential technology implementation (see Figures 4 and 5).

Approximately 60% of Canadian homes are over 20 years old and the older homes account for about 70% of the total space heating load. The total space heating and domestic hot water use for homes is estimated to be responsible for approximately 20% of Canada's total greenhouse gas (GHG) emissions per year. As the types of heating systems constructed for the home ultimately dictate the type of energy source (fossil fuel in most cases) used for heat, we are "stuck" with this dependency on fossil fuel for building operation unless we can develop an alternate method for space heating. As the age of the buildings and homes increase, this will become a more urgent problem if our society is serious about reducing greenhouse gas emissions.

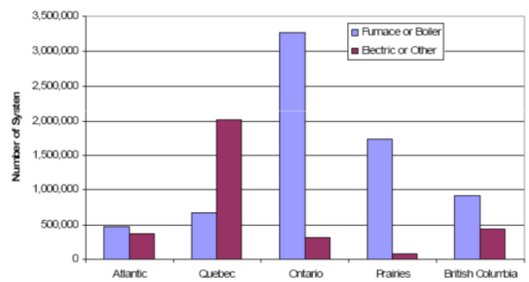

Figure 4: Regional Breakdown of Canadian Home Heating System Technology. (NRCan 2010)

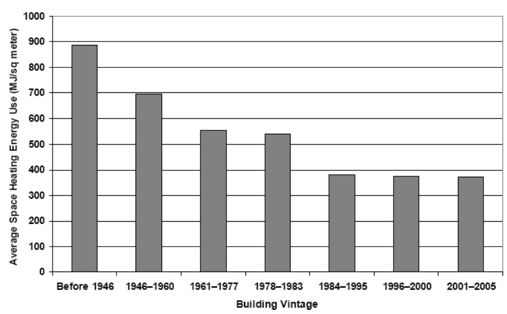

Figure 5: Space Heating Usage as a Function of Building Vintage. (NRCan 2010)

With the hot summers and cold winters in most of the high population areas, Canada has highly suitable climate conditions for solar seasonal thermal energy storage. The above observations coupled with the Canadian climate conditions provide a unique opportunity for the consideration of alternate building space heating technologies, including compact thermal energy storage technologies, if proven practical.

5.2 Canadian market requirements

The City of Pickering (Ontario) has developed a community sustainability plan with a strong focus on energy efficiency and renewable energy opportunities. As a part of the city's commitment towards sustainable development, the City of Pickering facilitated a focus group discussion involving local home builders, regulatory agencies, academia and energy management professional in March 2012. The concept of compact thermal energy storage was presented to the group and the informal discussion captured a number of challenges and barriers that we need to overcome in the commercialization of any new products involving compact thermal energy storage in Canada.

A number of market requirements were noted, as summarized below:

Reliability – People are used to having highly dependable energy sources and equipment based on fossil fuels (especially natural gas) and grid electricity; products involving compact thermal energy storage would need to be as reliable as conventional technologies.

Competitive pricing – New compact thermal energy storage products have to make economic sense, whether measured in terms of life cycle cost (LCC) or initial capital cost.

Simplicity in operation – In homes, people are typically used to controlling indoor comfort using a simple thermostat (or programmable thermostat); new compact thermal energy storage products would need to deliver space heating services in a similarly simple manner, without the homeowner having to carry out difficult tasks in equipment maintenance or operation.

Meeting appropriate regulatory standards – Canada currently has a well-established system of safety standards and quality assurance procedures in place for space heating and cooling equipment supply and operation. Appropriate national-level standards would need to be developed for products and services related to compact thermal energy storage technology.

6. A potential path forward for compact thermal energy storage in Canada

6.1 Canadian research advancement

Two recent state-of-the-art review papers [14] [15] published in international journals included a number of Canadian researchers active in thermal energy storage. The use of thermal energy storage technologies and applications has been documented in a recent text book by Canadian academia [16]. Research work has been conducted and published by a number of Canadian researchers in recent years in areas related to the advancement of compact thermal energy storage concepts and technologies. Researchers with experience and capabilities in this area include Tezel (University of Ottawa), Hosatte (NRCan), Rosen (University of Ontario Institute of Technology). Many other researchers are working on thermal energy storage applications including Beausoleil-Morrison (Carleton University) and Dincer (University of Ontario Institute of Technology).

Compared to the R&D effort demonstrated in European countries, the Canadian effort has been relatively small. However it should be noted that progress has been made in Canada in this subject area. Furthermore, there is research capacity and expertise to carry out applied R&D for the potential commercialisation of the compact thermal energy storage technologies. The main areas of research expertise and capacities are summarized below.

University of Ottawa (Principal Researcher: Dr. Handan Tezel) – The main area of investigation covers the use of compact thermal energy storage materials. Dr. Tezel’s research team has built a laboratory-scale thermal storage charging and discharging reactor using zeolite and other materials and demonstrated thermal storage cycles in a laboratory setting.

Carleton University (Principal Researcher: Dr. Ian Beausoleil-Morrison: Canada Research Chair Sustainable Building Energy Systems Laboratory) – The main area of investigation is seasonal thermal energy storage in buildings and technology integration/applications. Dr. Beausoleil-Morrison's team has conducted a comprehensive research review on compact thermal energy storage and seasonal thermal energy storage technologies. He has developed a research and test facility on thermal energy storage integration in buildings.

University of Ontario Institute of Technology (Principal Researcher: Dr. Marc Rosen) – The main area of investigation is in thermal energy storage systems analysis and optimization, and the mechanical engineering aspects of thermal energy storage integration with building HVAC systems. Dr. Rosen's research team has conducted analytical work in compact thermal energy storage technology systems.

CANMETEnergy (Principal Researchers: Dr. Sophie Hosatte and Mr. Doug McClenahan) – There are two teams of researchers at CANMETEnergy with work relating to thermal energy storage. One group is based in the Varenne Campus with its main area of investigation in the application of thermal chemical materials in chemical heat pumps. Material investigated included metal hydrides and adsorption systems. The second group is based in Ottawa with its main focus on active solar thermal technologies and seasonal thermal energy application through underground thermal energy storage technologies.

6.2 Technological challenges for compact thermal energy storage

The R&D review of the current activities in compact thermal energy storage presented in section 4 highlighted a number of technical challenges facing the development of compact thermal energy storage. In going forward, future key technical challenges are summarized below:

Sorption materials – A main objective is to find new materials with improved properties, including higher storage density or more suitable sorption temperatures. Classes under research are metal-organic frameworks (MOFs) and aluminium-phosphorous oxides (ALPOs). In addition, opportunity exists to develop improved techniques for the production of zeolites and other sorption materials.

Thermochemical materials – A number of research priorities are underway in order to advance the compact thermal energy storage concept. These include finding new materials with higher heat storage densities or more advantageous reaction temperatures and reaction characteristics, improving the structural integrity of the material by composites or additives, and the development of compound materials, such as mixtures of salt hydrates with improved properties or combinations of sorption materials with salt hydrates with improved structural and heat storage properties.

Technology development – Research should also be focused on the development of systems and interface methods. This area of research may include the design of reactors suited to the compact TES material used (moist grains, pellets, etc.), specialized heat exchanger design, the development of conveyor systems for thermochemical materials as well as the development of sensors and methods to determine the state of charge of novel TCM-based energy storage systems.

6.3 Possible Canadian R&D and commercialization direction

The eventual goal for the research effort in compact thermal energy storage is the commercialization of a suite of products for retrofitting the heating systems of the existing building stock. The research capacity and the availability of resources in Canada is limited in comparison to the effort demonstrated in other countries. However the research work on the emerging compact thermal energy storage systems is in the very early stages of development and Canada can still contribute to the international effort in compact thermal energy storage and potentially play an important role in the commercialization of the technology. Canada will need to invest in a range of compact thermal energy storage research areas, including the development of suitable thermal energy storage materials, and join the existing research institutions in Europe in the development of better materials and systems for this application. Resources required for this scenario will include materials research networking from other Canadian industries; investment in testing methods and standards development; as well as the design and development of mechanical thermal energy systems for potential implementation in homes.

The capacity for mechanical engineering design, systems analysis and optimization, as well as the strong foundation in advanced building mechanical systems in Canada makes the development of mechanical systems a natural path to pursue.

One possible starting point for this scenario is for Canadian researchers to partner with European research organizations with strong materials research experience and with active involvement in the development of compact thermal energy storage materials. The earlier entry into the development of the mechanical systems specifically suitable for colder (northern) climates will help position Canada in a systems development leadership role for potential product commercialization.

In terms of engineering and technology implementation, it may be worthwhile to pursue a parallel path in systems design with the search for better thermochemical materials. Over the next 10-15 years, Canadian researchers may work through some of the unique challenges in Canada and the northern climate requirements in the implementation of compact thermal energy storage for the existing building stock by going through a series of focused technology studies starting from laboratory scale system to field scale testing, and to pilot system demonstration. The initial systems study may utilize lower storage density materials such as zeolite or a combination of zeolite and salt hydrates as a starting point.

7. Conclusion

Canada has an ideal climate for the application of seasonal thermal energy storage technologies. The potential positive impact from the ability to store summer heat for winter heating use is significant. Research efforts in Europe on compact thermal storage solutions are showing some signs of promise. However, many technical challenges are still present and commercialization requires more work. A number of research opportunities have been identified and Canadian researchers may work through some of the unique challenges in Canada and the cold climate requirements in the development of compact thermal energy storage for the existing building stock.

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9. Acknowledgements

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10. Biography

Mr. Wong is the Manager of the Renewable Energy and Climate Change Program in the Ottawa office of SAIC Canada. He makes his contribution by finding innovative ways to incorporate renewable energy into sustainable communities. Dr. van Helden is a consultant in renewable energy technologies in the Netherlands. He is the current Operating Agent of the IEA SHC and ECES Joint Task 42/24 on compact thermal energy storage. Dr. Rosen is a Professor of Engineering at the University of Ontario Institute of Technology, He is Editor-in-Chief of the journal Sustainability and Editor of Energy Conversion and Management.