Thermal Energy Storage
Latent Heat Storage
Part 1

Justin Chiu, PhD

Dept. of Energy Technology

KTH Royal Institute of Technology, Sweden

Intended Learning Outcome

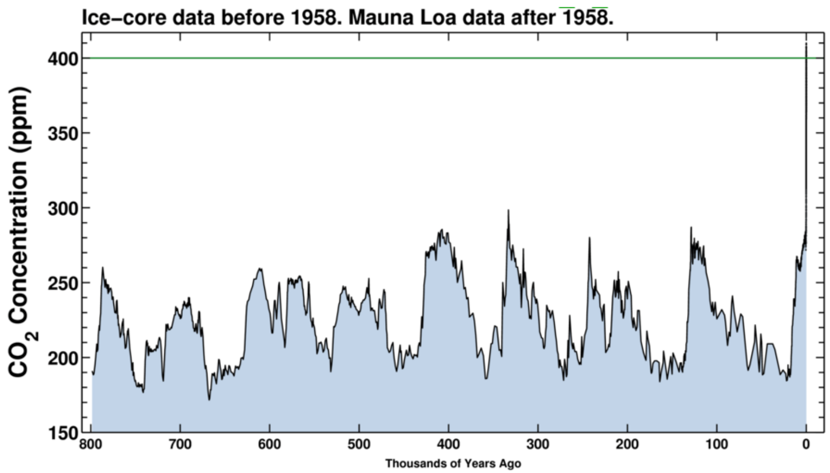
After completion of this lecture, you will be able to:

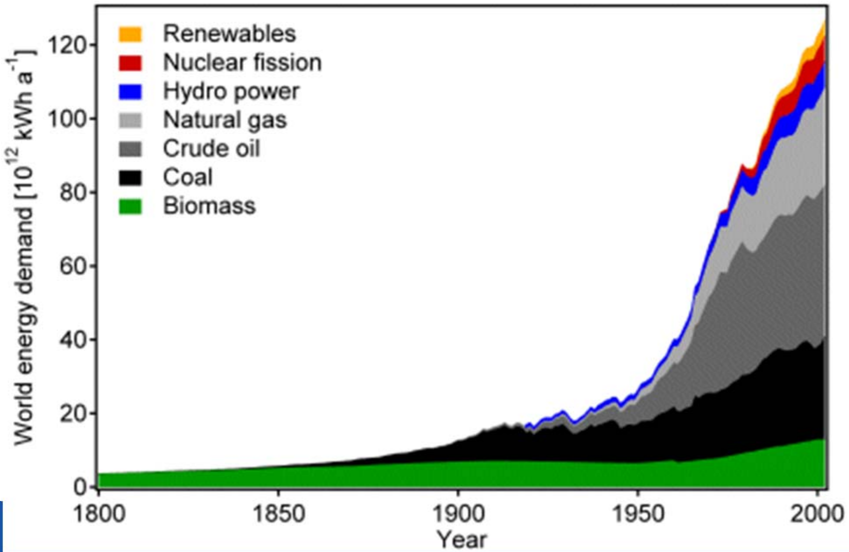
- Explain the advantages of using Thermal Energy Storage (TES)
- Calculate the amount of energy stored in a Latent Heat based TES
- Be familiar with the Packing Factor

Table of Content

1. Introduction

- CO_2 concentration in the last 650,000 years: 200 ppm to 400 ppm.
- Business as usual: 40% CO_2 increase from 2007 to 2030.
- Heating and Cooling: 40-50% of final energy use worldwide.





Source: NOAA, 2017.
IEA TCEP 2013, BP Statistical Review of World Energy

1. Introduction

Europe's first 100 % solar heated apartment building, completed in 2007, Oberburg, Switzerland.

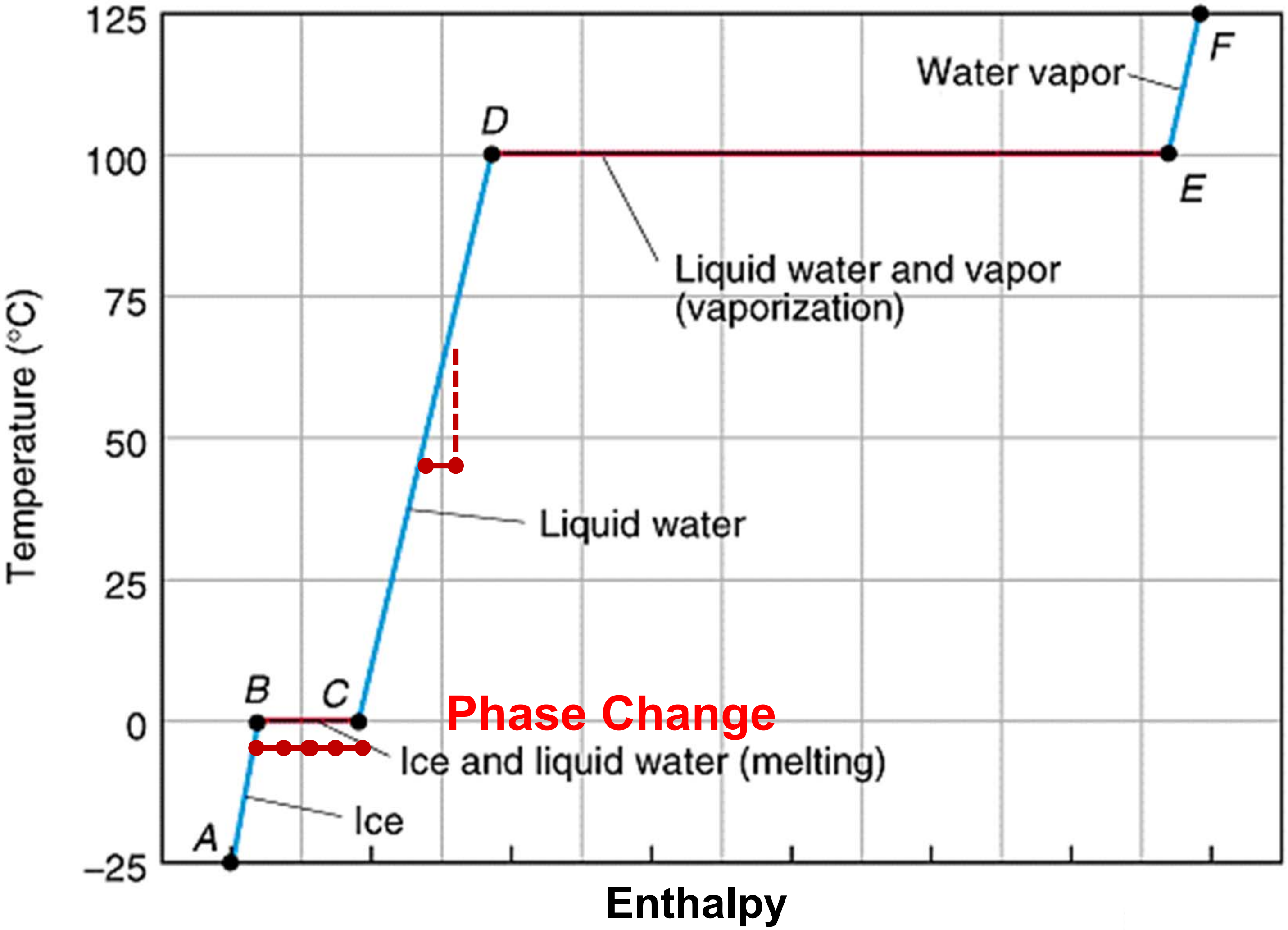
200'000 L capacity

276 square meters of solar roof

How can we reduce the storage size?

Source: P. Widmer

2. Enthalpy Diagram of Water



Adapted from PJ Brucat

3. Stored Thermal Energy

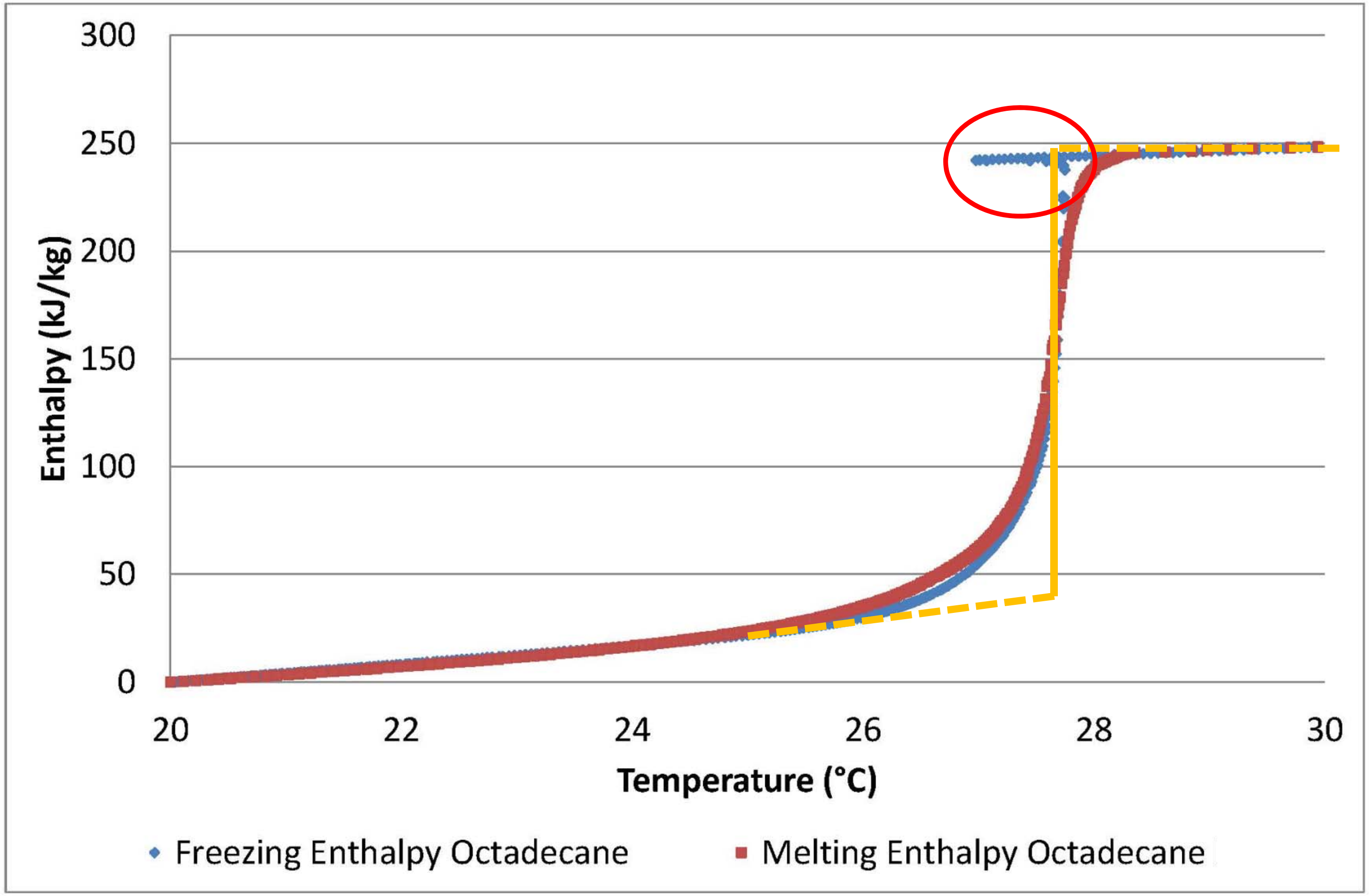
Amount of energy stored (Q) over temperature range $[T_1;T_2]$ with λ specific latent heat, h specific enthalpy, m mass, and c_p specific heat capacity:

$$Q_{pcm} = \int_{T_1}^{T_{PC}} m \cdot c_{p\,sol}(T) \cdot dT + m \cdot \lambda + \int_{T_{PC}}^{T_2} m \cdot c_{p\,liq}(T) \cdot dT$$

In most cases, phase transition is accompanied with temperature change, hence:

$$Q_{pcm} = \int_{T_1}^{T_2} m \cdot dh_{pcm}(T) = \int_{T_1}^{T_2} m \cdot c_{p\,pcm}(T) \cdot dT$$

3. Experimentally Obtained Enthalpy Curve of a PCM



Source: J. Chiu. 2012

4. Volume Uptake with LHTES

T1 = 50°C; T2 = 70°C; packing factor (PF) of the PCM as 0.8

For water: q_{water} (c_p= 4.18 kJ/kg-K and ρ=1 kg/L)= 4.18* (70-50)= 83.6 kJ/kg or 83.6 kJ/L

For PCM S58 (c_p= 2.55 kJ/kg-K, λ=145 kJ/kg and ρ=1.5 kg/L): q_{PCM} = 2.55*20+145 =196 kJ/kg or 294 kJ/L

$V_{pcm}/V_{water}= q_{water}/(q_{pcm}*PF)=1/3$ in volume uptake

S58 properties: PCM Products, 2013

Further Reading and Reference

J. NW. Chiu, V. Martin, and F. Setterwall
“A Review of Thermal Energy Storage Systems with Salt Hydrate Phase Change Materials for Comfort Cooling”, 11th International Conference on Thermal Energy Storage, Effstock, June 14-17, 2009, Stockholm, Sweden. Available online, link is placed on the course homepage.

H. Mehling and L. F. Cabeza
“Heat and cold storage with PCM: An up to date introduction into basics and applications.” Springer, 2008. Available as Google ebook.

Thank You for Your Attention

Justin Chiu

justin.chiu@energy.kth.se

Thermal Energy Storage
Latent Heat Storage
Part 2

Justin Chiu, PhD

Dept. of Energy Technology

KTH Royal Institute of Technology, Sweden

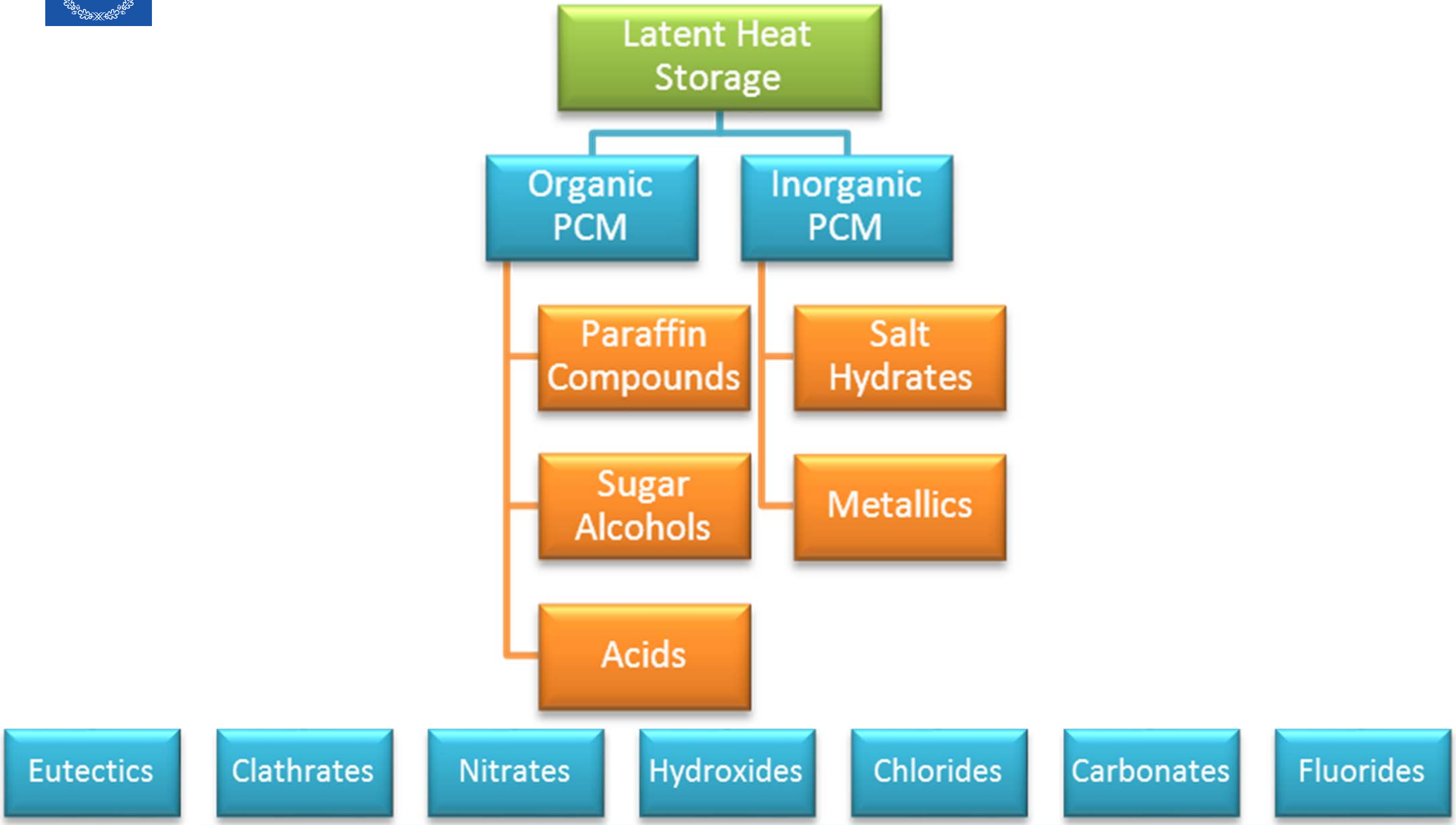
Intended Learning Outcome

After completion of this lecture, you will be able to:

- Classify PCMs into relevant categories, and present some examples per category
- Describe commercial LHTES materials and their main properties
- Reflect on thermal properties of PCMs, including phase equilibrium aspects

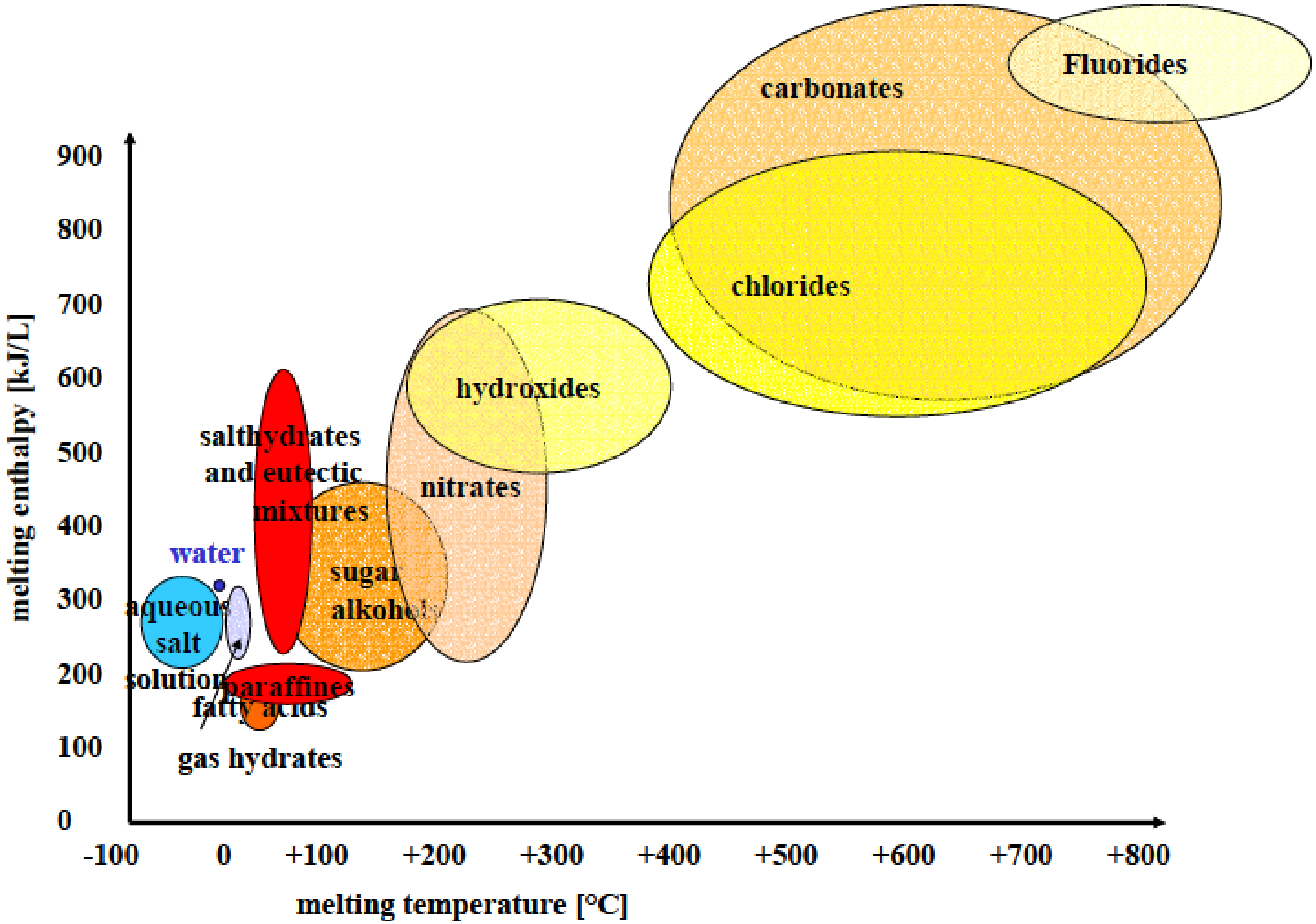
Table of Content

1. PCM Classifications



Adapted from Zalba et al. 2013, Sharma et al.2009, IEA ECES Annex 17

1. Storage Capacity of PCMs



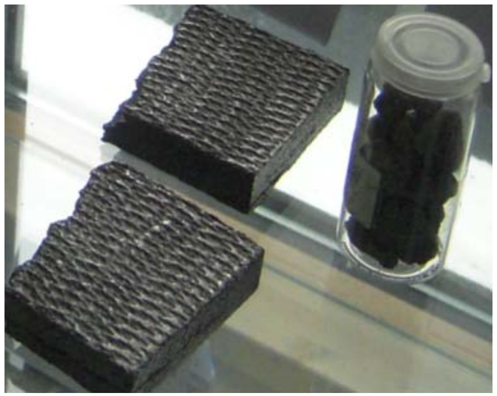
Source: ECES Annex 17

1. PCM in Different Containers

Container

Bulk Storage

Encapsulation



Foam and Matrix

Pouches

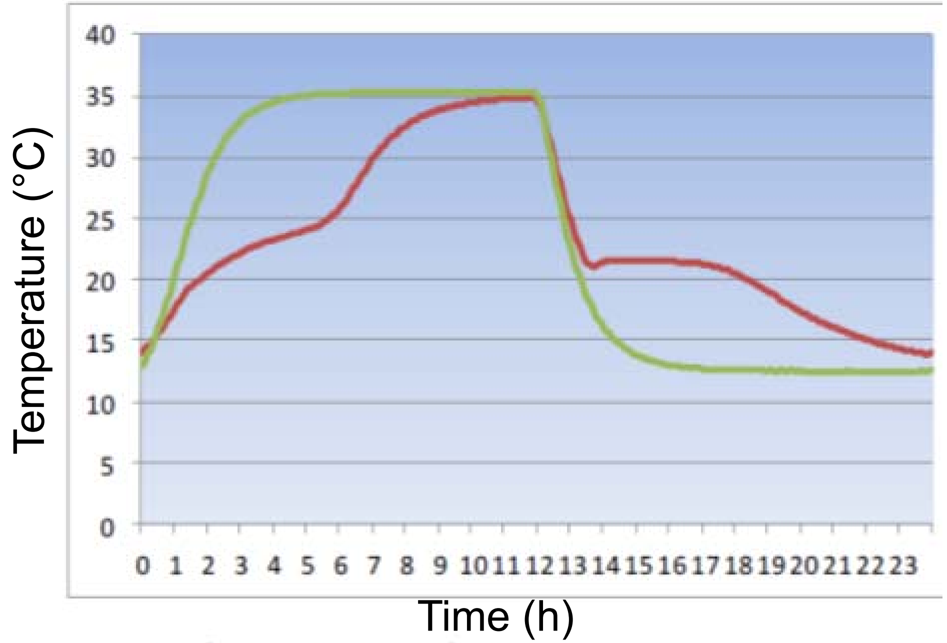
Source: Climator, Swerod, PCM Products

2. Main Characteristics of Organic and Inorganic PCMs

	Organic Materials	Inorganic Materials
Advantages	• Self-nucleating • Chemically inert and stable • No phase segregation • Available in large temperature range	• High volumetric storage density (180-300 MJ/m^3) • Non flammable • Low volume change
Disadvantages	• Flammable • Low thermal conductivity (0.2W/m-K) • Low volumetric storage density (90-200 MJ/m^3) • Non compatible with plastics	• Large supercooling • Low thermal conductivity (0.6W/m-K) • Phase segregation • Corrosion of metal containments

2. Typical Thermal Properties of Commercialized PCMs

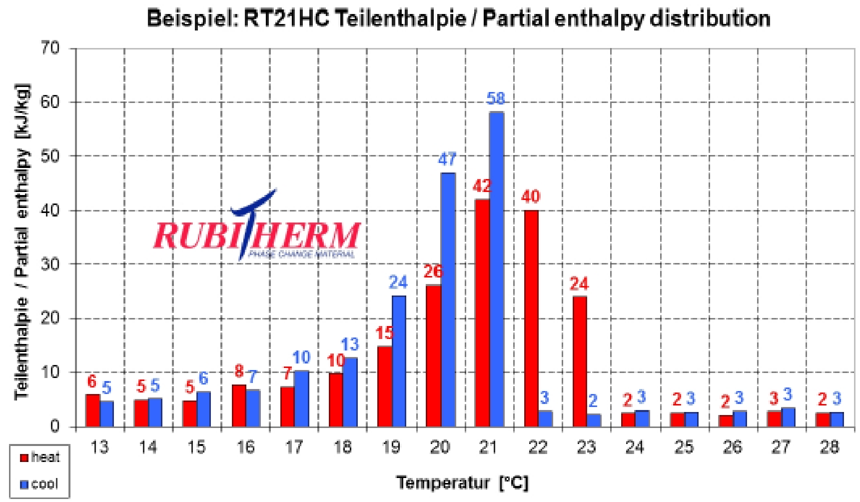
T-History Curve for C21



Physical Data for ClimSel C21

Phase Change Temperature:	21°C
Maximum Temperature:	35°C
Storage Capacity 15-30°C:	60 Wh/ Litre
Latent Heat of Fusion:	43 Wh/ Litre
Approx. Specific Heat in PCM:	1Wh/kg/°C
Specific Gravity:	1,38kg/ Litre
Thermal Conductivity:	0,5-0,7W/m/°C

Melting area	**20-23** main peak: 21	**[°C]**
Congealing area	**21-19** main peak: 21	**[°C]**
Heat storage capacity ± 7,5%	**190**	**[kJ/kg]***
Combination of latent and sensible heat in a temperatur range of 13°C to 28°C.	**53**	**[Wh/kg]***
Specific heat capacity	**2**	**[kJ/kg·K]**
Density solid at 15 °C	**0,88**	**[kg/l]**
Density liquid at 25 °C	**0,77**	**[kg/l]**
Heat conductivity (both phases)	**0,2**	**[W/(m·K)]**
Volume expansion	**14**	**[%]**
Flash point (PCM)	**140**	**[°C]**
Max. operation temperature	**45**	**[°C]**



Measured with 3-layer-calorimeter.

Source: Climator, Rubitherm

2. Typical Thermal Properties of Commercialized PCMs

PlusICE PCM (EUTECTIC) (E) RANGE

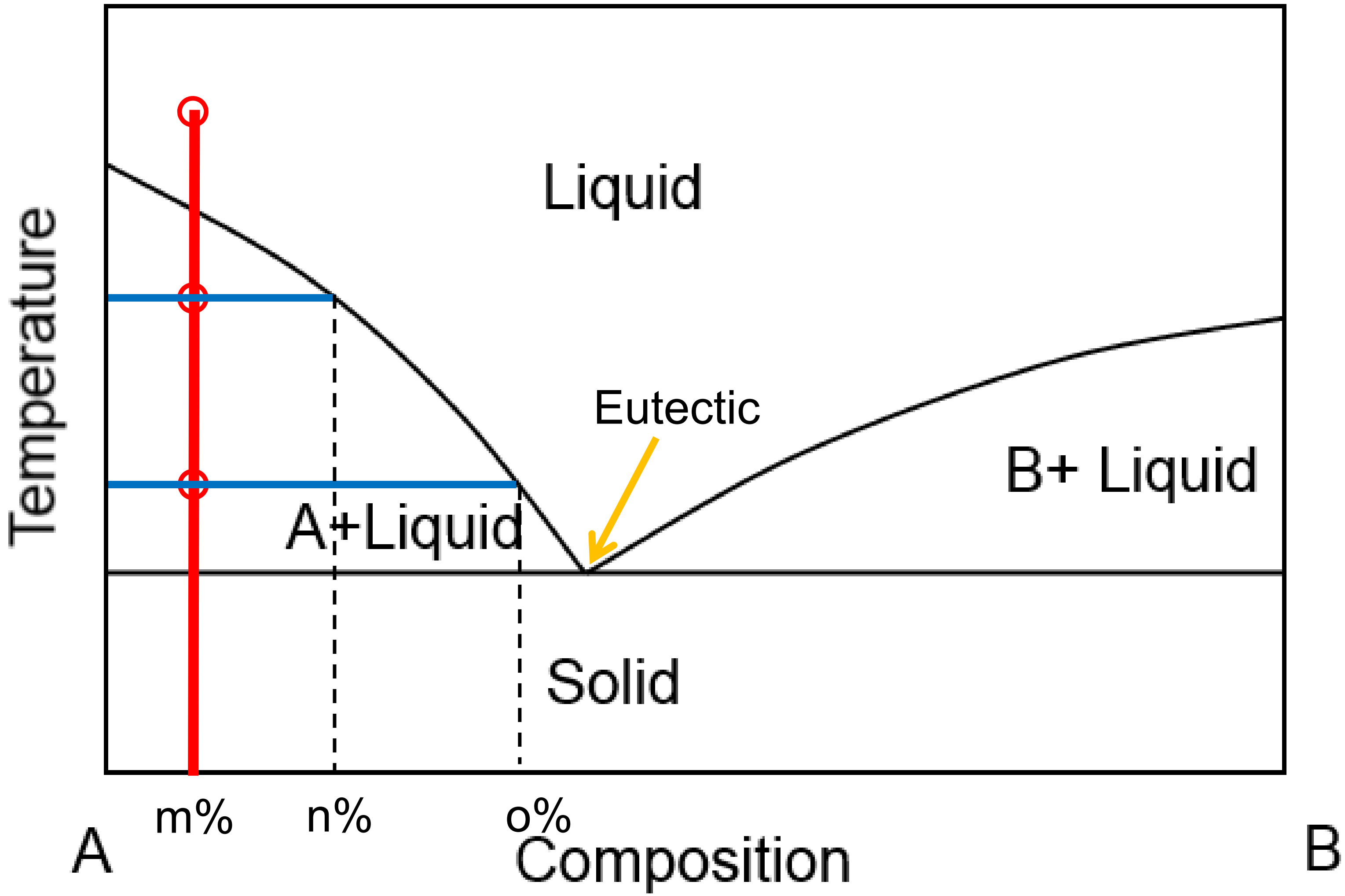
2013-1

PCM Type	Phase Change Temperature (°C)	Phase Change Temperature (°F)	Density (kg/m3)	Density (lb / ft3)	Latent Heat Capacity (kJ/kg)	Latent Heat Capacity (Btu / lb)	Volumetric Heat Capacity (MJ/m3)	Volumetric Heat Capacity (Btu / ft3)	Specific Heat Capacity (kJ/kg K)	Specific Heat Capacity (Btu / lb°F)	Thermal Conductivity (W/m K)	Thermal Conductivity (Btu / ft2h°F)
EUTECTIC PCM SOLUTIONS												
E0	0	32	1,000	62.4	332	143	332	8,911	4.186	0.992	0.580	0.335
E-2	-2.0	28	1,070	66.8	306	132	327	8,777	3.80	0.900	0.580	0.335
E-3	-3.7	25	1,060	66.2	312	134	331	8,884	3.84	0.910	0.600	0.347
E-6	-6.0	21	1,110	69.3	275	118	305	8,186	3.83	0.907	0.560	0.324
E-10	-10.0	14	1,140	71.2	286	123	326	8,750	3.33	0.789	0.560	0.324
E-11	-11.6	11	1,090	68.0	301	129	328	8,804	3.55	0.841	0.570	0.329
E-12	-12.3	10	1,110	69.3	250	108	278	7,462	3.47	0.822	0.560	0.324
E-14	-14.8	5	1,220	76.2	243	105	296	7,945	3.51	0.832	0.530	0.306
E-15	-15.0	5	1,060	66.2	303	130	321	8,616	3.87	0.917	0.530	0.306
E-19	-18.7	-2	1,125	70.2	282	121	344	9,233	3.29	0.779	0.580	0.335
E-21	-20.6	-5	1,240	77.4	263	113	326	8,750	3.13	0.741	0.510	0.295
E-22	-22.0	-8	1,180	73.7	234	101	276	7,408	3.34	0.791	0.570	0.329
E-26	-26.0	-15	1,250	78.0	260	112	325	8,723	3.67	0.869	0.580	0.335
E-29	-29.0	-20	1,420	88.6	222	95	264	7,086	3.69	0.874	0.640	0.370
E-32	-32.0	-26	1,290	80.5	243	105	313	8,401	2.95	0.699	0.560	0.324
E-34	-33.6	-28	1,205	75.2	240	103	286	7,676	3.05	0.723	0.540	0.312
E-37	-36.5	-34	1,500	93.6	213	92	302	8,106	3.15	0.746	0.540	0.312
E-50	-49.8	-58	1,325	82.7	218	94	283	7,596	3.28	0.777	0.560	0.324
E-75	-75.0	-103	902	56.3	102	44	92	2,469	2.43	0.576	0.170	0.098
E-78	-78.0	-108	880	54.9	115	49	101	2,716	1.96	0.464	0.140	0.081
E-90	-90.0	-130	786	49.1	90	39	71	1,906	2.56	0.606	0.140	0.081
E-114	-114.0	-173	782	48.8	107	46	84	2,255	2.39	0.566	0.170	0.098

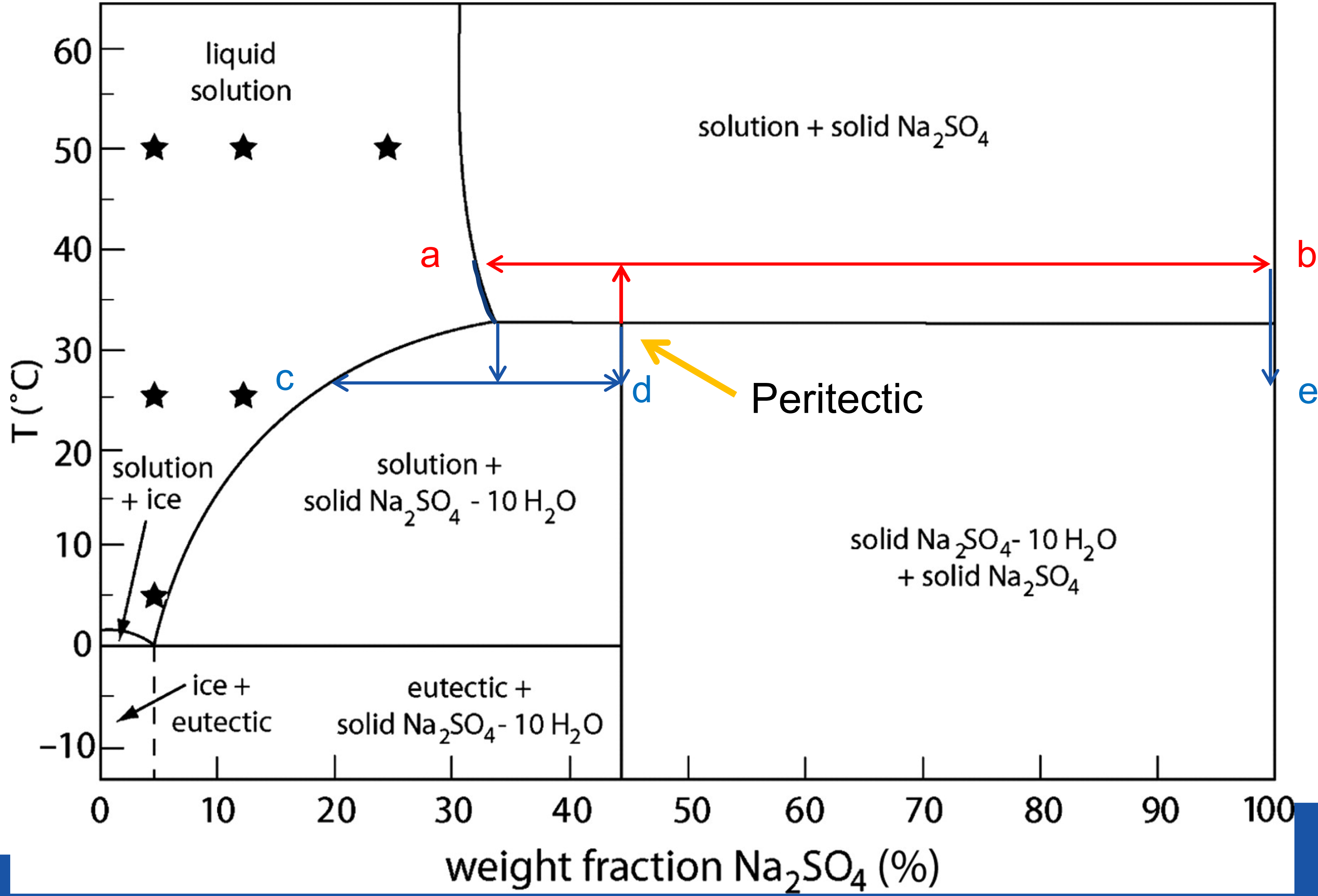
PCM Products has a policy of continues product and product data improvement and reserves the right to change design and specifications without notice

Source: PCM Products

3. Binary Phase Diagram



3. Phase Diagram of Sodium Sulfate and Water



Source: Hougen et al. 1954

Further Reading and Reference

Paul W. Parfomak

“Chapter 11 Thermal Energy Storage in Buildings”, CRS Report for Congress 2012. Available online, link is provided on the course homepage.

S. N. Gunasekara, V. Martin and J. NW. Chiu

"Phase Diagrams as Effective Tools in Thermal Energy Storage Design Using Phase Change Materials", the 5th International Conference on Applied Energy, July 1-4, 2013, Pretoria, South Africa.

Website: Energy Conservation through Energy Storage, IEA. http://www.iea-eces.org/

Thank You for Your Attention

Justin Chiu

justin.chiu@energy.kth.se

Thermal Energy Storage
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Part 3

Justin Chiu, PhD

Dept. of Energy Technology

KTH Royal Institute of Technology, Sweden

Intended Learning Outcome

After completion of this lecture, you will be able to:

- Describe some typical applications of LHTES, and relate them to existing examples and performances
- Assess the cost structure of a LHTES and its economic aspects

Table of Content

- Applications of LHTES
- Economic Aspects

LHTES Applications- Free Cooling and Heating of Buildings

- Utilization of free cooling
  - night time cold air
  - lake/sea water
  - Underground geothermal

Skövde Library

- Utilization of free heating
  - solar heating
  - waste heat

Concept House

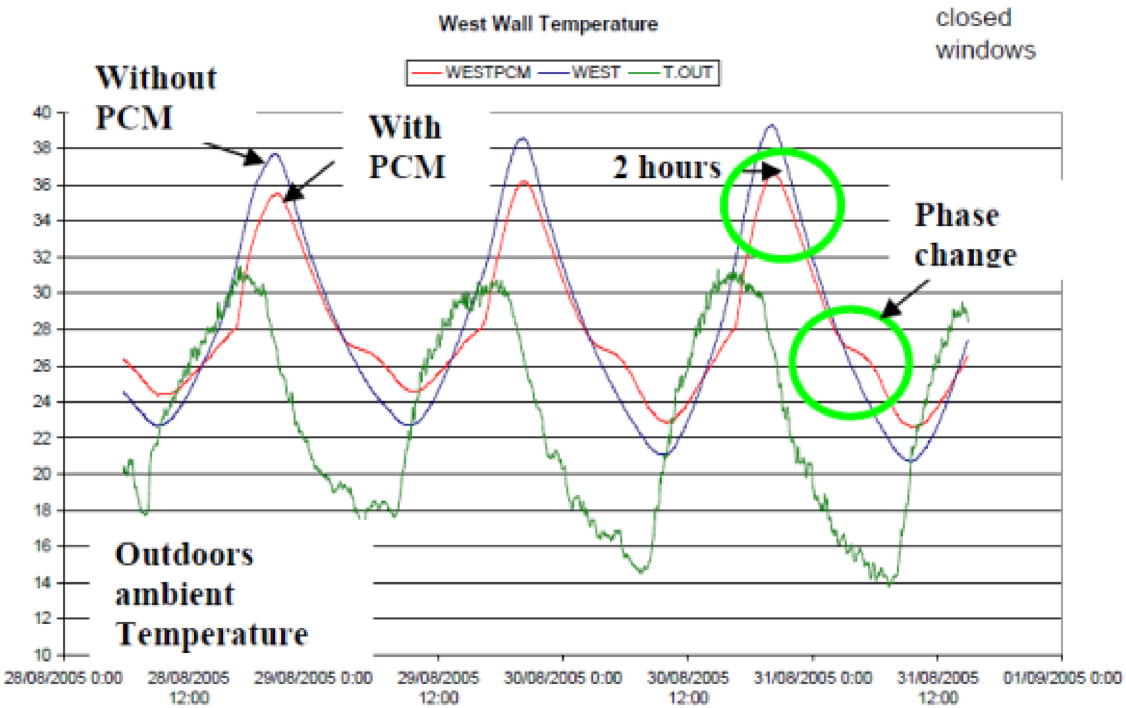
➢ Use of energy when available

Source: Climator, Allthingsrenewable

LHTES Applications- Building Thermal Mass Increase

PCM in building materials

→ Reduction of indoor temperature fluctuation



Source: Castellon et al.

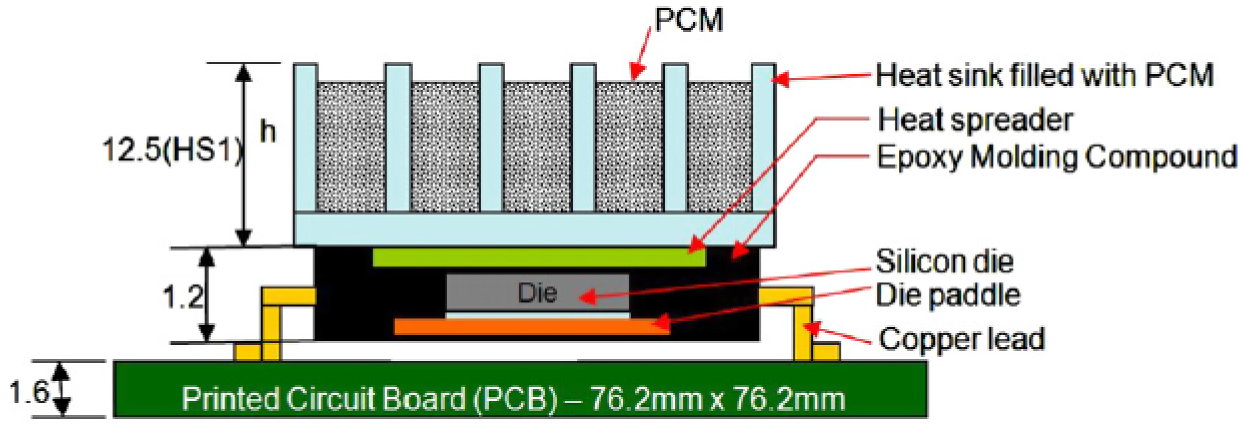
LHTES Applications- Pharmaceutical Transportation, Body Comfort

Temperature Control in Transportation

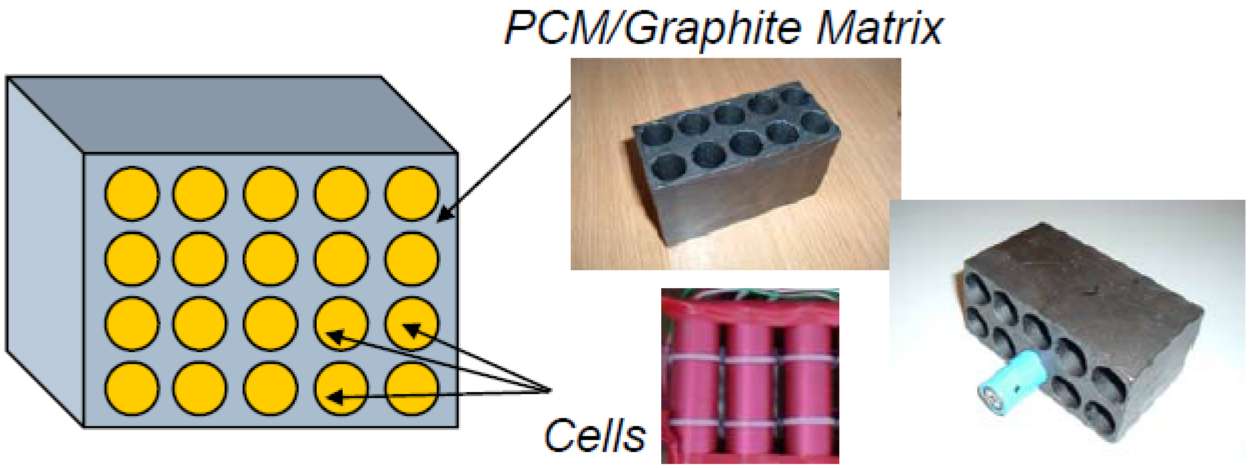
Body Temperature Control

Source: PCM Products, Va-Q-Tec, RPCM Cool Vest

LHTES Applications- Cooling of Electronics and Batteries



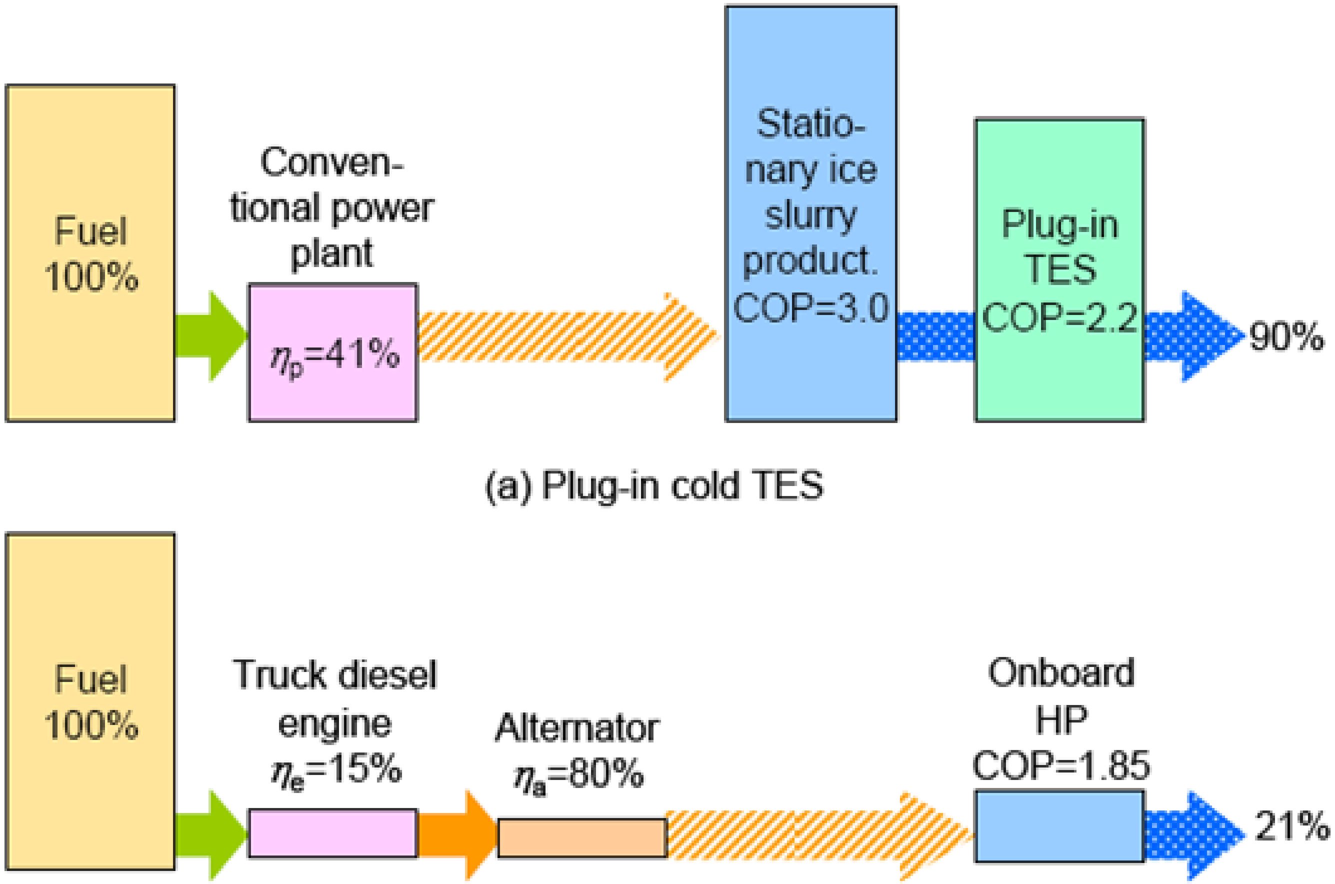
Cooling of Electronic Chips



Cooling of Battery Packs

Source: Kandasamy et al., NREL

LHTES Applications- In Vehicles



(a) Plug-in cold TES

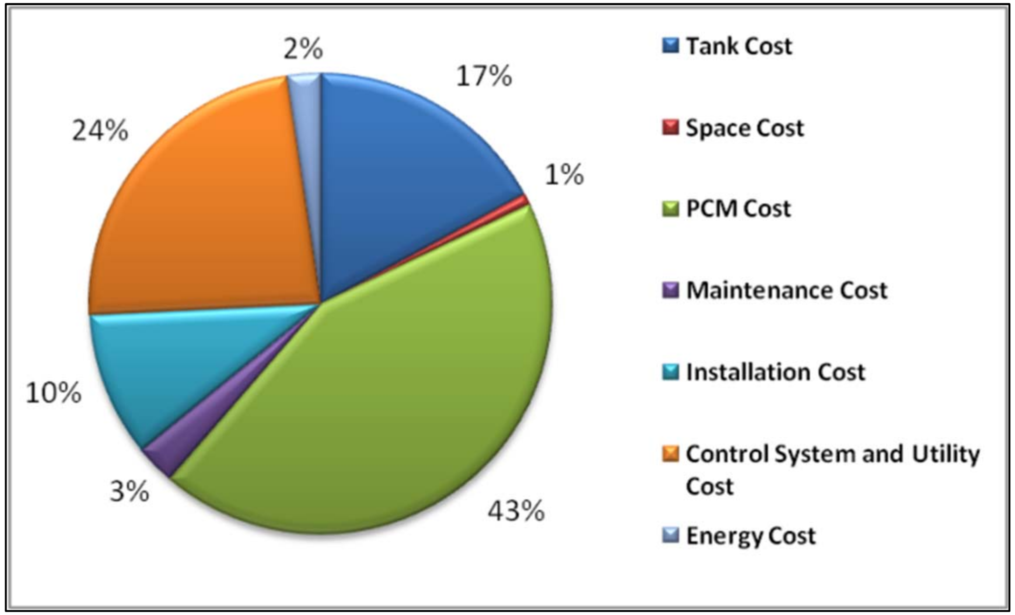
(b) Onboard HP cooling

Source: Yukitaka Kato

Cost Structure

Total cost of a LHTES unit includes:

- Storage material
- Storage unit
- Auxiliary units
- Space
- Installation
- Maintenance
- Operation/ energy



Cost break down example of a salt hydrate based 13 kWh LHTES

Source: Chiu et al. 2009

Economic Aspects (as of 2013)

- Lab-grade material: around €300/kWh
- Commercial material: around €100/kWh
- Latent heat storage capacity: 25 to 100 Wh/kg
- Inorganic PCM: density of around 1.5 kg/L
- Organic PCM: density of around 0.8 kg/L

- Estimate for storage system: $500/kW- $3000/kW
- In comparison: open cycle gas turbine $600/kW; IGCC with carbon sequestration: $6000/kW

Source: Parfomak et al.; EIA, 2013

Further Reading

- Bo Nordel

  “The Sundsvall snowstorage- six years of operation”. Chapter 21, Thermal Energy Storage for Sustainable Energy Consumption. Springer 2007. Available as Google ebook.

Thank You for Your Attention

Justin Chiu

justin.chiu@energy.kth.se

Thermal Energy Storage
Latent Heat Storage
Part 4

Justin Chiu, PhD

Dept. of Energy Technology

KTH Royal Institute of Technology, Sweden

Intended Learning Outcome

After completion of this lecture, you will be able to

- Analyze deployment challenges of LHTES
- Plan future research and development activities

Table of Content

- Deployment Challenges
  - Material
  - Component
  - System
  - Social and Environmental
- Future Research Focus

Technical Challenges

- Material:

Organic Materials	Inorganic Materials
• Flammable • Low thermal conductivity (0.2 W/m-K) • Low volumetric storage density (90-200 MJ/m^3) • Non compatible with plastics	• Large subcooling • Low thermal conductivity (0.6 W/m-K) • Phase segregation • Corrosion of metals

- Component:

  Thermal energy extraction/storage rate.

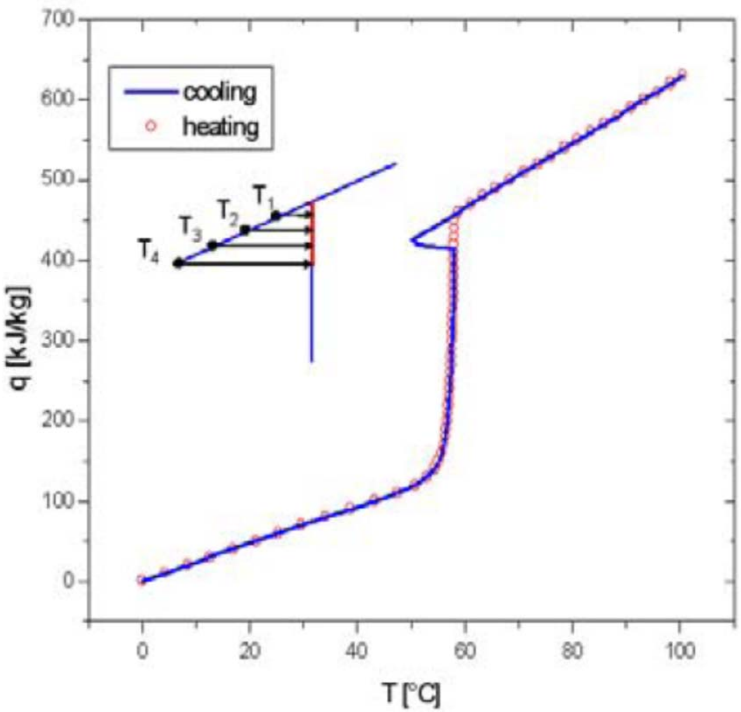
- System:

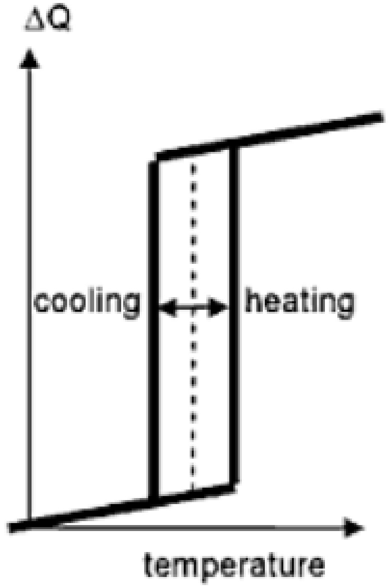
  Control strategy.

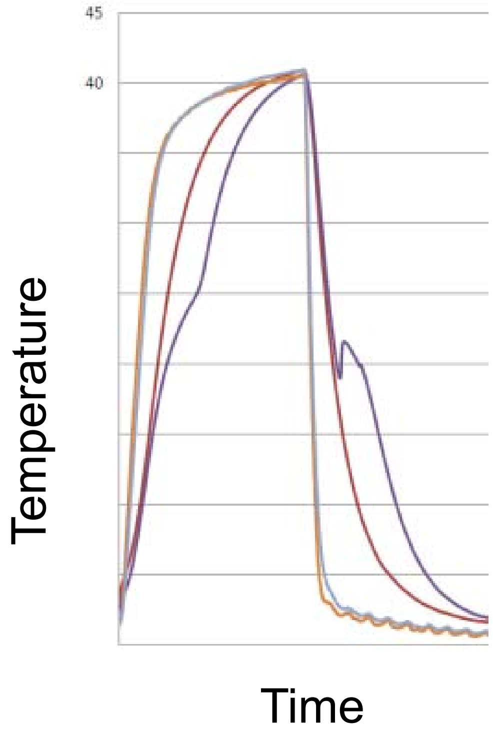
  Cost effective LHTES integration and utilization.

Material- Subcooling and Hysteresis

- Subcooling and hysteresis delay phase change







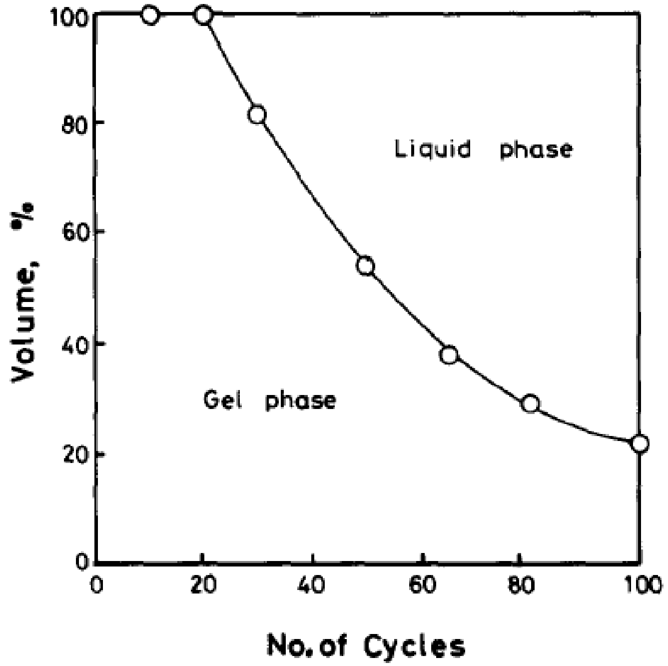
➢ Consequences in charge/discharge.

Source: IWT, Austria, Chiu et al.

Material: Phase Separation

Phase separation lowers the amount of functional PCM.

- Gelling agents: bentonite, starch, cellulose, super absorbent copolymer, carboxymethyl cellulose, and others.
  - 20%~35% latent enthalpy drop.



- Artificial mixing heat storage system
  - Parasitic electricity load

Source: Ryu et al. 1992

Material- Power Rate Enhancement

- Heat exchanger surface extension
  - Fins
  - Encapsulations
  - Metallic structures
  - ➢ 40-70W/m²K

- Thermal conductivity improvement
  - Metallic particles
  - Foams and matrices impregnation
  - ➢ up to 800W/m²K

➢ Impact of power enhancement on energy storage performance

Source: NREL

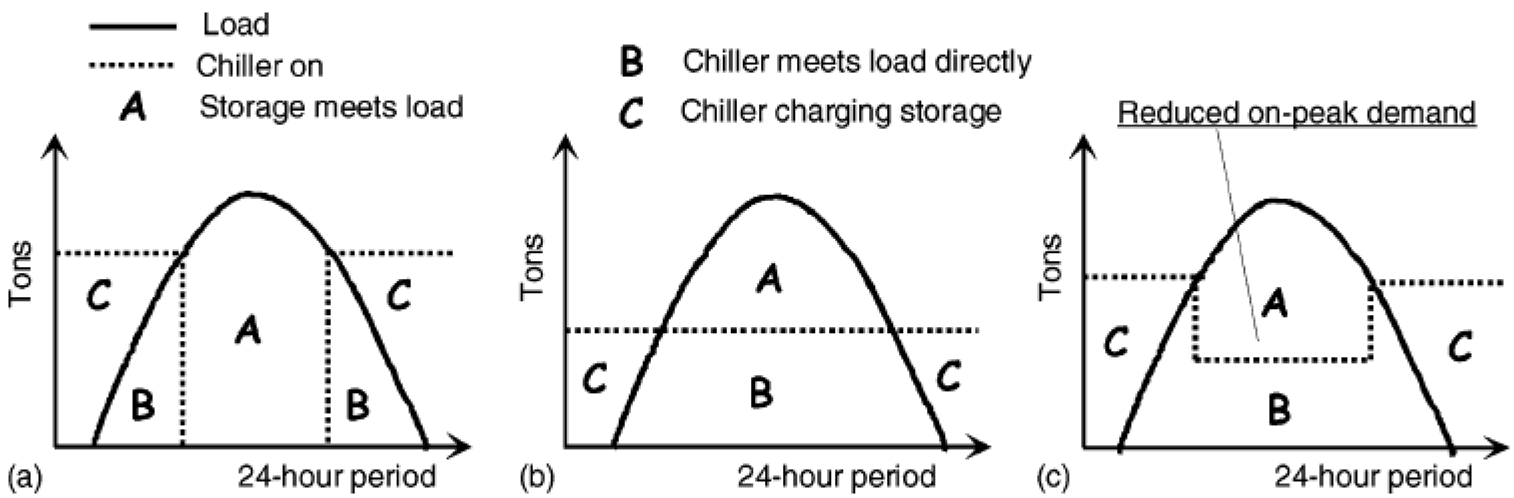
Component Design

- Packing Factor (PF) → storage density
- Heat Exchanger Design
  - → solidification/melting time
  - → power
  - → storage capacity

➢ Storage density is a tradeoff to solidification/melting time and storable/extractable power.

Fin and Tube Spacing (mm)	10	20	30	40	50	60	70	80	90	100	110	120	130	140
PF	59%	78%	86%	90%	93%	94%	95%	96%	96%	97%	97%	98%	98%	98%
Solidification Time (hr)	0.18	0.71	1.6	3.1	4.8	6.4	8.7	11	14	18	21	25	30	35

System- Control Strategy



Operating strategies. (a) full-storage; (b) partial-storage load-leveling and (c) partial-storage demand-limiting.

Source: Dincer et al.

Other Challenges

- Social awareness/ Public acceptance
- Landlord-Tenant/ Supplier-User dilemma
- Involvement of Decision Makers
- Long Standing Demonstration Unit

Future Research Focus

- Material:

More stable and cost effective PCMs

- Component:

Power matching storage units

Robust storage systems

- System:

Concept validation and demonstration

Techno- economic optimization of system integration

- Social and Environmental Study

Further Readings

- Justin Ning-Wei Chiu, Viktoria Martin, and Fredrik Setterwall
“System Integration of Latent Heat Thermal Energy Storage for Comfort Cooling Integrated in District Cooling Network.”, 11th International Conference on Thermal Energy Storage, Effstock, June 14-17 , 2009, Stockholm, Sweden. Link available on course homepage.

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Justin Chiu

justin.chiu@energy.kth.se