

# Technical and Economic Feasibility of Thermochemical Heat Energy Storage Systems for Residential Space Heating in New Zealand

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# Background

The excessive consumption of fossil fuels, oil shortages and greenhouse gas emission are becoming increasingly severe.

The alternative to this is renewable energy.

Various types of energy consumed in residential buildings can be supplied via renewable energy systems.

There is a mismatch between the supply and demand of these energy sources.

The development and improvement of energy storage can result in renewable energy being implemented throughout society.

# Why Solar Energy and Space Heating?

Solar energy has been implemented in both industrial and residential settings

There is the dependence of solar energy on weather conditions and the fluctuations of availability make it difficult to control.

In regards to space heating, energy is needed at night-time or in the winter season when there is little/no solar energy available.

34% of all energy usage in residential housing in New Zealand is a result of space heating (Energy Use, Otago).

Development of seasonal heat energy storage system (3-6 months) would maximize the use of solar energy for space heating.

# Types of Thermal Energy Storage

**Sensible heat storage (SHS):** the heat absorbed or released when a substance undergoes a change in temperature.

**Latent heat storage (LHS):** release of energy as a result of a phase change process.

**Thermochemical heat storage (TCHS):** collected heat energy is used to excite a reversible endothermic chemical reaction.

TCHS has the following advantages over SHS and LHS (Ding and Riffat, 2013):

- Higher energy density compared with physical change
- Long-term storage as energy stored in chemical bonds
- Easily transmitted to generate heat at another location
- Wide temperature range and characteristics

# Objectives and Methods

To investigate the technical and economic feasibilities of thermochemical heat storage technology for seasonal energy storage of space heating for residential homes in New Zealand.

A mathematical process model has been established to investigate the thermodynamic performance of thermochemical heat storage.

# Principle of Thermochemical Energy Storage

In the following chemical reaction equation, with a heat supply the compound C can be dissociated into the compounds A and B, which can be stored and then brought together to release heat.



The forward reaction with chemical bonds being broken is endothermic, allowing absorption of heat (e.g. solar heat energy).

The reverse reaction with chemical bonds being formed is exothermic, releasing heat.

# Principle of Thermochemical Energy Storage

The three main processes in the thermochemical energy storage cycle are as follows:

1. **Charging:** an endothermic reaction that requires an energy source in order to dissociate the compound C into the compounds A and B.
2. **Storing:** where the chemical compound(s), A and/or B are stored, and therefore the energy is stored. As the compounds are stored at ambient temperature, there is no thermal losses except for initial cooling. There may be other losses as a result of degradation of materials (Kouskou et al., 2014).
3. **Discharging:** the two compounds, A and B, which are holding the energy are combined to give an exothermic reaction and release heat energy.

# Separate vs. Integrated Reactor

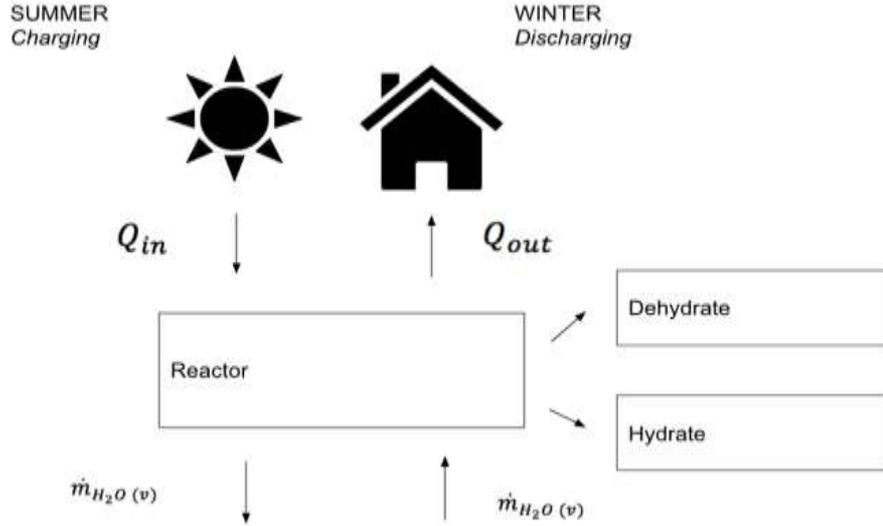


Figure 1. A separate reactor configuration for an open system.

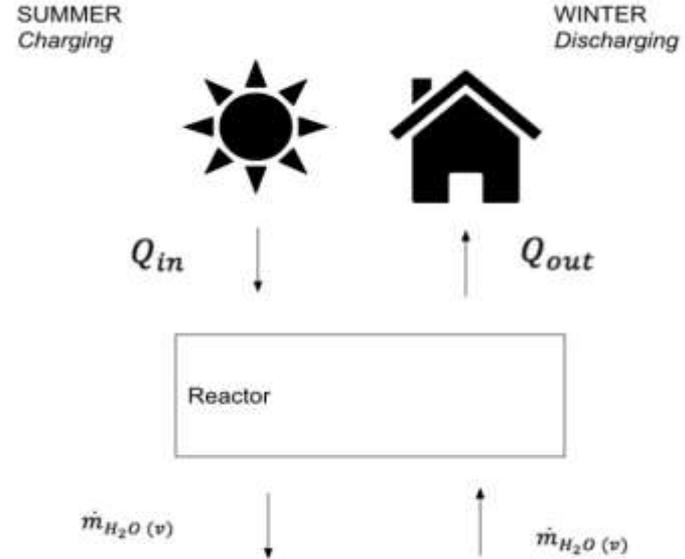


Figure 2. A integrated configuration for an open system.

# Open vs. Closed Systems

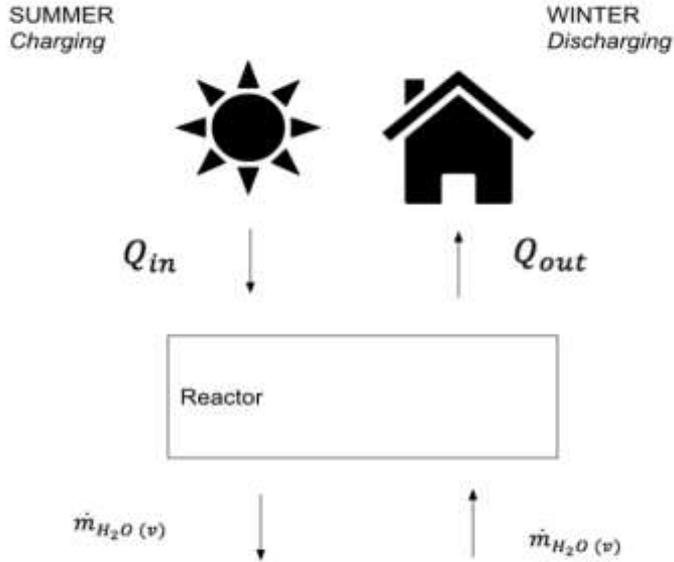


Figure 2. A integrated configuration for an open system.

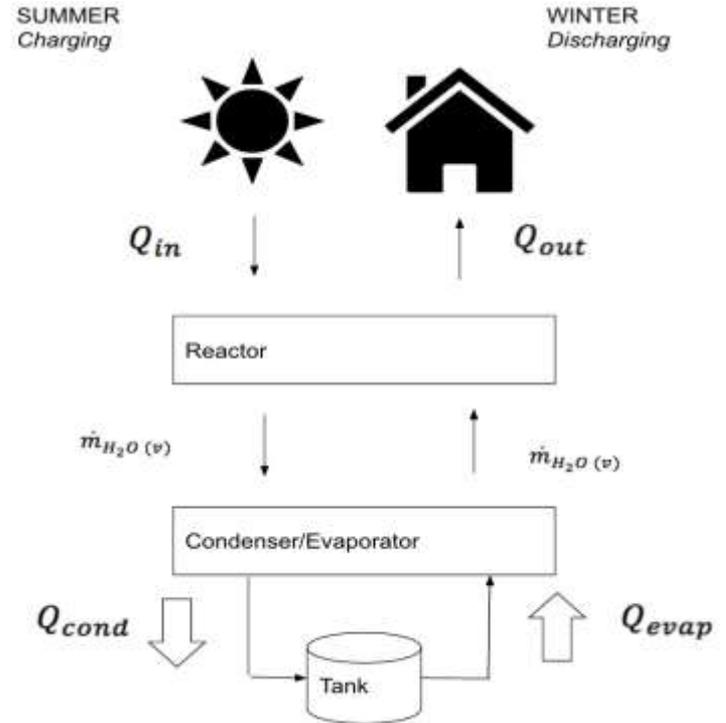


Figure 3. A integrated configuration for a closed system.

# Advantages and disadvantages of closed and open systems

| Type                                     | Advantages  | Disadvantages   |
|--|---|---|
| Closed systems with vacuum conditions    | <ul style="list-style-type: none"><li>• Low pressure</li><li>• Higher reaction power</li><li>• Can give a cooling effect in summer and heating effect in winter</li></ul> | <ul style="list-style-type: none"><li>• Presence of non-condensable gases</li><li>• Good heat and mass transfer, still being investigated</li><li>• <b>High capital cost</b></li><li>• <b>Big size</b></li><li>• Energy heat source when the system is discharging, in order for evaporation to occur</li></ul> |
| Open systems with atmospheric conditions | <ul style="list-style-type: none"><li>• Easy design</li><li>• Better heat and mass transfer</li><li>• Economical</li><li>• Small size</li></ul>                           | <ul style="list-style-type: none"><li>• High pressure</li><li>• Low reaction power</li><li>• Additional humidifier to wet air</li><li>• Limitation of pressure drop</li><li>• <b>Weather conditions are limiting</b></li><li>• <b>Materials used must be non-toxic and non-flammable</b></li></ul>              |

## Decision on type of reactor to be modelled

A fixed bed was chosen for simplicity.

An integrated reactor was chosen as this will decrease capital cost and size of the reactor system.

The open system was chosen as this will decrease capital cost and size of the system, making it feasible to the New Zealand consumers. An open system provides dehumidified air for the New Zealand homes, catering to the issue of damp homes in New Zealand.

# Choice of TCHS Materials

There is a wide range of thermochemical materials available and the  $\text{SrBr}_2 \cdot 1-6\text{H}_2\text{O}$  working pair was chosen.

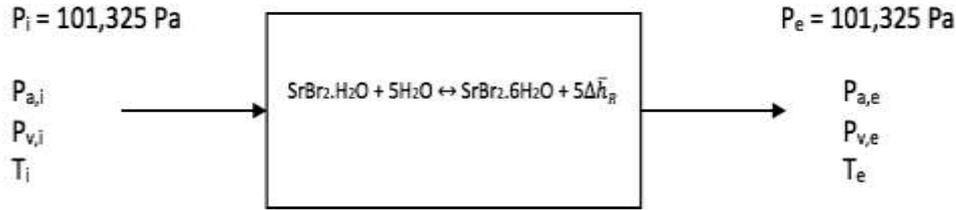
This salt hydrate has been investigated in Europe and shows good results for a  $1 \text{ m}^3$  prototype.

It has increased energy and exergy efficiencies when used in open systems.

It is inexpensive to purchase, has a high energy density and is not corrosive.

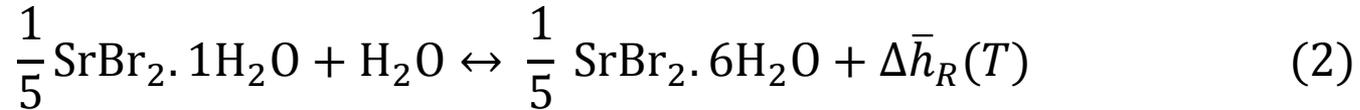
The disadvantage is irritability when skin contact is made.

# Model



The thermochemical process is based on the thermal effects of a reversible reaction between a solid and a reactive gas (water vapour).

Figure 4. Schematic drawing of the model.



or



# Model Assumptions

1. The pressure drop of the moist air across the reactor, due to friction, is neglected. i.e.  $\Delta p = 0$
2. The hydration or dehydration reaction is fast enough to achieve chemical equilibrium. Thus, the Gibbs function change,  $\Delta G = 0$ .
3. There is no accumulation of dry air or water vapour, and no accumulation of the energy contained by the dry air and water vapour inside the reactor. The water vapour that accumulates inside the reactor is only what water undergoes the chemical reaction.
4. It is assumed there is no heat loss from the chemical reactor to the surroundings.
5. The kinetic and potential energy effects are negligible.
6. For simplicity, the reactor system is described as one control volume.
7. It is assumed that the solid phase is uniform and has a uniform temperature. Due to assumption 2, the temperature of the gas phase inside the reactor is the same as that of the solid phase.

# Model Equations

## Mass Balance

The following mass balance equations for dry-air and vapour are,

$$\dot{m}_{a,i} - \dot{m}_{a,e} = 0 \quad (4) \quad \text{and} \quad \dot{m}_{v,i} + \dot{m}_{v,r} - \dot{m}_{v,e} = 0 \quad (5)$$

The mass balance equations for B and C are expressed as,

$$\frac{dm_B}{dt} = \frac{1}{5} \frac{M_B}{M_v} \dot{m}_{v,r} \quad (6) \quad \text{and} \quad \frac{dm_C}{dt} = -\frac{1}{5} \frac{M_C}{M_v} \dot{m}_{v,r} \quad (7)$$

## Energy Balance

$$\frac{d(m_B u_B + m_C u_C)}{dt} = (\dot{m}_a h_a + \dot{m}_v h_v)_i - (\dot{m}_a h_a + \dot{m}_v h_v)_e \quad (8)$$

Using humidity ratio,  $\omega$ , and the enthalpy relation for an ideal gas, at steady state eqs. (8) can be rewritten as,

$$\dot{m}_{a,i} [C_{p,a}(T_{a,i} - T) + \omega_i C_{p,v}(T_{v,i} - T)] + \dot{m}_{v,r} \Delta h_R(T) = 0 \quad (9)$$

# The chemical equilibrium relation

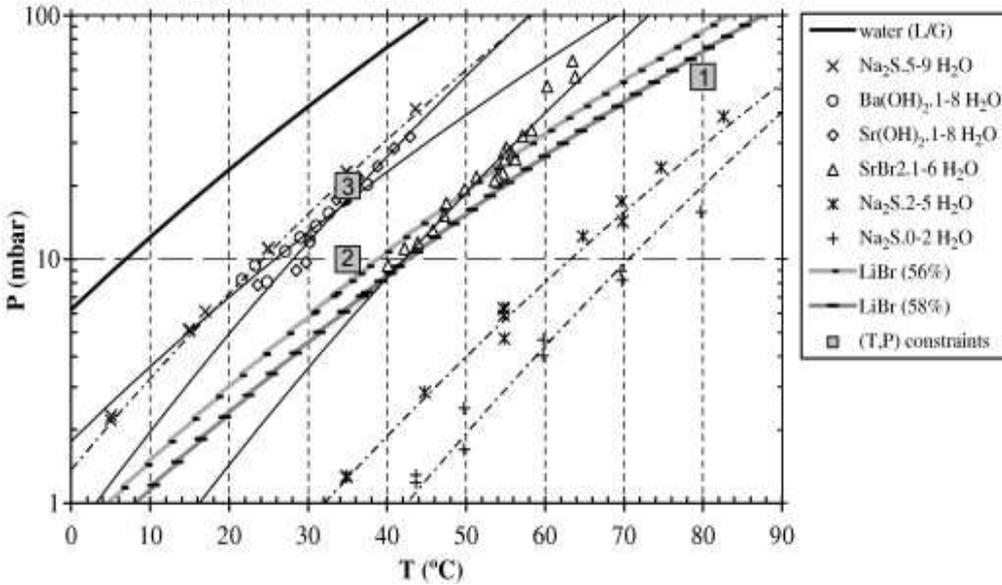


Figure 5. Experimental data showing relationship between partial pressure of water vapour and the salt hydrate solid at different temperatures (Mauran et al., 2008).

The equilibrium relationship for the system of the water vapour and  $\text{SrBr}_2 \cdot 1-6\text{H}_2\text{O}$ ,

$$p_{eq} = (3.3421 \times 10^{-4}) \times e^{0.0801(T_{eq} - 273.15)} \quad (10)$$

The enthalpy of the reaction over a range of temperatures is expressed as,

$$\Delta h_R = \frac{-0.0801RT_{eq}^2}{M_v} \quad (11)$$

# Climate Conditions

The average seasonal temperature and relative humidity at Dunedin and Auckland are listed in table below. The average seasonal data was used to simplify the model, as the aim of the thesis is to determine the feasibility and economic analysis.

|                             | Dunedin |        | Auckland |        |
|-----------------------------|---------|--------|----------|--------|
|                             | Summer  | Winter | Summer   | Winter |
| Humidity $\phi$             | 65.4    | 69.9   | 79.8     | 83.8   |
| Average temperature<br>(°C) | 14.2    | 9.5    | 18.8     | 12.9   |

Source: NIWA and Physics Weather Station.

## Results and Discussions: Energy Discharging Process

The dry-air mass flow rate,  $\dot{m}_{a,i}$ , was evaluated to be 0.25 kg/s to give power output of 5.24 kW and 4.75 kW for Dunedin and Auckland respectively, which are between 2 and 10 kW of the average output of a mechanical heat pump (Burrough et al., 2015).

The results show that in Dunedin humidification of the air will be needed, in order for the reactor to release an air temperature of 30°C.

In Auckland humidification of the inlet air will not have to occur, because the evaluated exit temperature, 30.65°C, is satisfactory for space heating.

# Results and Discussions: Energy Discharging Process

| Scenario         | Dunedin (humidification required) |                     |                        | Auckland (no humidification) |                     |                        |
|------------------|-----------------------------------|---------------------|------------------------|------------------------------|---------------------|------------------------|
|                  | $m_B$ consumed (kg)               | $m_C$ produced (kg) | Size (m <sup>3</sup> ) | $m_B$ consumed (kg)          | $m_C$ produced(kg)  | Size (m <sup>3</sup> ) |
| (1) 300 h        | $4.910 \times 10^3$               | $6.577 \times 10^3$ | 2.75                   | $4.355 \times 10^3$          | $5.833 \times 10^3$ | 2.44                   |
| (2) 500 h        | $8.183 \times 10^3$               | $1.096 \times 10^4$ | 4.6                    | $7.258 \times 10^3$          | $9.721 \times 10^3$ | 4                      |
| (3) 740 h/ 817 h | $1.211 \times 10^4$               | $1.622 \times 10^4$ | 6.8                    | $1.19 \times 10^4$           | $1.6 \times 10^4$   | 6.7                    |
| (4) 1000 h       | $1.637 \times 10^4$               | $2.192 \times 10^4$ | 9.2                    | $1.452 \times 10^4$          | $1.944 \times 10^4$ | 8.1                    |
| (5) 426 h/ 148 h | $6.973 \times 10^3$               | $9.339 \times 10^3$ | 3.9                    | $2.148 \times 10^3$          | $2.878 \times 10^3$ | 1.2                    |

# Results and Discussions: Energy Charging Process

As for both Dunedin and Auckland,  $p_{v,i} < p_{eq}$  and  $\dot{m}_{v,r} > 0$ , thus heating the air to 70°C can remove water vapour from  $\text{SrBr}_2 \cdot 6\text{H}_2\text{O}$ .

| Scenario | Dunedin               | Auckland              |
|----------|-----------------------|-----------------------|
|          | Time to dehydrate (h) | Time to dehydrate (h) |
| (1)      | 355.75                | 363.7                 |
| (2)      | 593.97                | 606.17                |
| (3)      | 879.1                 | 990.6                 |
| (4)      | 1188                  | 1212                  |
| (5)      | 506.1                 | 179.4                 |

As the total daylight hours are approximately 1210 h from December to March, every scenario is applicable.

If a solar heater is used in winter time, the charging process is possible during the day time in winter too. The charging process was also investigated without solar heating, it was found that neither systems could work without the solar heating.

# Initial Economic Analysis

For the economic analysis, the following assumptions were made:

1. The coefficient of a performance (COP) of a heat pump in New Zealand is 2, as a result of atmospheric conditions (Burrough et al., 2015).
2. The cost of fans and other equipment for the thermochemical reactor has not been considered at this stage.
3. The average cost of electricity in New Zealand is 0.2812 NZD (Ministry of Business, Innovation and Employment, 2016).
4. Purchase of the anhydrous salt ( $\text{SrBr}_2$ ) will occur in bulk, thus it will cost \$1.40 NZD/kg (Chongqing Hua'nán Inorganic Salt Chemical Co., 2016).
5. The average heat pump costs approximately \$3000 (Burrough et al., 2015).

# Initial Economic Analysis

The following data is an estimate on cost of thermochemical heat storage instead of a mechanical heat pump system based on average usage of a heat pump by locations (Burrough et al., 2015).

|  | Auckland | Dunedin |
|--|----------|---------|
| Output (kWh)                                     | 700      | 2230    |
| Cost   | \$3008   | \$9762  |
| Additional Capital Cost (= Cost – Cost of HP)    | \$8      | \$6762  |
| Savings per year                                 | \$100    | \$315   |
| Pay back time of additional capital cost (years) | 0        | 21.5    |

# Conclusions

Thermochemical heat storage systems are economically feasible for households in warmer climates.

This can also be applied to smaller NZ houses where the space heating requirement is less.

The Auckland region houses 1,415,550 people, 33.4% of the New Zealand population (Statistics New Zealand, 2016).

Thus, thermochemical energy storage technology is promising for New Zealand as it can provide year round renewable energy at an affordable price for over one third of the population.

The potential applications of thermochemical heat storage systems in commercial buildings will be investigated.