Thermochemical energy storage in energy storage mixed system

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Symposium on Thermochemical Energy Storage,
Zwarte Doos, TU/e, Eindhvohen Univ. of Tech., The Netherlands
14:00-14:40, 8th March, 2023

Tokyo Inst. Tech., 東京工業大学

Established in 1881, National Univ., the best Science and Technology Univ. in Japan
Student: Total 10k (Undergraduate: 5k, Graduated: 5k, Foreigner 1.5k, Faculty staff: 1.8k
Department: Science, Engineering, Material Sci., Inter-disciprinary
Laboratories: 4 main Laboratories and 10 Centers Under Institute of Innovative Researches, including Lab. Zero-Carbon Energy.

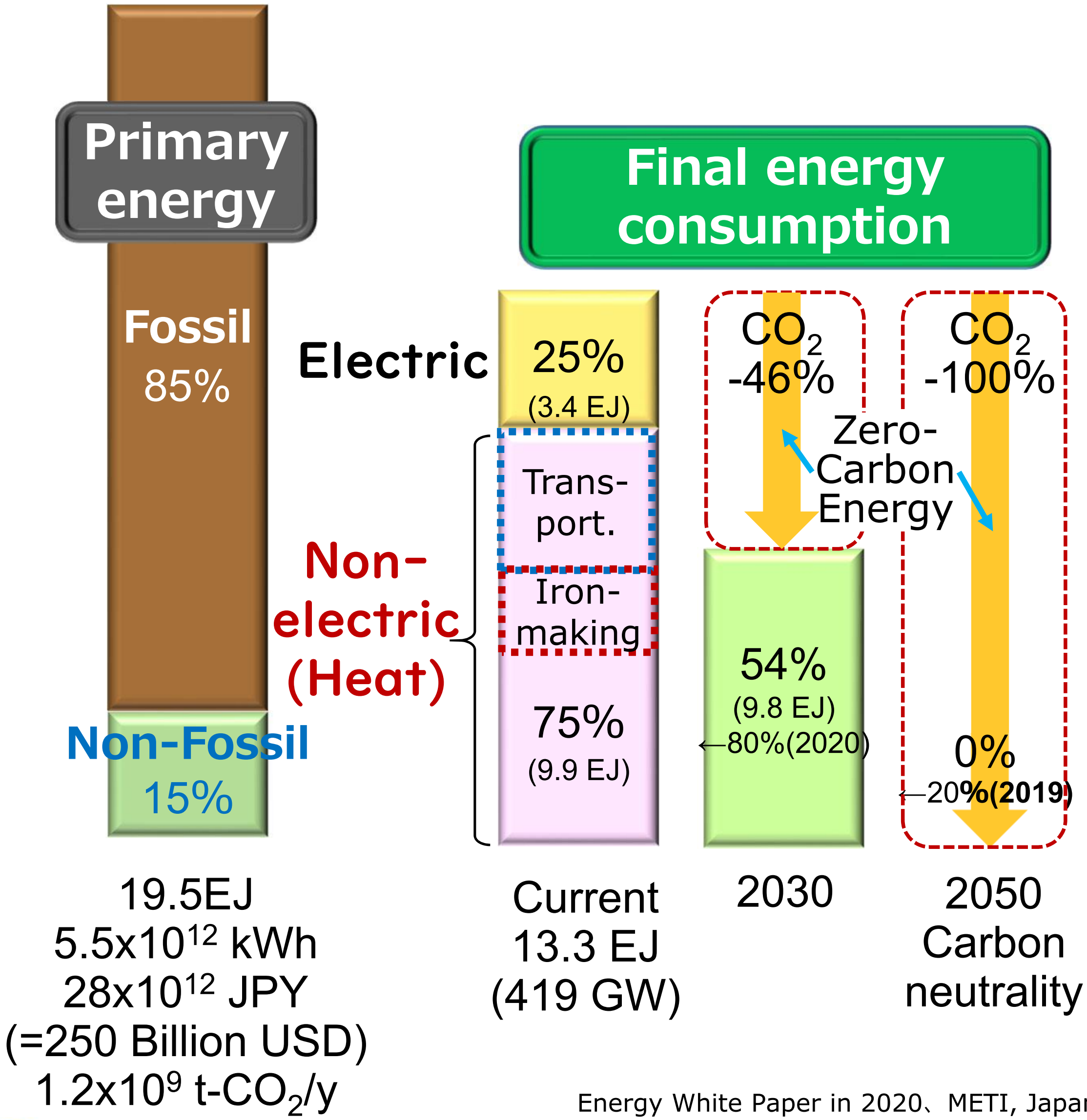
Ex. Tokyo Tech, Asakusa-Kuramae, Tokyo

Ookayama Campus, Tokyo Tech

Green Transformation Initiative, Tokyo Tech GXI

Energy Vision

Road to Carbon Neutrality for Japan



- ✓Heat demand is three times larger than electricity.
- ✓Heat and enthalpy supplies on thermal processes and heat storage are crucial for low-carbon society
- ✓Zero-carbon energy (ZCE) and its secondary energies (H_2, carbon materials)

Fig. Energy balances for carbon neutrality by 2050 in Japan (based on 2018FY)

Energy White Paper in 2020、METI, Japan (2020)
https://www.enecho.meti.go.jp/about/whitepaper/2020html/2-1-1.html

Electricity surplus: Renewable power suppression in Japan

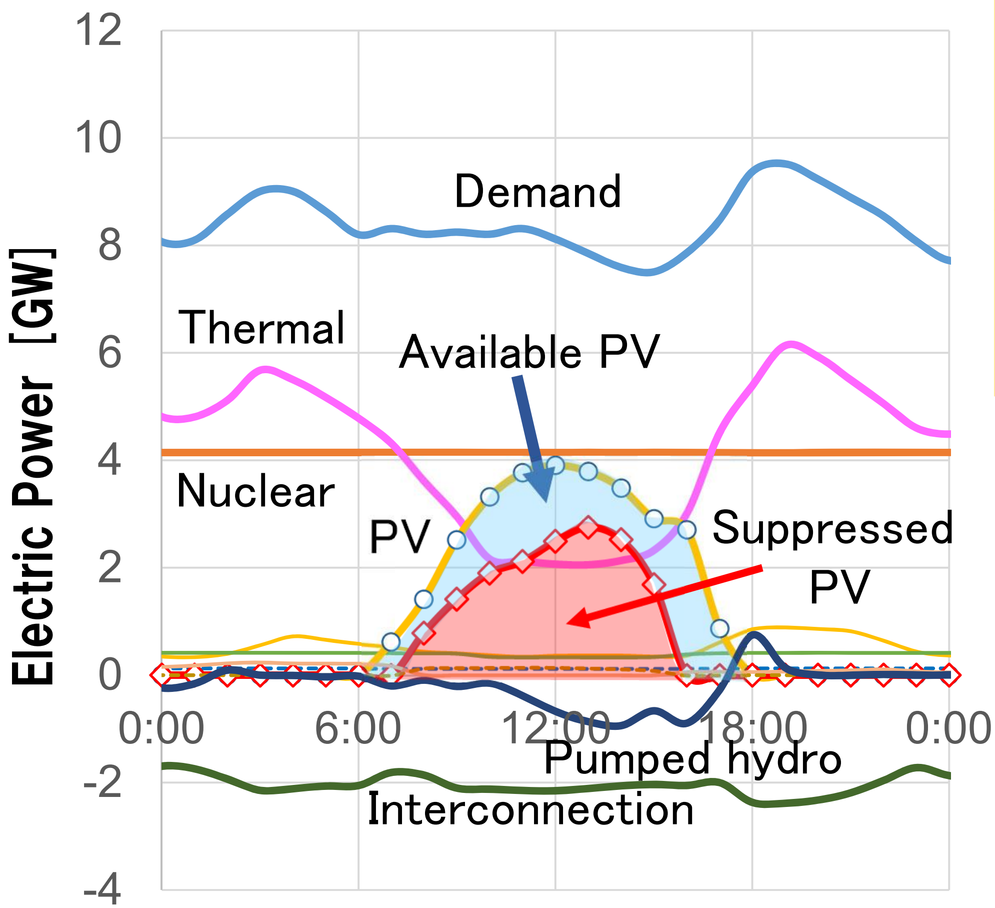


Fig. Power demand /production in a part of Japan, on Sun, 8 March, 2020

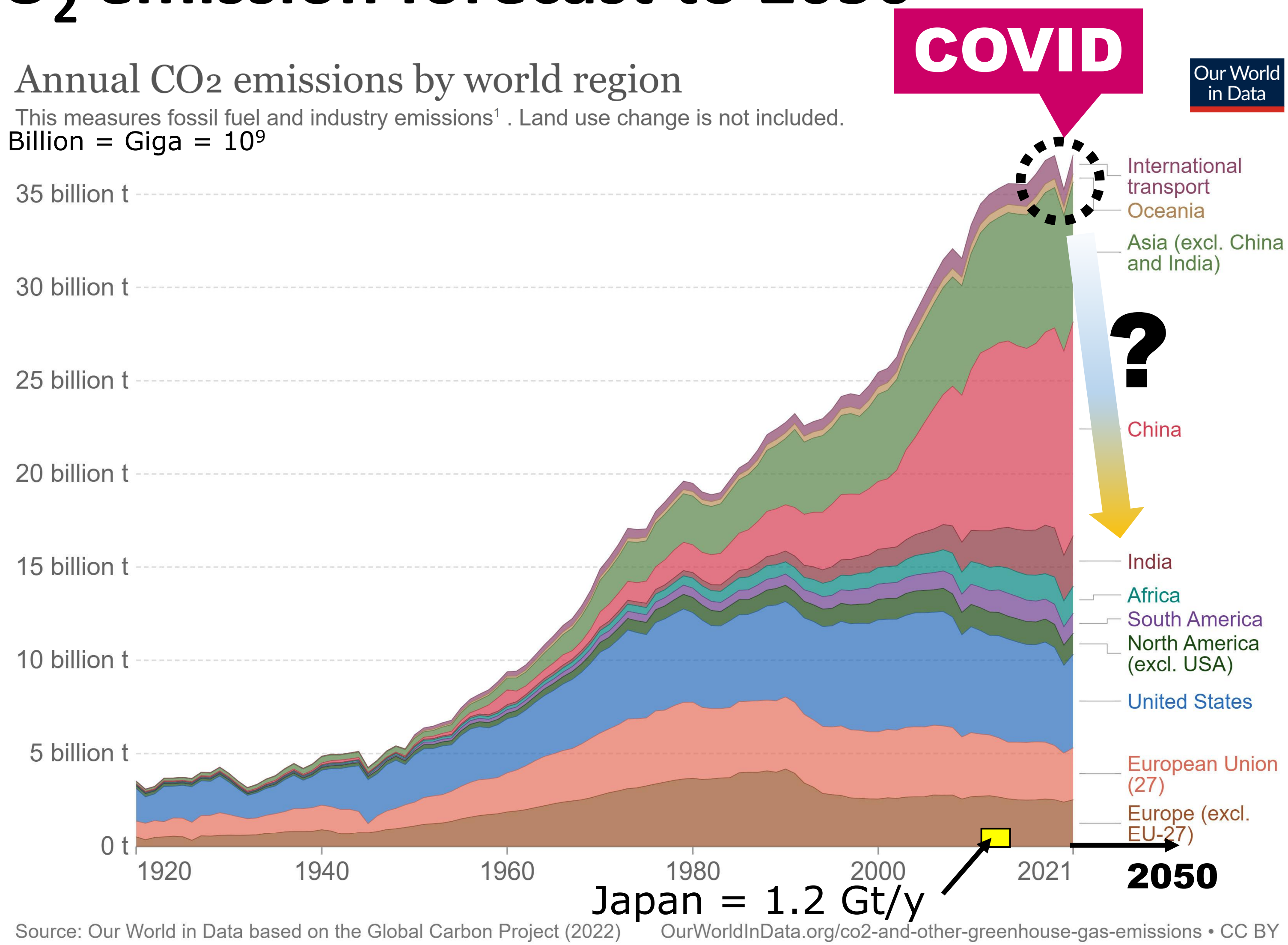
https://www.kyuden.co.jp/var/rev0/0254/3848/area_jyukyu_jisseki_2019_4Q.csv

Norway's electricity consumption
17.8 million people,
109 TWh, 12.4 GWe
Fossil fuel 93%, Renewable 7%
CO_2 Emissions: 8.52 t-CO_2/capita
Japan: 120 Million people, 971 TWh,
111 GWe. Fossil 85%, Renew. 15%,
8.4 t-CO_2/capita(2020)[2]

Kyushu, 14 million people:
3.6 GW solar PV power was suppressed on the day.
→ Soaring renewable energy costs
→ Deterioration of power quality
◆ Stabilization of power grid including renewable energy
◆ Research on low-cost energy storage other than batteries

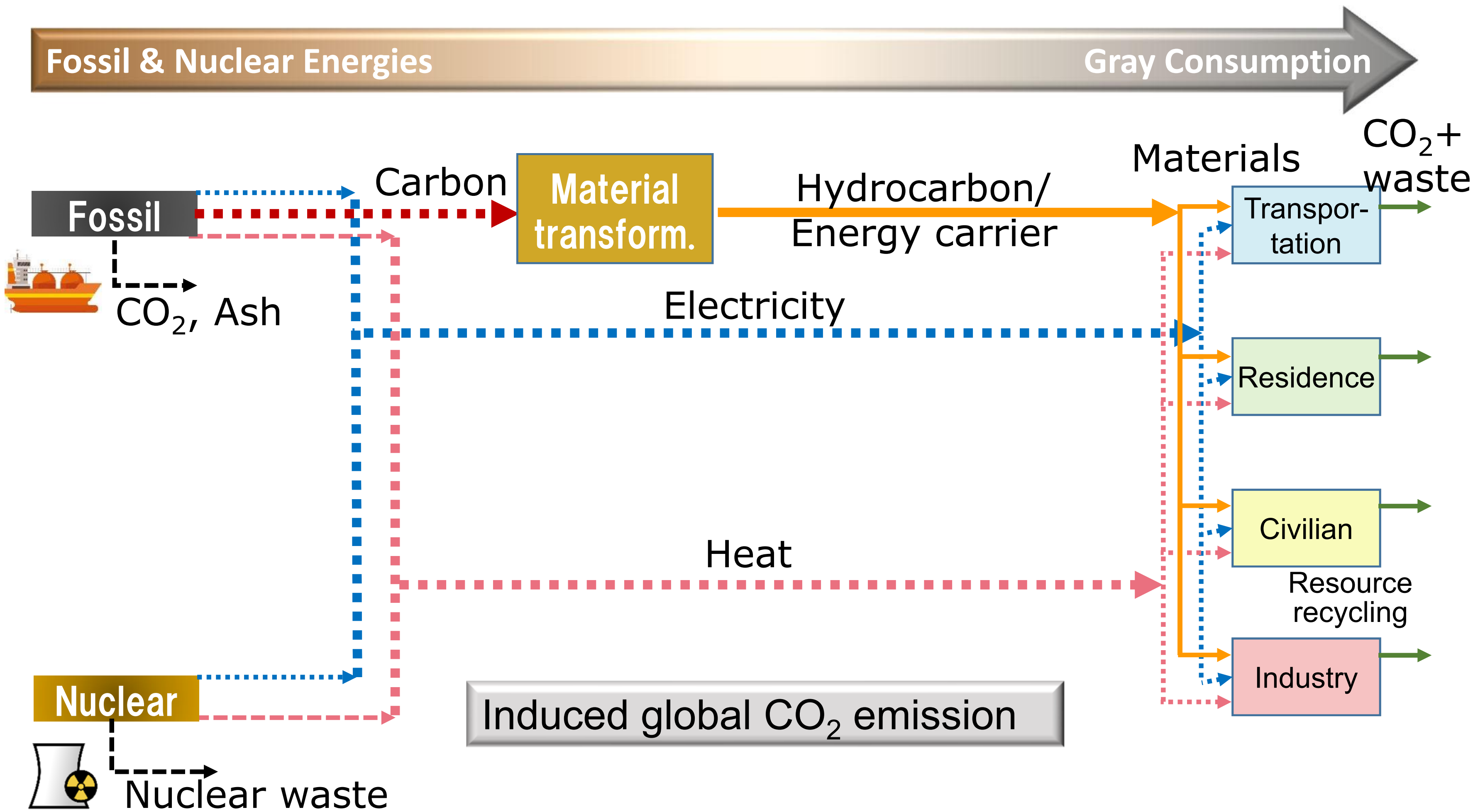
[1] https://www.worlddata.info/asia/singapore/energy-consumption.php
[2] IEA, https://www.iea.org/countries/japan

CO_2 emission forecast to 2050

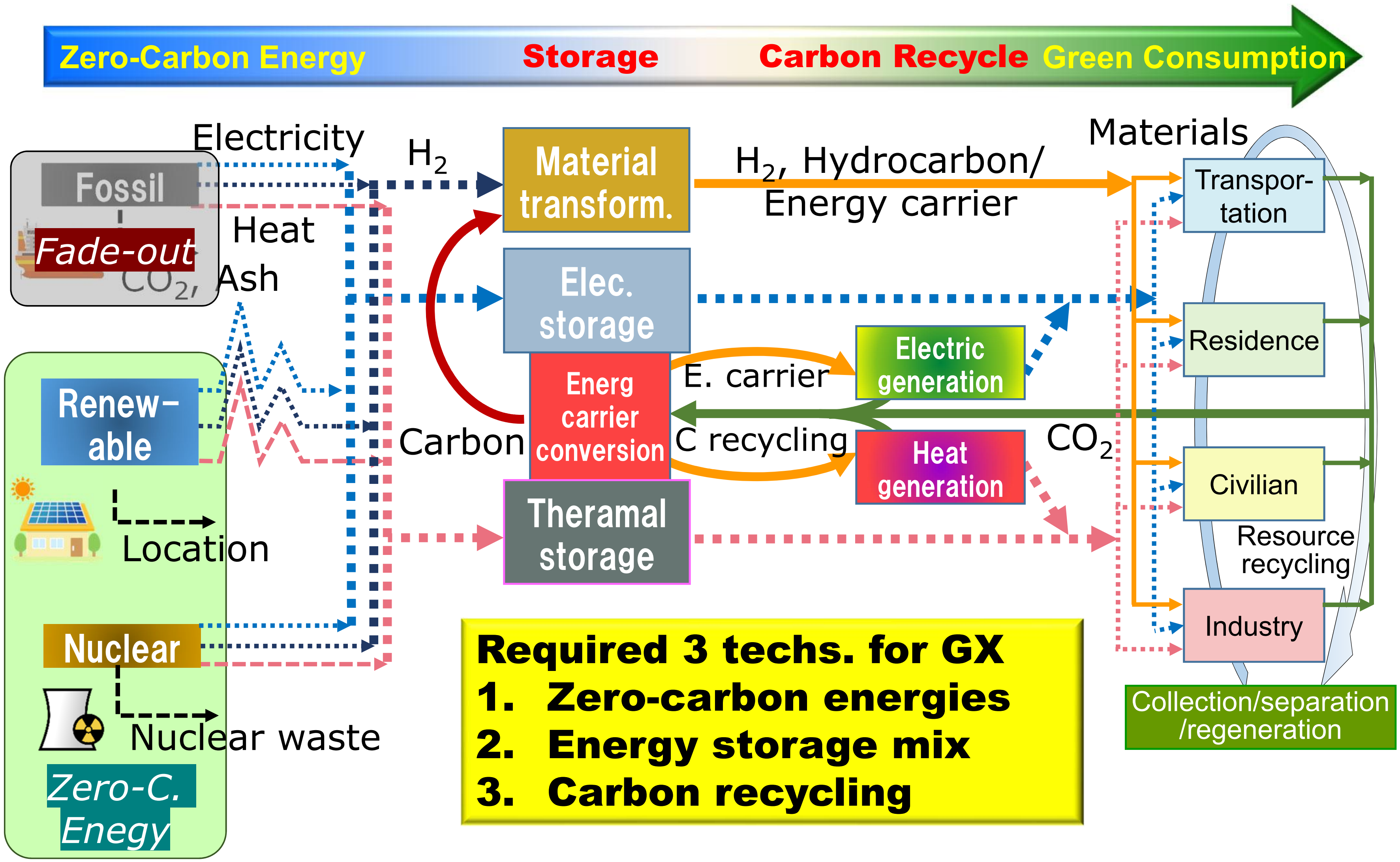


Our World in Data, https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Grey Society System before renewable energy age



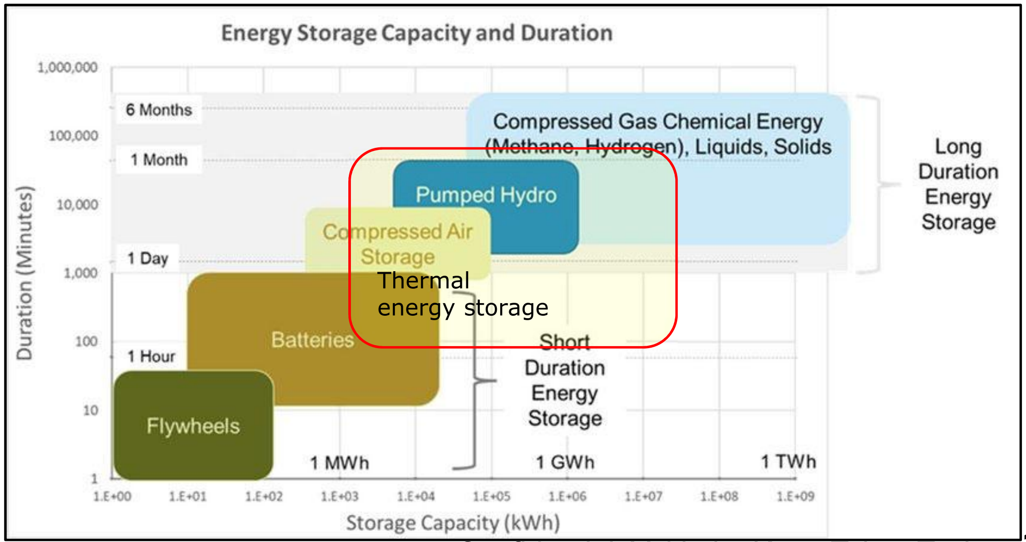
Vision for Green Society



Energy Storage Mix Technologies

Energy storage mix

- Energy storage is required for massive use of variable renewable energy (VRE) in GWh order.
- Energy storage
  - Electric storage: Battery, capacitor
  - Chemical storage: Hydrogen, e-fuel, energy carrier
  - Heat storage: Sensible, latent and thermochemical, heat pump storage
  - Gravity storage: Pumped hydro power
  - Kinetic storage: Compressed air (CAES), fly-wheel
  - Biological: biomass
- Energy storage mix optimization will be required.

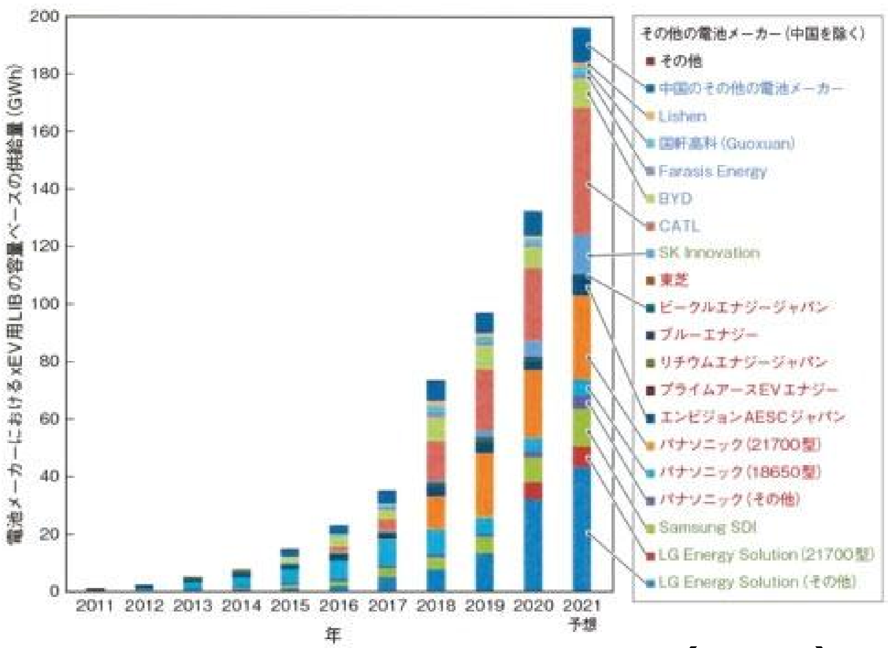


William Liss, Long-Duration Utility-Scale Energy Storage, February 2022
DOI:10.13140/RG.2.2.16786.32968

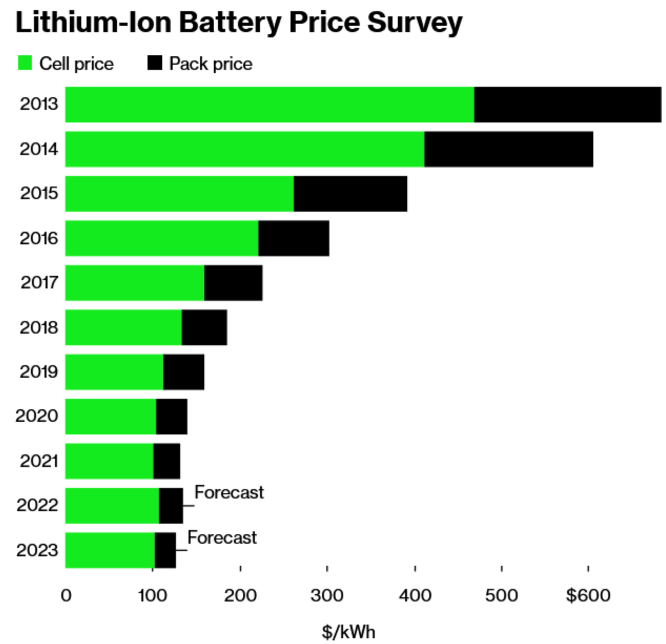
Market development of BEV and LIB

BEV: Battery Electric Vehicle
LIB: Lithium ion battery

Model Y, Tesla, (505 km run, 7 passengers, 50,000 USD)
https://www.tesla.com/ja_jp/modely



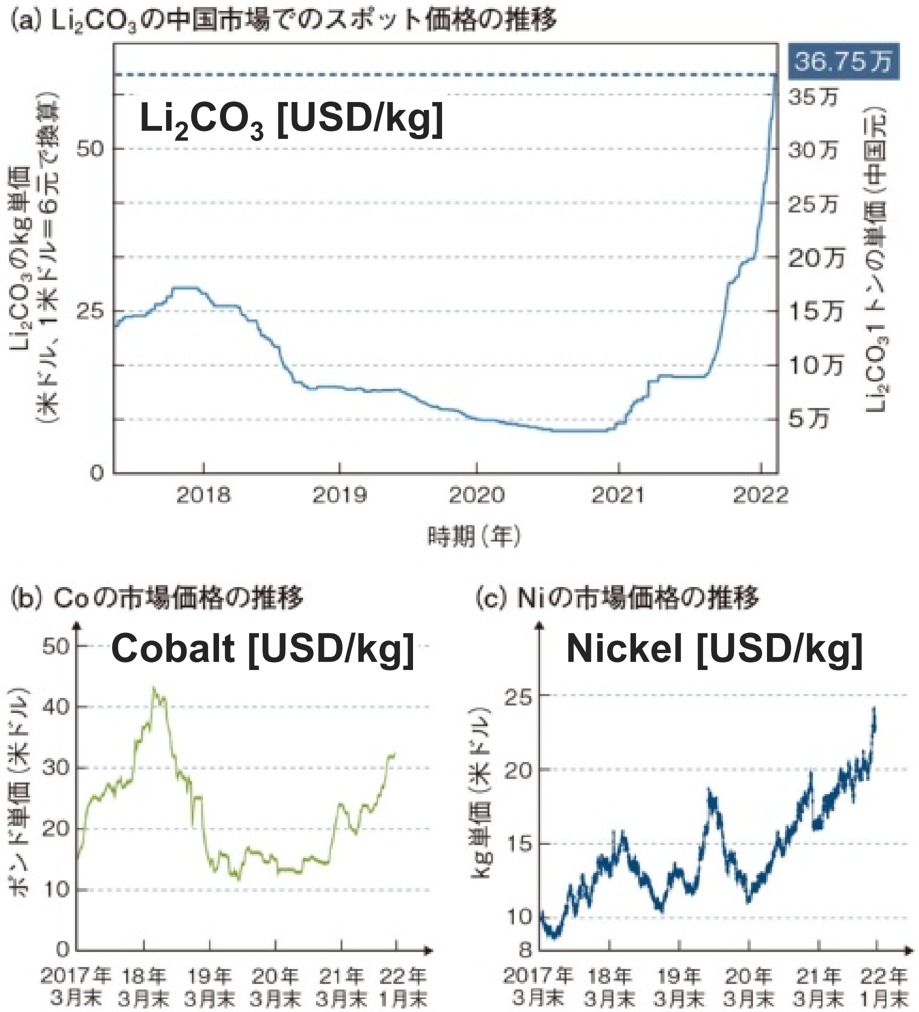
Market of LIB for vehicles（2021）
LG Energy Solution(50GWh), CATL(43 GWh), Panasonic(40 GWh)
Nikkei XTECH, 2022.01.04
https://xtech.nikkei.com/atcl/nxt/column/18/00001/06396/



LIB Price Declines Slow Down in Latest Pricing Survey (2022)

Bloomberg, 2021/11/30
https://www.bloomberg.com/news/articles/2021-11-30/battery-price-declines-slow-down-in-latest-pricing-survey

Runup of LIB materials



- ✓ BEV had risk of resource constraint and rising cost.

Rising cost of LIB material [1]

Lithium carbonate (Li_2CO_3) of 6700 JPY/kg = 50 USD/kg in Feb., 2022, was 9 times of one in 2020.
Ni price is highest in the last 10 years.

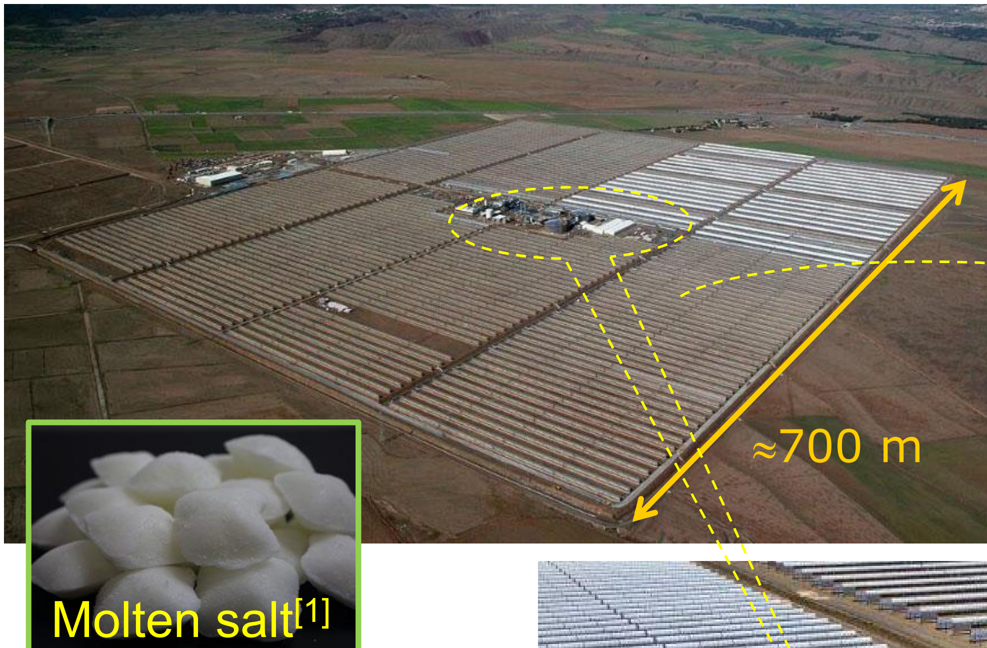
Model 3 of Tesla price increase, 9000 USD in one year[2]

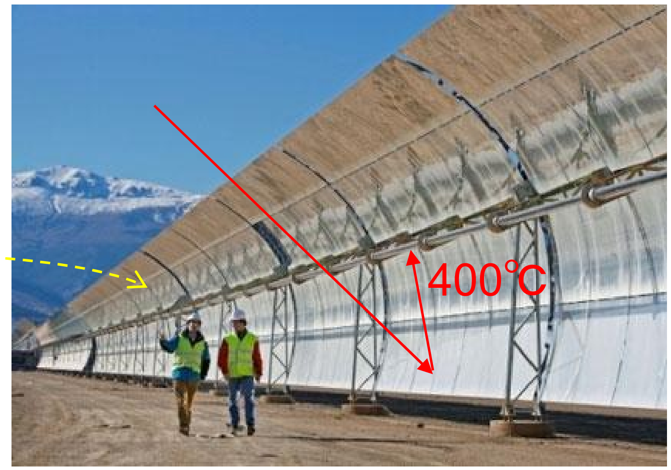
[1] Nikkei X tech, 2022.02.15
https://xtech.nikkei.com/atcl/nxt/column/18/01948/00001/
[2] Nikkei, 2022/04/03,
https://www.nikkei.com/article/DGXZQOGN313YG0R30C22A3000000/

Sensible TES for massive renewable energy storage

Andasol Solar Thermal Power Station, Spain, 150 MWe, Solar Filed 5.1e5 m^2, TES = 400°C, Power conversion efficiency = 16%, 3,000 USD/kWe

https://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=3





http://euro.typepad.jp/blog/images/2010/01/09/andasol_1.jpg

KNO_3-$NaNO_3$

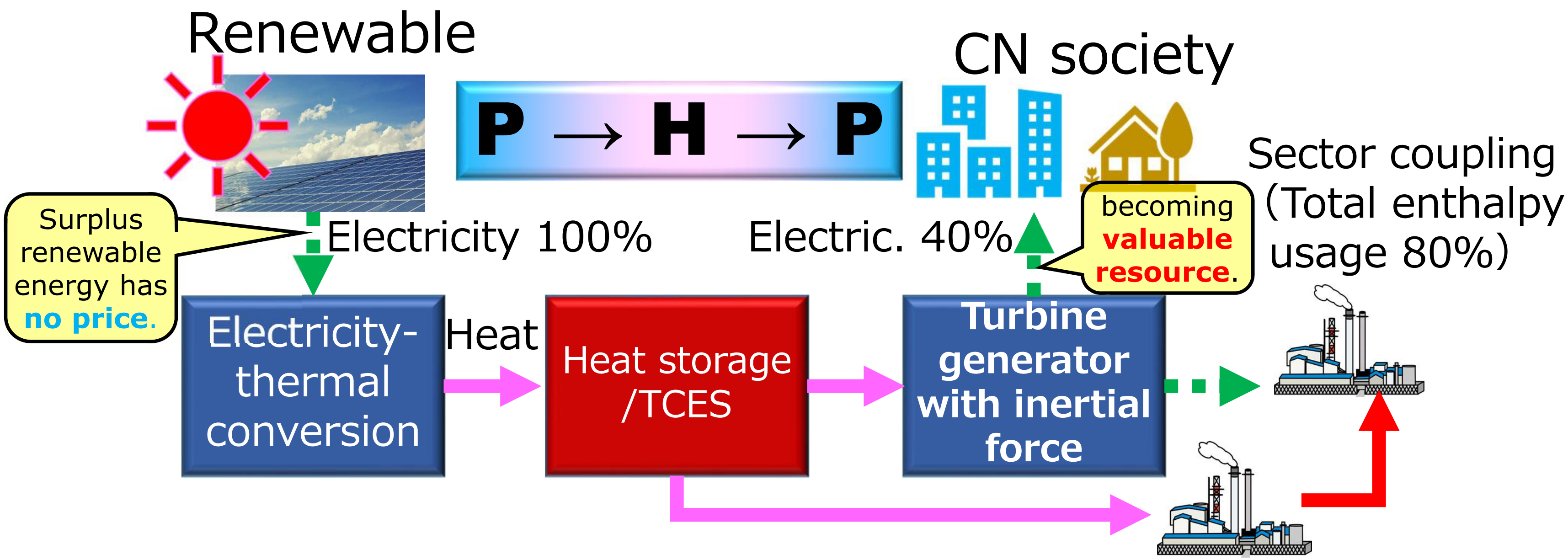
[1] Neo-SK, Soken, https://www.soken-tx.com/heating_medium/

[2] https://upload.wikimedia.org/wikipedia/commons/thumb/e/e5/12-05-08_AS1.JPG/1200px-12-05-08_AS1.JPG

http://d2r42o2f7hk334.cloudfront.net/wp-content/uploads/2011/10/andasol-3.jpg

Process vision of P2H2P

P2H2P: Power to Heat to Power



1. Lower cost than electric battery system. Ease scaling-up for larger capacity system, and building-up sector coupling systems.
2. Because it owns turbine generator with inertial force, the stable electricity supply with high-quality is available.

Thermochemical Energy Storage

Heat storage densities

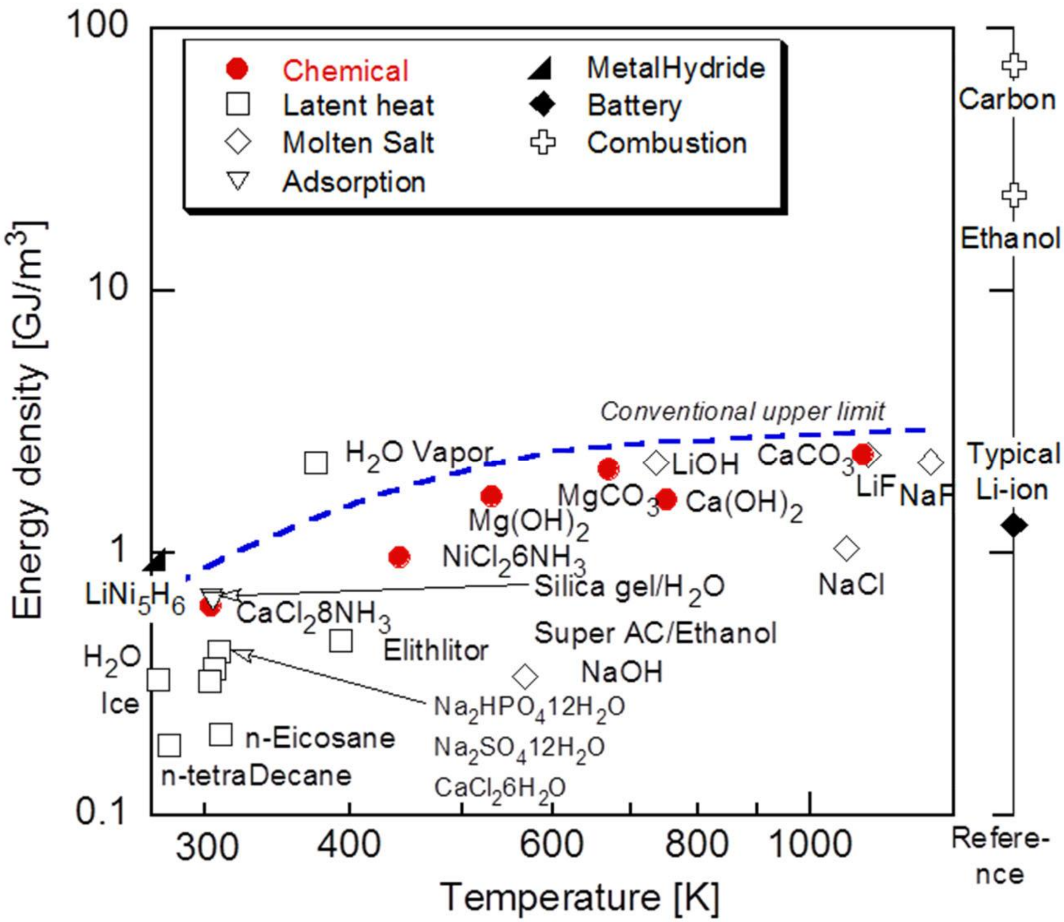


Fig. Heat storage/output temperature and energy densities for energy storage materials[1].

Order of heat storage density

1. Thermochemical (≅ Battery)
2. Latent heat
3. Sensible heat

[1] Kato, Energy Technology Roadmaps of Japan, 2016, Springer

Thermochemical energy storage (TCES)

$$A\,(s) + B\,(g) \underset{\text{Endothermic (Heat storage)}}{\overset{\text{Exothermic (Heat output)}}{\rightleftarrows}} AB\,(s) \qquad \Delta H_r < 0 \qquad (1)$$

- ✓ One of the thermal energy storage technologies
- ✓ Advantages
  - Higher energy storage density
  - No energy loss for long storage
  - Constant output temperature
  - Chemical heat pump (CHP) system can be composed.
- ✓ Operation temperature depends on reaction system.
- ✓ Thermal conductivity enhancement is required for practical usage.

Thermochemical energy storage (TCES)

Calcium oxide/water (CaO/H_2O) reaction system[1]

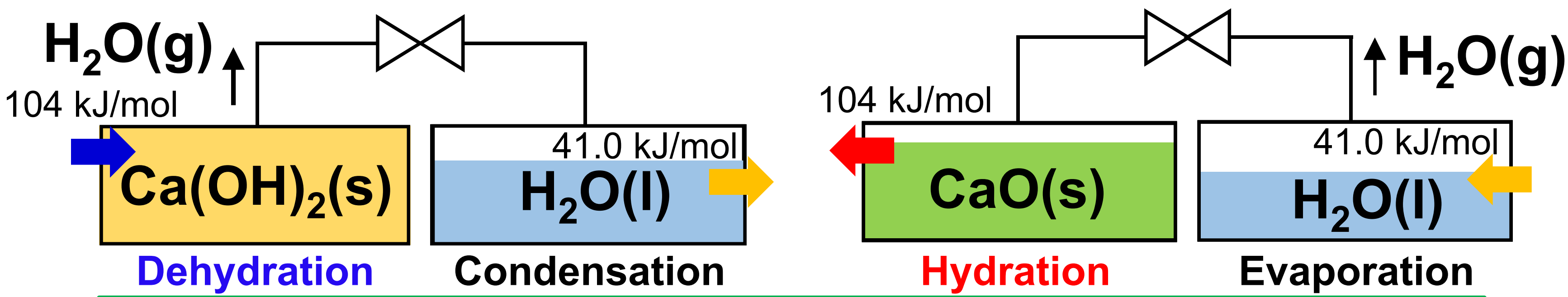
Dehydration (Endothermic reaction)

$$Ca(OH)_2(s) \rightleftarrows CaO(s) + H_2O(g),\ \Delta H^\circ = 104\ \mathrm{kJ\ mol^{-1}}$$ [2]

Hydration (Exothermic reaction)

$$H_2O(l) \rightleftharpoons H_2O(g),\ \Delta H^\circ = 41.0\ \mathrm{kJ\ mol^{-1}}$$

Thermal charging | **Thermal discharging**



1. High thermal charging/discharging temperature: **~400–600 °C**
2. High energy density: **0.5–1.8 MJ L-$Ca(OH)_2^{-1}$** [3,4]
3. Low costs, high reactivity, non-toxicity

[1] Ervin, G., J. Solid State Chem, 22, 1977, 51-61, [2] Halstead PE and Moore AE, J Chem Soc 1957, 3873–5, [3] Ogura, H *et al*., Kagaku Kogaku Ronbunshu, 17, 1991, 916-923, [4] Schmidt, M. *et al*., Appl Energy, 188, 2017, 672–81.

TCES Material

CaO nature

$CaO + H_2O \rightarrow Ca(OH)_2$, $\Delta H° = -104$ kJ/mol

Fig. Overflow of $Ca(OH)_2$ material from bed trays after reactions by material expansion.

CaO hydration causes material expansion. The expansion decreases bed thermal conductivity, vapor diffusivity and thermal performance.

菊地ら、J. Japan Soc. Energy and Resources, 40(4), 111-118 (2019).

Problems in pure $CaO/Ca(OH)_2$ powder

Practical TCES reactors require:

High energy density and power (High TCES performance)

High durability

Problems

Pure $Ca(OH)_2$ powder

Low thermal conductivity [1-3]
0.1~0.4 (loose~compressed) $W\ m^{-1}\ K^{-1}$

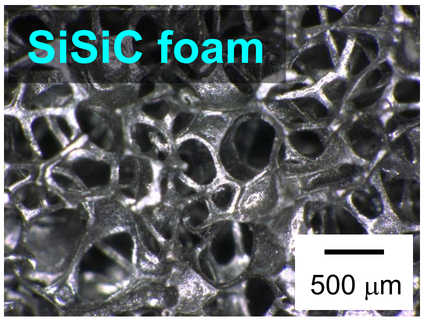
Bulk volume change [4-6]

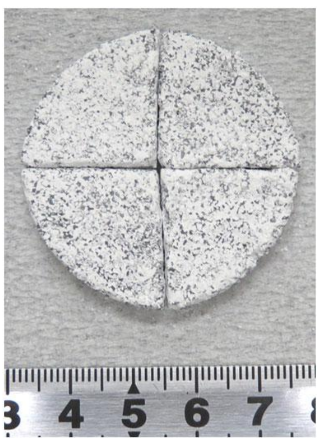
Formation of centimeter-scale agglomerates [7-9]

[1] A. Kanzawa and Y. Arai, Sol. Energy. 27 (1981) 289–294. [2] H. Ogura *et al.*, Kagaku Kogaku Ronbunshu. 17 (1991) 916–923. [3] F. Schaube *et al.*, J. Sol. Energy Eng. 133 (2011) 031006. [4] M. Schmidt and M. Linder, Appl. Energy. 203 (2017) 594–607. [5] C. Roßkopf *et al.*, Energy Convers. Manag. 97 (2015) 94–102. [6] F. Watanabe *et al.*, Kagaku Kogaku Ronbunshu. 39 (2013) 378–383. [7] C. Roßkopf *et al.*, Energy Convers. Manag. 86 (2014) 93–98. [8] J. Yan and C.Y. Zhao, Appl. Energy. 175 (2016) 277–284. [9] L. Dai *et al.*, Appl. Therm. Eng. 133 (2018) 261–268.

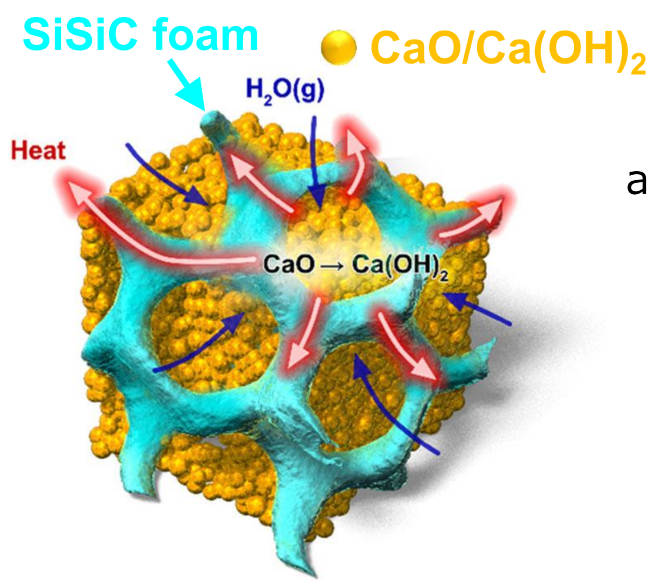
SiSiC/CaO composite

1. silicon carbide (SiSiC) foam and honeycomb with CaO
2. High thermal conductivity, high repeated durability of materials, high reactivity, high output.
3. Suppresses volumetric expansion and agglomerate formation in SiSiC





Composite [1]



Ca(OH)$_2$+SiSiC foam composite[2]

[1] Funayama, Kato, *et al*., *Energy Storage*,1, e53 (2019).
[2] Funayama, Kato, *et al., Appl. Therm. Eng.*, 220 (2023), 119675.

Fig. Packed bed reactor apparatus for TCES composite[1]

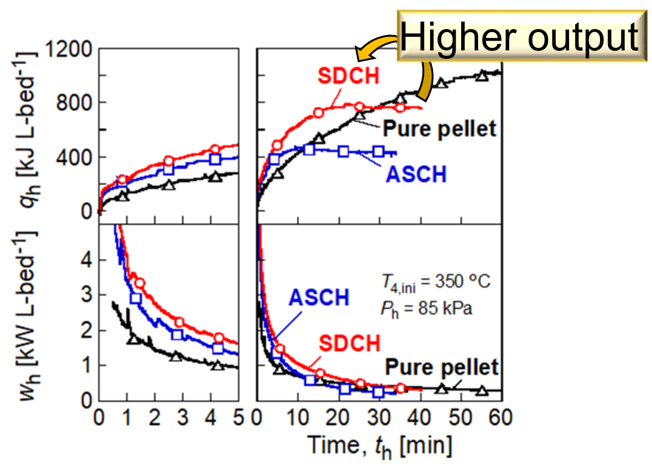


Fig. Thermal output rate of the composite and pure CaO pellets[1]

Initial and boundary conditions

Initial conditions

$T_{\mathrm{ini}} = 350\ °\mathrm{C}$ over Ω

$\boldsymbol{u}_{\mathrm{ini}} = \mathbf{0}\ \mathrm{m\ s^{-1}}$ over Ω

$P_{\mathrm{ini}} = 0\ \mathrm{kPa}$ over Ω

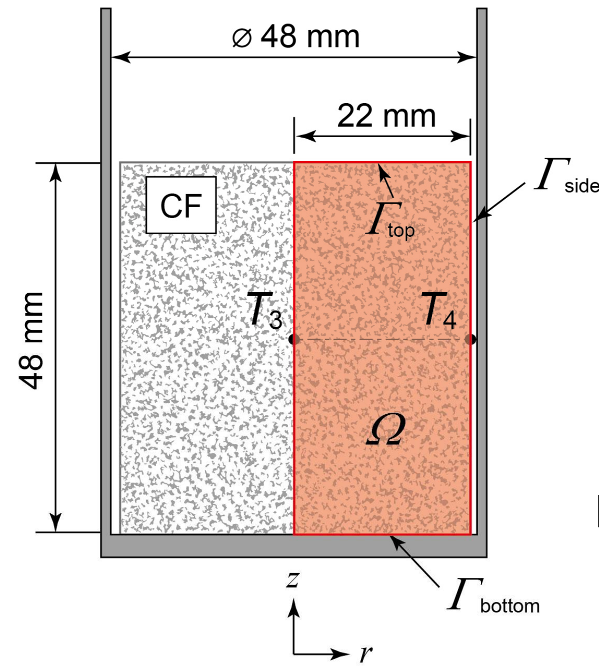


Fig. 1 Computational domain Ω (2D)

Foam composite (ASCH)

Boundary conditions

$r = 0$ mm : Symmetry

$\Gamma_{\mathrm{top}}\ (0 < r < a,\ z = 48\ \mathrm{mm}):\ T = 350\ °\mathrm{C},\ P = 58\ \mathrm{kPa}$

$\Gamma_{\mathrm{side}}\ (r = a,\ 0 < z < 48\ \mathrm{mm}):\ T = 350\ °\mathrm{C},\ \boldsymbol{u} = \mathbf{0}\ \mathrm{m\ s^{-1}}$

$\Gamma_{\mathrm{bottom}}\ (0 < r < a,\ z = 0\ \mathrm{mm}):\ T = 350\ °\mathrm{C},\ \boldsymbol{u} = \mathbf{0}\ \mathrm{m\ s^{-1}}$

[1] Funayama *et al.*, 58th Japan Heat Transfer Symposium, D134, 25 (25-27) May, 2021

Numerical results of the hydration of CaO

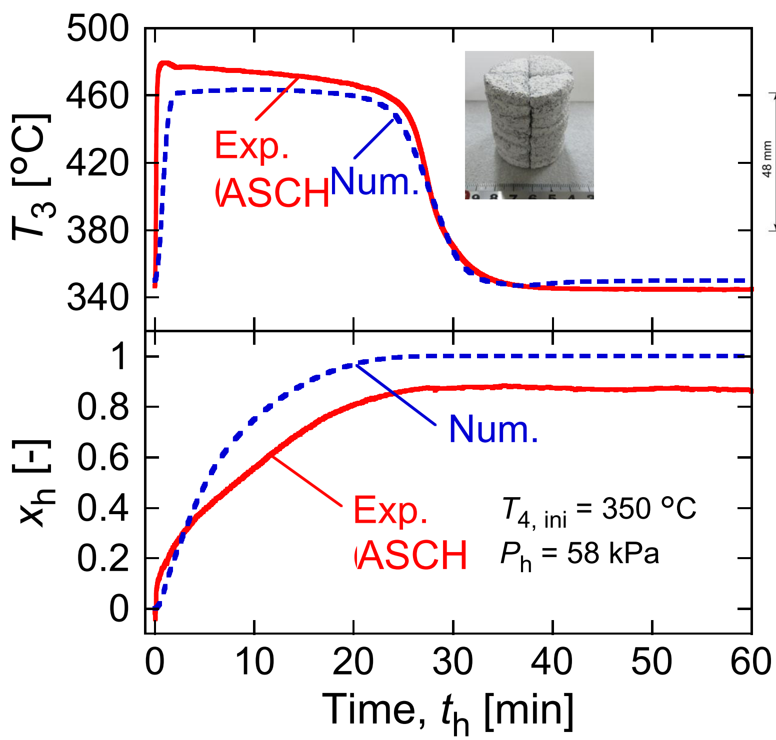


Fig. 1 The center temperature and conversion of a foam composite.

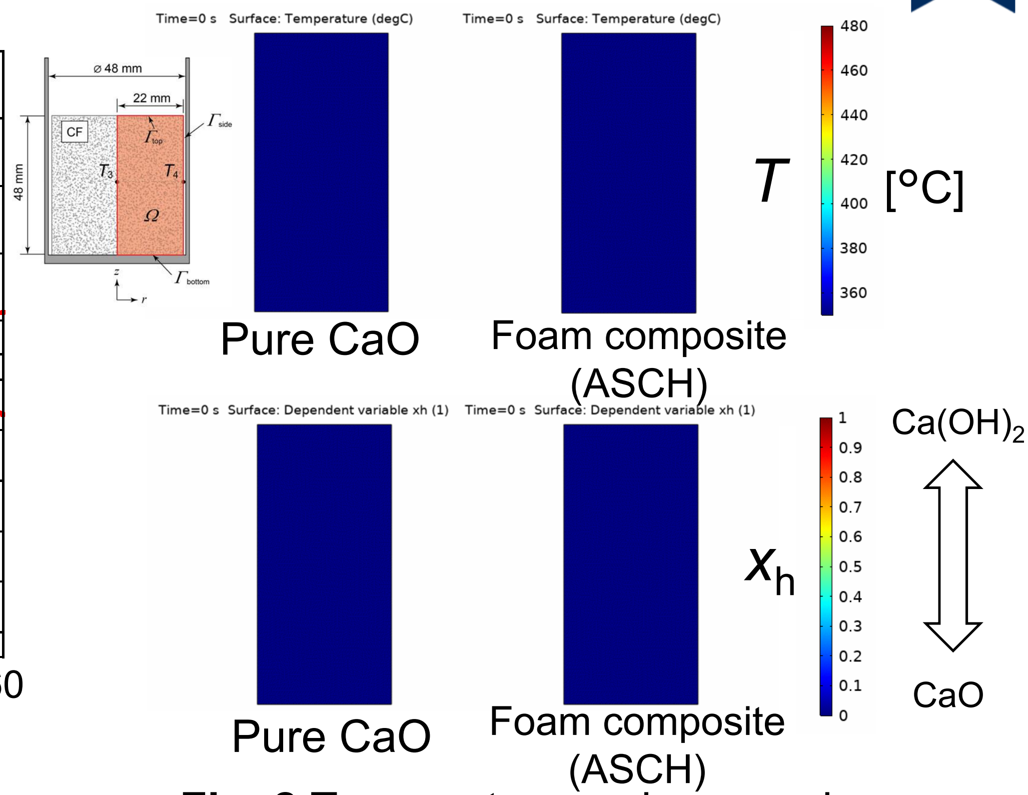


Fig. 2 Temperature and conversion distribution.

1. The center temperature and conversion were reproduced using the numerical model to a certain extent
2. The reaction front of the composite progresses more rapidly towards the center of the bed

[1] S. Funayama, Y. Kato, et al., *Energy Storage*, 1(2019), e53
[2] Funayama *et al.*, 58th Japan Heat Transfer Symposium, D134, 25 (25-27) May, 2021

TCES System

Chemical heat pump function

- ✓ Mechanical heat pump needs electric work. Chemical heat pump is driven thermally by heat(CHP) with higher-efficiency and mechanical robustness, and silent.
- ✓ CaO/H_2O CHP can upgrade a heat from 500°C to 600°C (ΔT = 100°C).

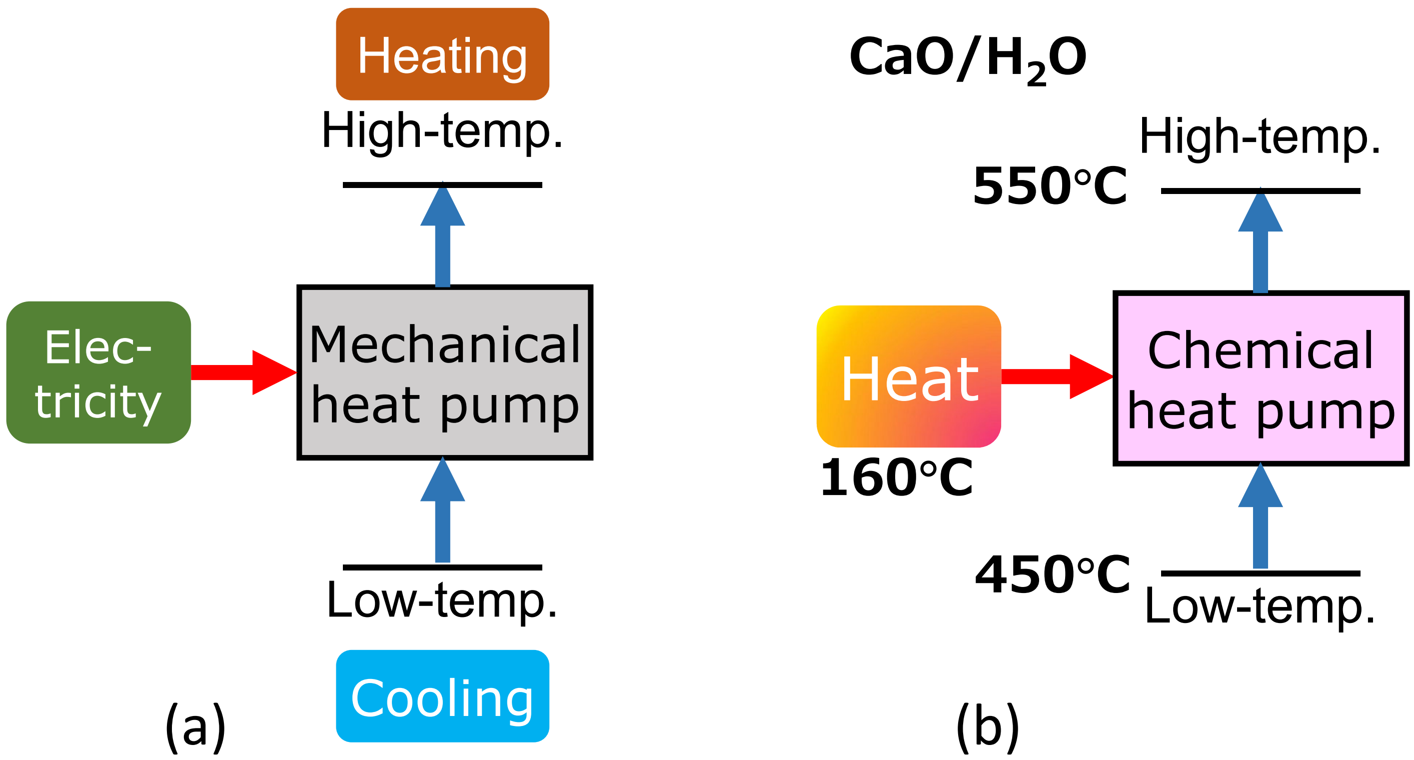
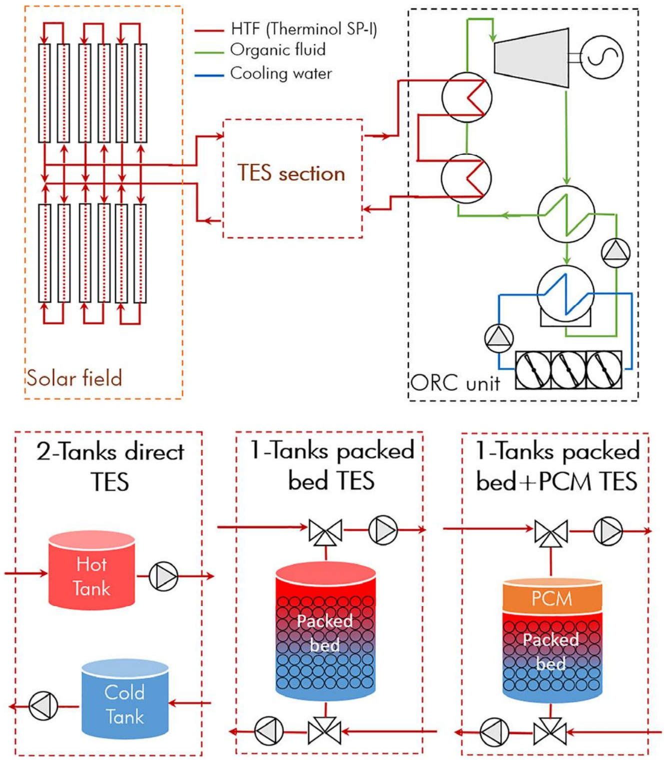


Fig. (a)Mechanical heat pump, (b) chemical heat pump

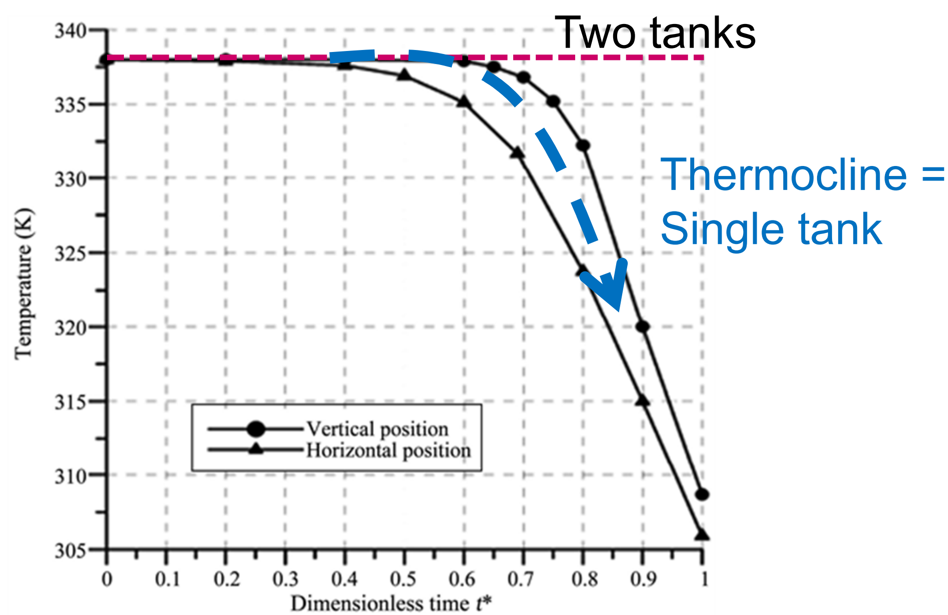
Thermocline from Two-tanks

Thermocline tank is more compact than two-tanks storage, however, tends to reduce output temperature gradually.



Two tanks

Thermocline (Single tank)



Boubou, Energy and Power Engineering, 13(10), 2021

Hybrid thermal energy storage system

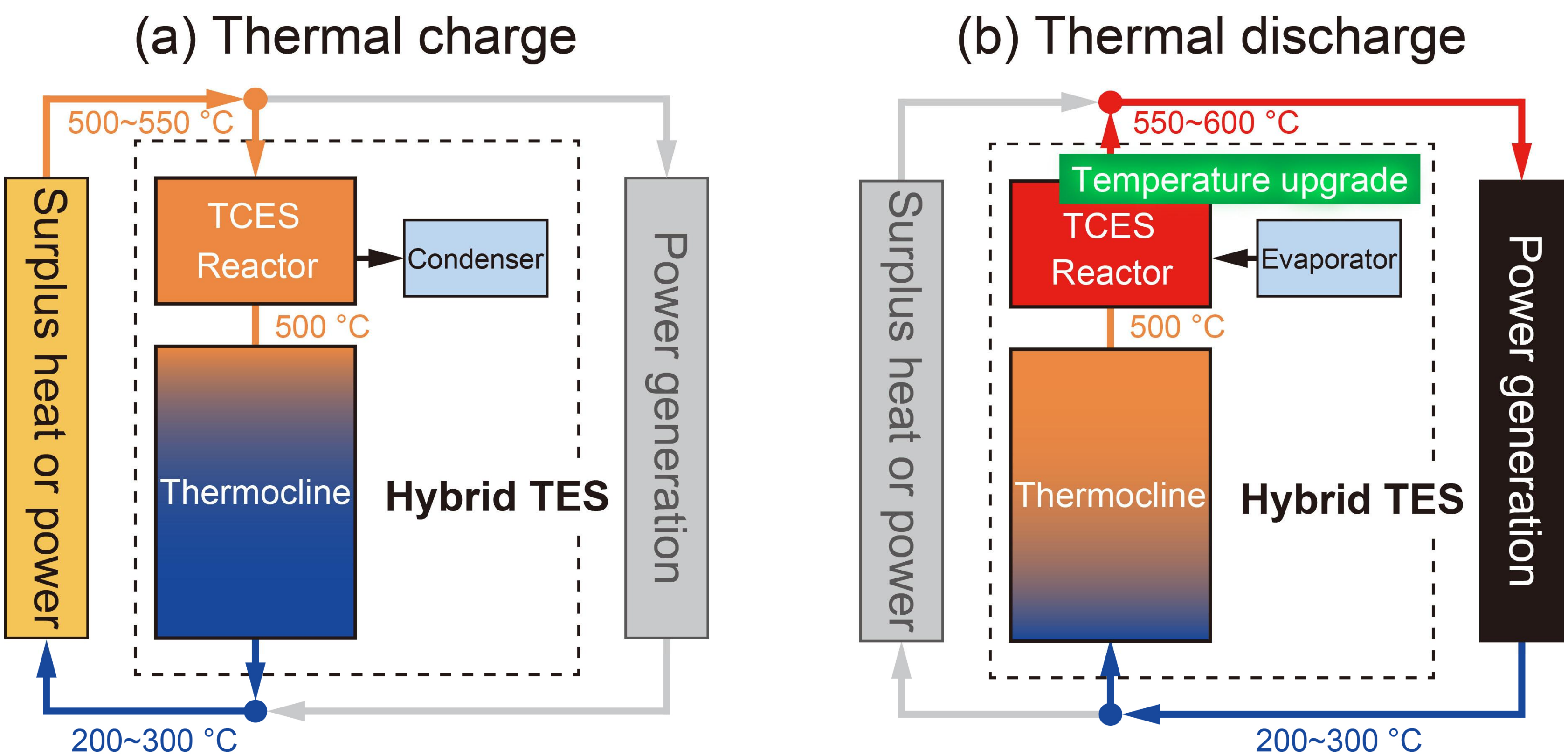


Fig. Hybrid thermal energy storage system: (a) thermal charge; (b) thermal discharge.

- ✓ Thermocline sensible storage and TCES were combined
- ✓ Hybrid system has stable and flexible thermal discharge performance

Experimental setup

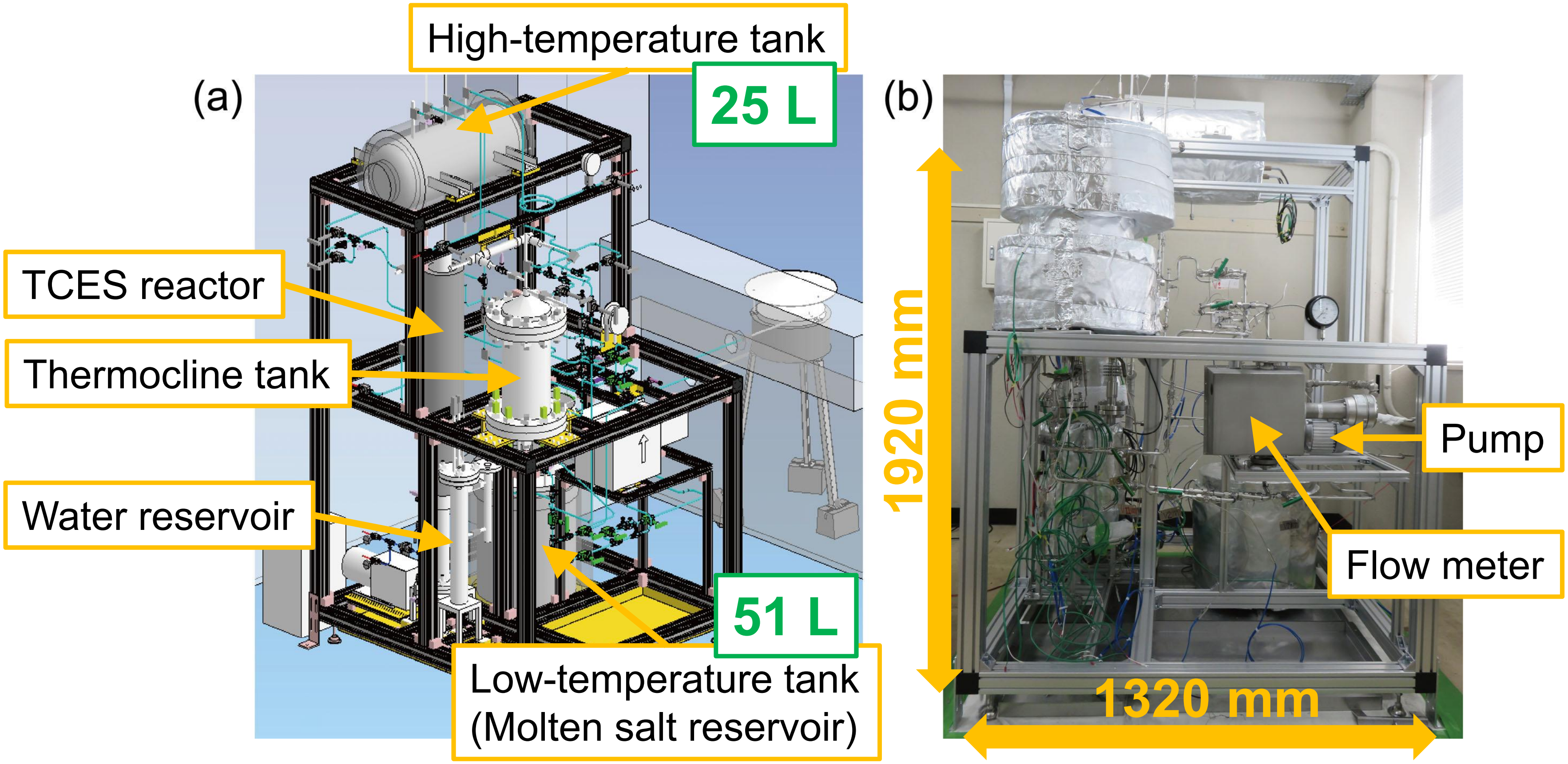


Fig. Experimental setup: (a) 3D layout; (b) photograph.

- ✓ The low-temperature tank: 51 L, high-temperature tank: 25 L
- ✓ The width of the setup: 1.3 m; height: 1.9 m

Energy Storage for massive storage

Table Energy storage techs. for massive renewable energy storage
◎: Very good, ○: good, △: modest, ↓: negative

Storage tech.	Battery	TES	Hydrogen
Storage	Charge	Electricity to Heat	Water electrolysis
Stored media	Batter	TES material	Compressed/Liq. H_2
Power generation	Discharge	Steam turbine	H_2 turbine
Round-trip efficiency	◎ (90%)	△ (40%)	↓(<40%)
Cost	○	◎	△
Inertia force	↓	◎	↓
Storage Safety	△	◎	↓
Scale up	○	◎	△
Domestic produce ability	↓ overseas dependence	◎	◎

✓ TES has advantage at cost, inertia force, safety for massive energy storage

Summary

1. Thermal energy storage (TES) is needed for energy storage mix for massive energy storage
2. Thermochemical TES has potential of higher energy storage density, chemical heat pump ability and relative lower cost than a battery.
3. Composite material is expected to be had higher kinetic and thermal performances.
4. The hybrid thermal energy storage system with sensible TES and TCES exhibited adjustable discharge performances, and it can be used for load-following operations.

Open Innovation in Tokyo Tech GXI

Tokyo Tech
Green Transformation Initiative

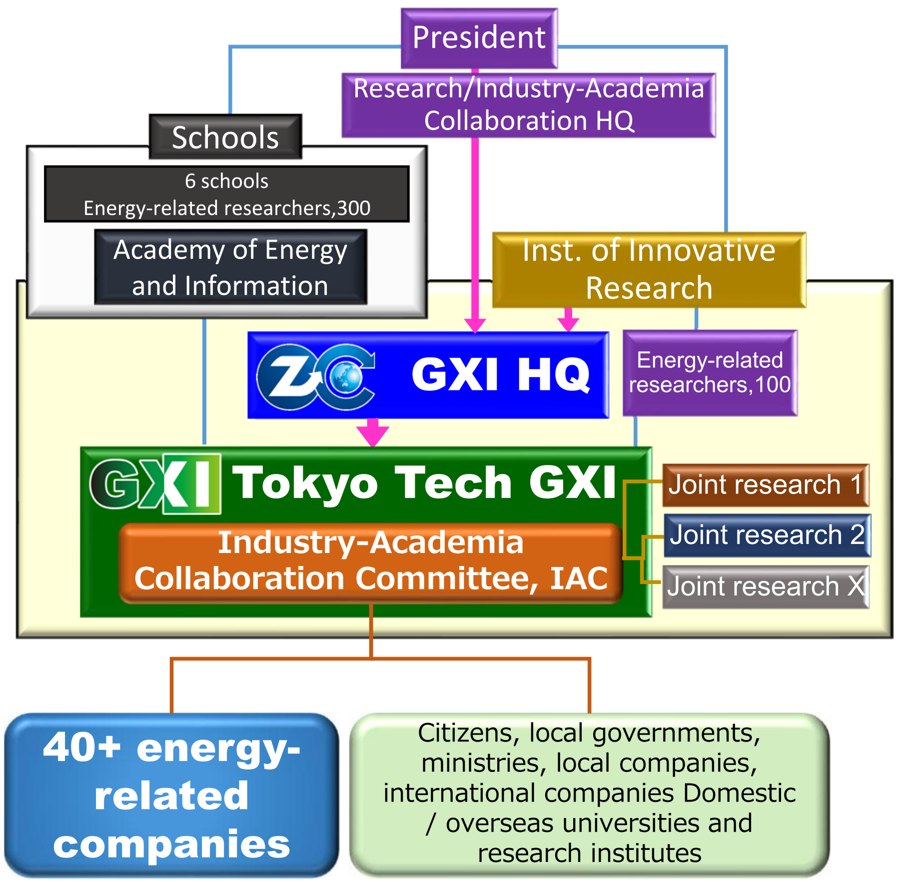
http://www.zc.iir.titech.ac.jp/en/GXI/

Green Transformation Initiative (Tokyo Tech GXI)

Mission-Acceleration Fund in 2022 by MEXT, Ministry of Education, Science, and Technology, Japan

For the realization of Carbon Neutral (CN), green transformation (GX, change of industrial and social structure according to CN conversion) is indispensable. Tokyo Tech GXI promotes GX research for the GX society establishment through industrial and social collaboration.

Green Transformation in Tokyo Tech



GXI open-innovation network

- Laboratory for Zero-Carbon Energy, Institute of Innovative Research, Tokyo Institute of Technology, is established in 2021.
- Head quarter of Tokyo Tech GXI

Green Transformation Initiative (Tokyo Tech GXI)

- GXI is a collaboration platform between 40 energy-related companies and 400 energy research-related faculty members of Tokyo Tech.
- The industry-academia collaboration committee, IAC, will be organized to promote and accelerate CN for problem-solving through open innovation.

Participan companies to Tokyo Tech GXI

Tokyo Tech

- IHI Realize your dreams
- AsahiKASEI
- 安藤ハザマ
- NTTファシリティーズ
- ENEOS
- 大阪ガス
- 大林組 OBAYASHI
- 100年をつくる会社 鹿島
- Kawasaki
- KANKEN
- つぎの「うれしい!」へ。 KeiYO GAS
- KOBELCO
- KOMATSU
- 西部ガス
- sala サーラエナジー株式会社
- 三機工業
- JFE
- SHIZGAS 静岡ガスグループ
- SHIMIZU CORPORATION 清水建設
- DAIKIN
- TAISEI
- 想いをかたちに 未来へつなぐ TAKENAKA
- TECHNOVA
- TESS テスホールディングス
- 「建てる」を超え、未来を生みだす。 東急建設
- エネルギー・フロンティア TOKYO GAS
- 誰もできない、に挑む。 TGES
- TEPCO 東京電力エナジーパートナー
- TOSHIBA
- TMEIC We drive industry
- TOHO GAS
- TODA
- NIKKEN EXPERIENCE, INTEGRATED
- JES 日本環境技研 Japan Environment Systems
- NIHON SEKKEI
- KITAGAS
- MAEDA 前田建設
- MIURA
- 三井不動産 MITSUI FUDOSAN
- 三菱マテリアル
- YANMAR

※ Japanese alphabet order
In November, 2022

Observer: EPRI, Electric Power Research Inst., USA, …

Tokyo Tech GXI Actions

1. Open Innovation for GX with industry, government, local region, academia
2. Joint research projects with industry and Tokyo Tech faculties
3. Joint collaboration projects in the subjects of,
   - Carbon neutrality
   - Energy storage & Energy carrier
   - Nuclear system
   - Energy Informatics & Social energy management
   - …
4. Establishmentt of GX for CN

Thank you for your attention.

Kato Lab. Members.

