Confidential

Thermochemical heat storage

Stage gate review

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Introduction

This document describes the current state of development of Thermochemical heat storage technology at ECN. The development was initiated within ECN-DEGO around the year 2002, starting with literature studies and material screening. The target application was for seasonal heat storage of solar heat for single family housings. The work was carried out within the unit “DEGO” and was later on included within the Efficiency & Infrastructure program, in a collaboration with TNO in the Building Future program, and continued in the EBI program.

In the period of 2010-2014 lab scale prototype system development was undertaken, as part of the E-hub project. The results from the laboratory prototype system are now collected and are included in this document.

This document serves as a discussion document to support the decision process on the preferred options and actions for the next development stage of thermochemical seasonal heat storage technology.
It addresses the status of the technology, the market, partners in the development, ECN’s IP position, an overview of future actions to bring the technology to the next stage and funding opportunities for further development.

The topics addressed in this paper are briefly answered and not intended to be a full description.

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Status of development

2.1 Technology

Description of the technology

Thermochemical heat storage technology (TCS) is based on the reversible reaction of a sorption material and a gas or vapour. The heat is stored as energy of the chemical bond, and can be stored for indefinite time, in contrast to heat storage based sensible heat and latent heat of a phase change. The energy level of the chemical bond is much higher than in conventional ways of heat storage (sensible or latent heat) and allows to achieve much higher energy storage densities.

TCS is a promising concept to achieve compact and long term heat storage that is suitable for individual households and/or heat storage on small to medium scale (up to ~20 GJ).

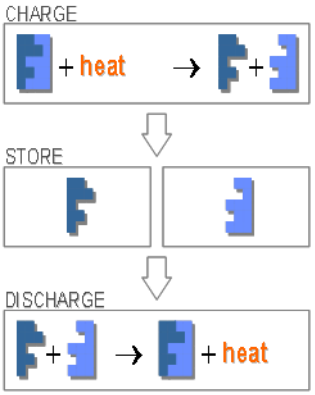


Figure 1: Working principle of thermochemical heat storage

What is the state of the art

***On the market*:**

Long term seasonal heat storage

-underground (aquifer/borehole) heat storage, (+ heat pump)
- centralized/collective hot water storage
- pit thermal storage

Short to medium term heat storage

- sensible heat storage in water tanks, (atmospheric and pressurized), stratified tanks, steam buffers
- latent heat storage: Phase Change Materials (range -20 to 80°C), mainly ice buffer tanks for air conditioning (off-peak charging)
- High temperature heat storage in molten salts for Concentrated Solar Power
- Heat storage in ceramics/bricks in cowper recuperators (windverhitters)

Emerging technologies

- Development of higher Temperature PCM heat storage >80°C
- Vacuum Super Insulated (VSI) storage tanks for sensible storage, also allowing long term seasonal heat storage
- High temperature ground storage up to 90°C (only possible for large scale collective applications in combination with suitable ground characteristics such as low ground water flow).

Figure 2: Large hot water storage combined with solar thermal district heating in Munich, Germany

Figure 3: Installation of VSI tanks for residential long term heat storage

Competing renewable heat supply technologies

A competing solution for 100% renewable heat is formed by heat pumps driven by solar (and wind) electric power. The problem of these systems is that the PV is producing electricity in summer while the heat pump consumes mainly in winter, so the electric grid is used as seasonal storage here. If this technology would be introduced on a large scale, massive unbalance in the grid would result. However, at present, financial regulations for PV electricity supply to the grid do not distinguish between electricity produced at peak hours and hours of low demand (yet). For this anticipated problem thermal energy storage can also offer relief.

What is the focus of ECN

- **What results have we achieved**
- **Have the development goals been met**
- **How do our results compare to the state of the art**

Focus: Prototype development of a thermochemical heat storage system, applicable for solar thermal seasonal heat storage. The 'open sorption system' concept selected to obtain 'low cost' solution. Humid air is both reactant and heat transfer medium. Developed as modular concept to obtain flexibility in storage capacities and thermal powers

Result: 2 laboratory prototypes designed, built and tested.

	Prototype 1 (TC reactor)	Prototype 2 (E-Hub)	Target	result
material	$MgCl_2.6H_2O$	Zeolite 13X	Salt hydrate	?
Temperature charging	130°C	200°C	130°C	Ok
Temperature discharging	60°C	60°C	60°C	Ok
Storage density	0.5 GJ/m3	0.25 GJ/m3	1 GJ/m3	?
Heat storage efficiency	?	15% (40% calculated neglecting air leakage)	70%	Not ok
COP (ratio of thermal energy over electrical energy)	12 (calculated assuming 50% fan efficiency)	1 (measured)	20	Not ok

Development goals have been met in prototype 1 but not in prototype 2 (not met: storage efficiency, COP).

-NB1) Air leakages in the prototype2 system played an important role in decreasing the overall performance.

-NB2) The use of zeolite as replacement for the instable salt leads to lowering of the thermal efficiency, an increase in heat losses, and a reduction of the storage density and higher required charging temperatures.

Comparison to state of the art:
Seasonal heat storage for buildings is currently only available as large scale collective systems. No direct comparison possible.

- New seasonal heat storage developments based on sensible heat in VacuumSuperInsulated (VSI) tanks are ongoing. These tanks can also store heat over long time, (>half year) with low losses.

What TRL level is ECN at?
TRL 4: technology validated in the lab both on materials development and on system scale, but further improvements needed.

Current issues are

- Improvement on system level (storage thermal efficiency, COP);
- Chemical stability of $MgCl_2.6H_2O$ on dehydration. (HCl formation).

Material stability is addressed within ADEM program. Alternative materials have been proposed.

2.2 Market

- What is the market for this technology?
- How big is this market?
- How is the market in The Netherlands and in Europe?
- How does the value chain look like (from material supplier to end user)
- What is the business case, how will the parties in the value chain benefit from this technology?
- How is the business case for ECN? Contract research, licenses op IP, services delivery, etc.?

Market: Single family houses, energy-neutral houses, newly built houses, or large scale renovation program.

In the most optimistic scenario, the market could be all residential buildings and office buildings in Europe. For the Netherlands, the amount of residences was over 7 million in 2013.

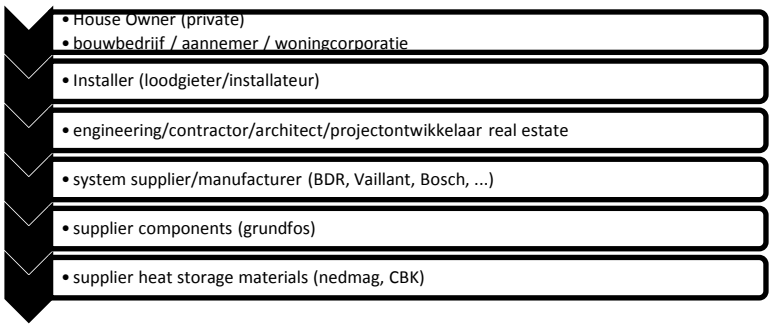
In a more realistic scenario, the market is primarily that of building projects for (near) zero energy houses(label A+) , which is currently a minor part (<3%) of the newly built residences. (NL 55.000, source CBS) The number of applicable houses is estimated at 1600 annually.

A point of attention is the development process for this market; this is strongly related to government regulations based on energy efficiency of buildings (EPC). On a European scale, initiatives are ongoing to drive the market towards energy neutral buildings (target EPBD: new buildings should by nearly energy neutral in 2020) and also regulations are under development for the energy performance of existing buildings. However, it is not clear when these will be implemented.

The implementation of heat pumps driven by renewable electricity and the expected impact on grid stability also will affect the need for longer term heat storage

The market development of seasonal heat storage is seen as strongly depending on how these two issues will evolve over time.

Value Chain:



Business Case:

The benefits for a house owner are:

- saves money for energy consumption,
- increases the share of renewable energy,
- more independent of energy infrastructure.

A study by ECN into the techno-economic feasibility showed that the estimated system investment cost of 10 kEuro can be earned back during the 30 years lifetime. Main uncertainties in the analysis are the price evolution of gas and the cost of the thermochemical storage material

The supplier of heat storage materials has new market, increased market volume for his materials.

Business case for ECN: contract research, or mixed funding.

2.3 Partners

- What partners do we have and what is their position in the value chain?
- Which partners do we need and how and when do we expect to find them?
- What and how do the partners contribute (knowledge, materials, funding)?

Current partners:
An intensive collaboration is ongoing between ECN and the TU Eindhoven on the subject of (thermochemical) heat storage. In this collaboration, presently 4 PhD projects are running on the subject of thermochemical heat storage (3 projects related to

materials and 1 project related to system optimization). Also a related project on PCM seasonal heat storage is ongoing. Herbert Zondag as employee of ECN-BEE is appointed as part-time professor on heat storage technology at the TU/e.

Furthermore, in the E-Hub consortium several commercial parties are active as partners.
The most relevant ones for the heat storage value chain are:

- *Ertzberg*, Belgium, project development, real estate
- *Acciona,* Spain, energy supplier, contractor
- *Solintel,* Spain, Engineering company

Vaillant, system supplier, was in contact with ECN in 2012 on a German funding proposition for TC heat storage development. They are currently involved with German R&D institutes in this field.

Which partners do we need:

1) Partners in the field of materials supply:
   Nedmag, Wendelin in the Netherlands. Salt suppliers. Current focus at Nedmag and Wendelin is on development of salt for use as PCM. Nedmag did already contribute materials (Magnesium chlorides)
   Need is for 'stable' materials development

2) System suppliers: BDR (Remeha) discussed with ECN on heat storage and heat pumps. Their main interest was on TA-heat pumps. They indicated that market demand for long term seasonal heat storage was not present within their current businesses. (difficult business case)
   Need is for product development and solar thermal system integration

3) Project development - real estate: We were involved in the past with Koppen vastgoed: Iqoon woning HHW. Now Koppen is linked with TNO.
   Need these partners for providing demonstration facilities. (Koppen now has a TNO demo-system)

We 'feel' that TCS is still quite far from application. Too low TRL for market parties to step into it. Market parties are only willing to participate using subsidy schemes, with very low risks. This situation may change when building energy performance regulations become more tight and/or PV will continue to boom resulting in decreasing tariffs for PV electricity at hours of peak solar supply.

2.4 Intellectual property

- Do we have protected IP on the subject?
  No: we have 'unprotected' knowledge

- What is our strategy?
  - Do we want to build an IP portfolio?

Target application is not in our programmatic focus

- In what field do we want to build an IP portfolio? (e.g., materials, system integration, etc.)
  System Development, reactor design, (idea of integration of additional HEX in open sorption systems for peak power)

- Publication of results
  - What have we published?
    - *Results on materials testing (MgSO4, MgCl2, CaCl2, Al2(SO4)3.*
    - *Material characterization studies (ADEM)*
    - *Techno-economical assessment of complete system*
    - *First design studies.*
    - *First tests on small scale closed reactor systems, as agitated reactor systems and open sorption reactor systems.*
    - *prototype 1 development and test: $MgCl_2$-H_2O*
    - *EU-report on results prototype 2 development and test with zeolite.*

  - Plan for dissemination of results
    stage 2 prototype, to be presented at heat storage conference and within project consortium

2.5 Roadmap

- What is needed to reach the next TRL level(s)?
  - *Stable salt-hydrate: materials R&D*
  - *Improvement of air handling concept: air tightness, thermal insulation reduction of auxiliary E-use*

- How much time to reach TRL 8 (market introduction)?
  Depending not only on technical development but also on development market conditions/regulations as indicated before.

- Milestones (e.g., duration test, pilot installation, field test, but also IP portfolio build, licensing partner found, etc.)
  -

- When should the milestones be reached?
  -

- Somewhat more detailed description of R&D needed in the next one or two years

This section is not elaborated very much. It depends strongly on the options for directions for further development and selections to be made for it.

2.6 Funding

- How can the development be funded

  The allocation of EZS EBI program funding is limited, since the application of TCS has only minor links with industrial energy efficiency. TCS is focused on application in buildings.

- Which public funding can be attracted?

  TKI-Energo: provides a subsidy program focused on compact long term heat storage. Deadlines for 2014: 20 May. Additional opportunity at TKI energo in a national consortium (to be build) deadline September 2014

- EU H2020: topic LCE 10 – 2014: Next generation technologies for energy storage (call deadline, 7 May 2014)
- EU –H2020: topic NMP-13: new materials for energy storage: 2 stage deadline stage 1: 6-May, contacts with proposers from Spain (Idener)
- Funding through STW in the Matthers proposal of TU/e

- Are there private companies that may fund ECN R&D.
  Toyota Motor Corporation is sponsoring TC heat storage development for automotive application.

3

Review Meeting Summary

A stage gate review meeting for TC-seasonal heat storage was held May 6, 2014.

In this meeting Program Development and Bussiness Development were represented by Peter Alderliesten, Ruud vd Brink, Rob Kreiter, and Jelle Blekxtoon. Simon Spoelstra, chairman of this meeting and PMC coordinator, and Robert de Boer as project manager.

A status summary was presented (appendix 2) and the results were discussed.

Important elements of the discussion were:

- Energetic performance of the storage technology needs further improvements, in terms of overall thermal efficiency, and reduction of auxiliary electricity use.
- Thermochemical materials research needed to obtain stable, high energy storage density materials.
- Interest of industry/market for TC storage is low.
- Renewable energy and energy saving for built environment are since 2011 no longer included in the ECN Energy Efficiency program.

The main conclusions of the meeting were:

1. Stop the internal (EZS) funding for the activities on thermochemical heat storage for buildings. Continuation of activities for TC seasonal heat storage can be done, only based on external funds.

2. Explore opportunities for application of the open sorption concept in industrial drying processes. (food, paper, construction materials)

Sponsored research activities for TC heat storage applications for niche markets (e.g. automotive) can be continued. These applications are subject to very different system requirements and different economic framework conditions.

Appendix A. Marktonderzoek/ partijen

In 2009 is door ECN een techno-economische analyse gemaakt en gepubliceerd, met de volgende conclusie:

> It is concluded that seasonal sorption heat storage is able to pay itself back within its lifetime under the following assumptions (1) a passive house with 6 GJ/yr heating demand and 9 GJ/yr tap water demand, (2) Dutch gas prices, (3) an effective interest rate on the initial investment of 4%, (4) an effective savings account interest of 2%, and (5) a technical system lifetime of 30 years, in which the system should pay itself back.
> An important assumption is the cost of the sorption material. It is shown that the cost of the sorption material has a strong effect on the overall systems cost and should be kept very low in order to reach this target. The evaluation method took into account the investment costs (based on future large-scale plug-and-play application of standardized systems and standardized dedicated building concepts) and the system lifetime, as well as interest (a low level for interest received and a high level for interest paid) and energy price scenario.
>
> A large uncertainty exists in the results of this calculation, due to the fact that interest and future energy prices, as well as system lifetime and system investment costs (especially for future large scale application) are only rough estimates, but have a strong effect on the economics.

In een brainstormsessie is een inventarisatie gemaakt van onderzoekspunten welke binnen het project E-hub onderzocht dienen te worden (zie: TC storage research issues, Herbert Zondag). Deze punten zijn onderverdeeld in 5 thema's. Eén van deze thema's is marktonderzoek. Om vooraf te inventariseren wat in het verleden aan marktonderzoek is gedaan, is gesproken met Marco Bakker en Wim van Helden.

Gesprek Marco Bakker

Volgens Marco is er geen marktonderzoek in de vorm van een studie gedaan. Wel is drie tot vier jaar terug het idee ontstaan om samen met een bouwpartij een TC-demo te realiseren. Hiervoor is een samenwerking opgestart met Koppen Vastgoed. Het idee was/is om in de iCOONwoning (www.icoonwoning.nl) een werkende demonstratieopstelling o.b.v. TC-opslag te realiseren. Mogelijk lopen dit contact nu via TNO (project Raak MKB), sinds de Gebouwde Omgeving activiteiten van ECN zijn overgedragen naar TNO. Er liepen al contacten tussen Koppen vastgoed en TNO aangaande gebouwschil concepten voor de iCOONwoning en isoZero.

Ten aanzien van luchtverwarming had Willem Koppen contacten lopen met Wim Hijmissen van Brink-Centrotec (http://linkd.in/z6sEbC). Wim komt/kwam ook regelmatig over de vloer bij Willem en was/is ook enthousiast over nieuwe technologieën zoals TC-opslag.

Hiernaast lopen, de ons bekende, contacten met Vaillant. Wim van Helden heeft in het kader van IEA-SHC Task 42: Compact Thermal Energy Storage ook met Vaillant gesproken. In Duitsland heeft een nationale call (20 M€) plaatsgevonden aangaande warmteopslag. ECN kon hierin als buitenlandse partij niet participeren. Echter, er waren wel mogelijkheden tot samenwerking met Vaillant in het ons bekende 'Spitzenkluster'.

In het algemeen heeft Marco bij de markpartijen waarmee contact is geweest t.a.v. toepassing van TC-opslag wel veel enthousiasme geproefd. Echter, concrete samenwerking strandde op het feit dat TC-opslag nog teveel in de onderzoeksfase zit.

Gesprek Wim van Helden

Volgens Wim is er in het verleden bij ECN ook geen marktonderzoek gedaan naar TC-opslag. Wel hebben er binnen WAELS (2006-2008) klankboardmeetings plaatsgevonden, waarbij ook 'de markt' in beeld is geweest. Echter, dat is gebleven bij beeldvorming aangaande een goede samenstelling van de gehele keten (partijen, randvoorwaarden, etc.). Bij deze meetings waren o.a. aanwezig: Nefit (intentie en interesse), ZEN, Ronald van Zolingen (één been Shell Solar, meer als prof. TU/E), Architect Piode (ontwerp- en adviesbureau BNA), Willem Koppen (Koppen Vastgoed) en Delta Energie (wel interesse maar door reorganisatie afgehaakt).

Hiernaast sprak Wim t.a.v. warmteopslag in het algemeen nog over het project Contesse(?) waarvoor hij de projectcoördinatie gaat doen. Dit project is i.s.m. AEE INTEC (www.aee-intec.at) naar aanleiding van de call van april vorig jaar (waar TC-store van Marco ook is ingediend). Ook heeft Wim onlangs gesproken met TNO (Lucienne Krosse) in het kader van het project Merits(?). Wim heeft ook contacten lopen in Bordeaux aangaande materiaal ontwikkeling en met ESE solar uit België (www.ese-solar.com).

Appendix B. POWERPOINT presentatie bij review meeting

ECN
Your energy. Our passion.

Thermochemische warmteopslag

Stage gate review

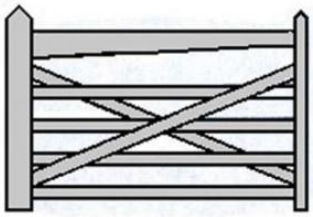
Petten
6 mei 2014

www.ecn.nl

ECN

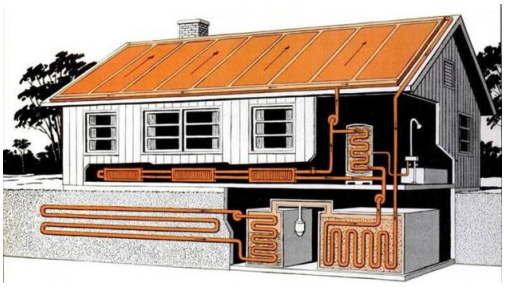
Agenda

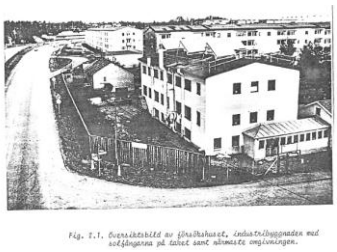
- Look Back
  - Presentatie status TC warmteopslag ontwikkeling
  - Vraag en antwoord
- The big picture
  - Go/NoGo besluit
- Look forward
  - Welke opties voor ontwikkeling/toepassing kennis en technologie zijn er, en bieden kans voor vervolg –toepassing/partners/geld
    - prioritering



Status TC-warmteopslag ontwikkeling

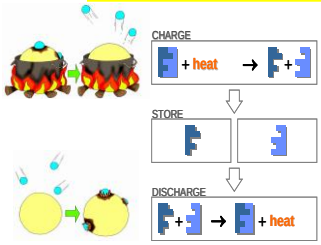
Er was eens …….

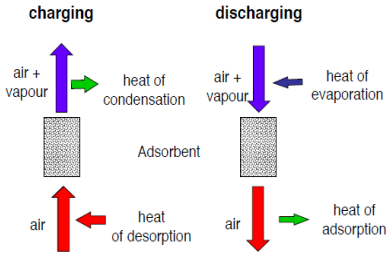




…. een Zweedse professor

Thermochemie: basics





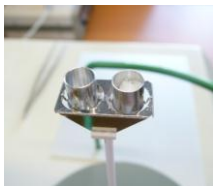
Open sorptie concept

$MgCl_2 \cdot 6H_2O(solid) \leftrightarrow MgCl_2 \cdot 4H_2O(solid) + 2\ H_2O(gas)$ $\Delta H = 3230$ kJ/kg H_2O

$MgCl_2 \cdot 4H_2O(solid) \leftrightarrow MgCl_2 \cdot 2H_2O(solid) + 2\ H_2O(gas)$ $\Delta H = 3785$ kJ/kg H_2O

The effective heat storage density of $MgCl_2 \cdot 6H_2O$ amounts to 2 GJ/m3 taking the density of the salthydrate to be 1.6 kg/dm3.

TC-warmteopslag: ontwikkelingen bij ECN



Materiaalselectie en karakterisering

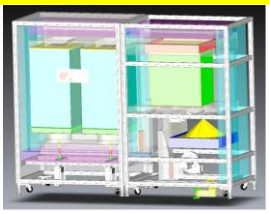
Reactorconcept ontwikkeling

Systeem ontwikkeling

5

ontwikkeling bij ECN

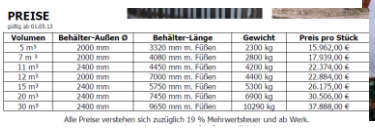
- Lab-Prototype→ E-Hub project
  - 2×100 dm^3 reactor met Zeoliet 13X (150 kg)
  - Opslag capaciteit 50 MJ /15 kWh (~ 0.25 GJ/m^3)
  - Vermogen laden-ontladen 0.5-1 kW



Current market seasonal heat storage

Individuele systemen-VSI

Collectieve systemen



PREISE

Volumen	Behälter-Außen Ø	Behälter-Länge	Gewicht	Preis pro Stück
5 m³	2000 mm	3320 mm m. Füßen	2300 kg	15.962,00 €
7 m ³	2000 mm	4080 mm m. Füßen	2800 kg	17.939,00 €
11 m³	2400 mm	4450 mm m. Füßen	4200 kg	22.374,00 €
12 m³	2000 mm	7000 mm m. Füßen	4400 kg	22.884,00 €
15 m³	2400 mm	5750 mm m. Füßen	5300 kg	26.175,00 €
20 m³	2400 mm	7450 mm m. Füßen	6900 kg	30.506,00 €
30 m³	2400 mm	9650 mm m. Füßen	10290 kg	37.888,00 €

Alle Preise verstehen sich zuzüglich 19 % Mehrwertsteuer und ab Werk.

Current performance

	Prototype 1 (TC reactor)	Prototype 2 (E-Hub)	Target	
material	$MgCl_2.6H_2O$	Zeolite 13X	Salt hydrate	?
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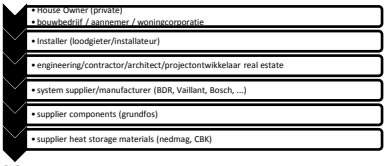
TRL 4: technology validated in the lab both on materials development and on system scale, but further improvements needed.

Current issues are

- Improvement on system level (storage thermal efficiency, COP)
- chemical stability of MgCl2.6H2O on dehydration. (HCl formation)

Market

- Newly built houses, E-label A++
  - EPC, EPBD (zero energy 2020)
- Value chain



- **Business Case:**
  - House owner saves money for energy consumption, increases the share of renewable energy, more independent of energy infrastructure. Pay Back time: >10 years in seasonal operation
  - Supplier heat storage materials has new market, increased market volume for his materials.
- Business case for ECN: contract research, or mixed funding.

Partners

- TU/e
  - ADEM
  - Part time prof : Herbert Zondag
- *E-HUB*
  - *Ertzberg*, Belgium, project development, real estate
  - *Acciona,* Spain, energy supplier, contractor
  - *Solintel,* Spain, Engineering company
- Vaillant, system supplier (2012)

- Partner needs:
  - material supply (Nedmag), system supplier (BDR), project development (Koppen, HHW)

IP

- *NO Patents: we have 'unprotected' knowledge*

What is our strategy?

- – Do we want to build an IP portfolio?
  Target application is not in our programmatic focus

- – In what field do we want to build an IP portfolio? (e.g., materials, system integration, etc.)
  System Development, reactor design, (idea of integration of additional HEX in open sorption systems for peak powers)

- Publication of results
  Results on materials testing (MgSO4, MgCl2, CaCl2, Al2(SO4)3.
  Material characterization studies (ADEM)
  Techno-economical assessment of complete system
  First design studies.
  First tests on small scale closed reactor systems, as agitated reactor systems and open sorption reactor systems.

  prototype 1 development and test: MgCl2-H2O
  EU-report on results prototype 2 development and test with zeolite.

- Plan for dissemination of results

Prototype 2 results, to be presented at heat storage conference and within project consortium

Roadmap

- What is needed to reach the next TRL level(s)?
  - *Stable salt-hydrate: materials R&D*
  - *Improvement of air handling concept: air tightness, thermal insulation, reduction of auxiliary E-use, reduce system cost*

- How much time to reach TRL 8 (market introduction)?
  - *Depending not only on technical development but also on development market conditions/regulations as indicated before.*

Funding

- How can the development be funded
  - the allocation of EZS EBI program funding is limited, since the application of TCS has only minor links with industrial energy efficiency. TCS is focused on application in buildings.

- Which public funding can be attracted?
  - TKI-Energo: provides a subsidy program focused on compact long term heat storage. Deadlines for 2014: 20 May. Additional opportunity at TKI energo in a national consortium (to be build) deadline September 2014 (contacts Hanze)
  - ~~EU H2020: topic LCE 10 – 2014: Next generation technologies for energy storage (call deadline, 7 May 2014)~~
  - EU H2020: topic NMP-13: new materials for energy storage: 2 stage deadline stage 1: 6-May, contacts with proposers from Spain (Idener)
  - Funding in the Matthers proposal by TU/e. (STW program)

- Are there private companies that may fund ECN R&D.
  - Toyota Motor Corporation is sponsoring TC heat storage development for automotive application, linked to our TC heat pump work. (salt-NH3)

Stop/Go/Adjust

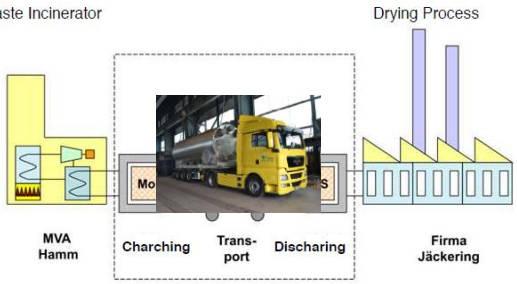
Thermochemical heat storage for buildings

+	-	?
100% Renewable energy	Business case/paybacktime	Link to ECN programs
USP: long term storage	Overall energy balance	Compactness
Temperature match supply-demand	Complexity compared to competitors	(co-)funding opportunities
ECN's knowledge + experience	Limited 3rd party involvement	

Opportunities

- Consultancy work on heat storage
- TKI-EnerGo

- Application of open sorption concept for drying processes
  - (waste heat recov



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