International Institute for Carbon-Neutral Energy Research

Thermal Science & Engineering Revised Roadmap

June 2017

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Division Objective

- **Expand material thermophysical property information and thermal science and engineering to help enable the most effective use of materials in carbon-neutral energy society technologies and to improve the energy efficiency of thermal processes.**

  - Expand our knowledge base of thermophysical properties of hydrogen and alternative refrigerants to enable their most efficient use to reduce CO_2 emissions.
  - Improve the understanding of the basic science of heat and mass transfer to enable the develop of more efficient energy systems.
  - Research new thermal energy heat pump and refrigeration systems focused on the use of waste heat and new refrigerants resulting in improved overall energy efficiencies and reduced CO_2 emissions.

Division Projects, Objectives, and Research Efforts (1)

Projects		Objectives	Research Efforts	Researchers
Area1: Thermophysical properties (TP)	**TP-1:** High Pressure Hydrogen	Measurement of thermophysical properties of hydrogen and development of its database in a wide range of temperatures and pressures needed for hydrogen energy system	・Accurate measurement of PVT relationship, viscosity, thermal conductivity, velocity of sound ・Development of thermophysical properties database	○Y. Takata, N. Sakoda
	TP-2: Next generation refrigerants	Measurement of thermodynamic properties of newly developed environmentally-friendly refrigerants that are candidates for next generation air-conditioning systems	・Measurement of thermodynamic properties and critical point ・Accurate measurement of PVT relationship and development of thermophysical properties database ・Development of a new equation of state (EOS)	Y. Takata ○Y. Higashi N. Sakoda B.B. Saha S. Koyama K. Uddin
	TP-3: Thermal transport in nanoscale	Elucidation of thermal transport of nano materials and interfaces for various energy devices (e.g. adsorbent of adsorption heat pump/refrigeration system).	・Measurement of thermal conductivity of nanowires ・Development of new measurement methods of thermal/electrical/optical properties of nano materials	○K. Takahashi X. Zhang M. Kohno N. Miljkovic S. Harish A. Askounis

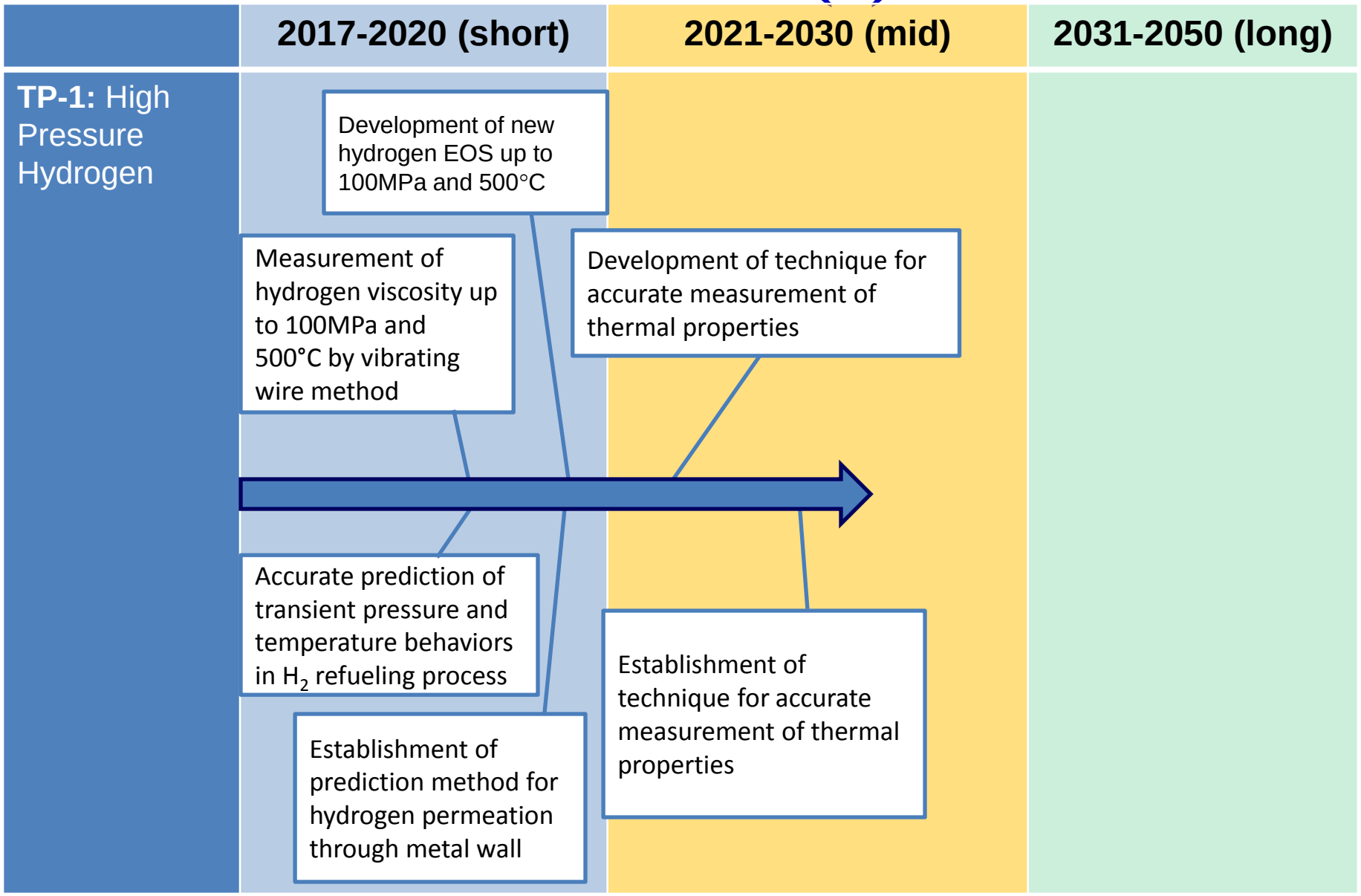
Division Projects, Objectives, and Research Efforts (2)

	Projects	Objectives	Research Efforts	Researchers
Area 2 : Heat/Mass Transfer (HMT)	**HMT-1:** Phase change heat transfer	Elucidation of effect of surface wettability and structure on liquid-vapor phase change process for effective heat removal for high-heat flux conditions	・Mechanism of bubble nucleation and condensation in nanoscale observation by AFM and FIB-ESEM ・Elucidation of heat transfer characteristics by pool boiling and droplet impingement for various wettability surfaces ・IR measurement and numerical simulation of liquid drop evaporation on heated substrate ・Condensation heat transfer from nano- to macroscale ・bio-mimetic surface	○Y. Takata K. Takahashi M. Kohno K. Sefiane D. Orejon B. Shen N. Miljkovic H. Sivasankaran A. Askounis
	HMT-2: Adsorption	Characterization of functional adsorbents and measurement of adsorption isotherms & kinetics for adsorption heat pump/refrigeration system/thermal energy storage	・Synthesis of activated carbon-based composite adsorbent ・Measurement of adsorption characteristics in a wide range of temperature and pressure ・HMT analysis of adsorbent bed ・Evaluation of thermodynamic models for adsorbed phase	○B.B. Saha S. Koyama T. Miyazaki K. Thu S. Mitra

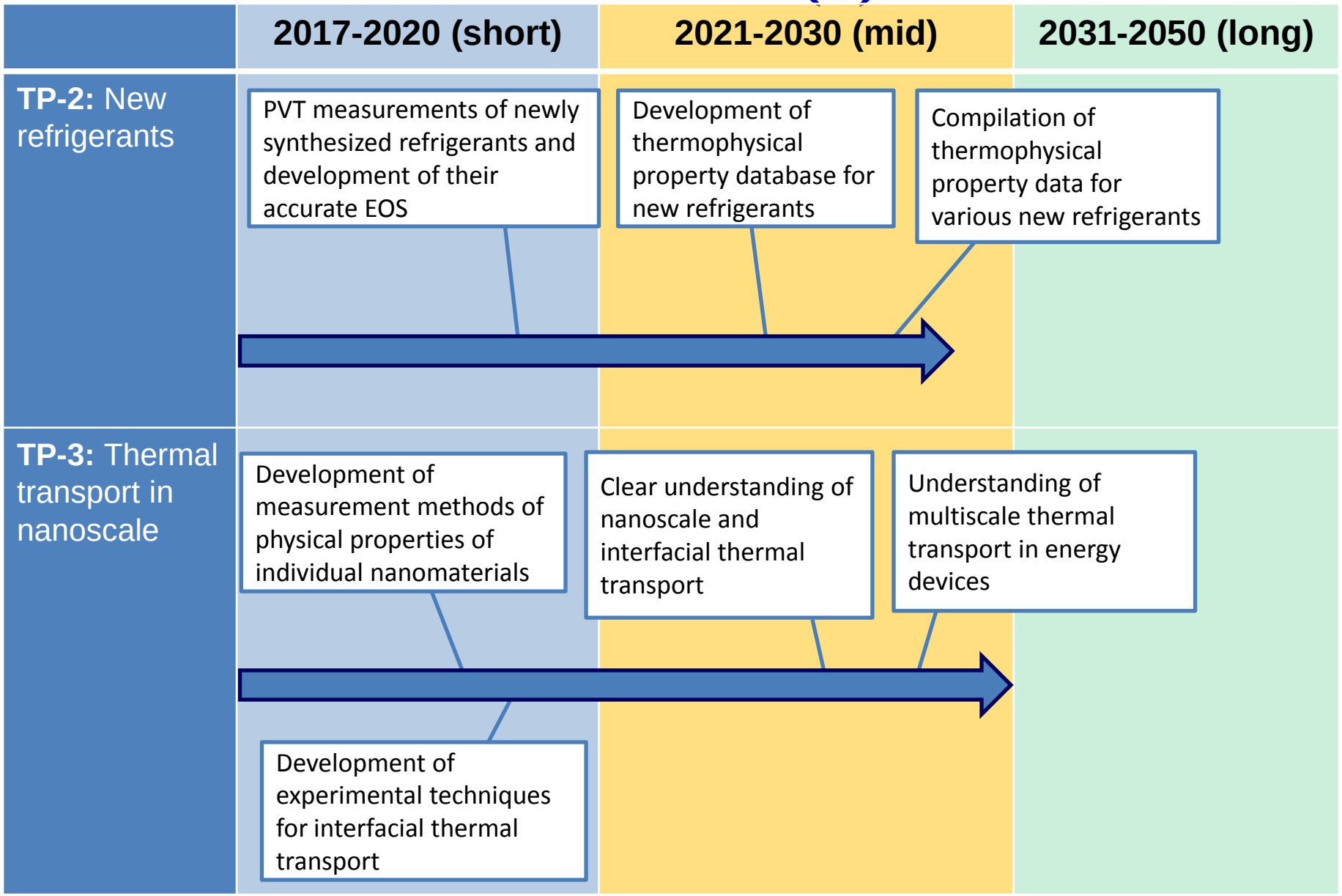
Division Projects, Objectives, and Research Efforts (3)

	Projects	Objectives	Research Efforts	Researchers
Area 3 : Thermal Energy Systems (TES)	**TES-1:** Waste heat-driven adsorption heat pump/ refrigeration system	Development of adsorption heat pump/refrigeration and energy storage systems for utilization of 50-200°C level waste heat Development of ultra efficient hybrid heat pump and power cycles	・System analysis of adsorption thermodynamic cycles ・Development of compact adsorption heat exchangers ・Theoretical and simulation of hybrid heat pump cycles ・Second law analysis of hybrid heat pump and power cycles	○B.B. Saha S. Koyama T. Miyazaki K. Thu S. Mitra
	TES-2: Vapor compression heat pump/ refrigeration system using new refrigerants	Development of heat pump/refrigeration system using low GWP refrigerants with high COP	・Optimization of thermodynamic cycle using thermophysical property data ・Design and optimization of evaporator and condenser ・Entropy and exergy analyses of heat pump/ refrigeration systems	○S. Koyama Y. Higashi B.B. Saha T. Miyazaki K. Thu Y. Takata N. Sakoda K. Uddin
	TES-3: High Efficiency Power Generation System	Development of highly efficient integrated power generation system including IGCC and H_2 (imported low carbon H_2) oxy-fuel combustion cycles using cold energy of liquid H_2 for ASU	・Thermodynamic cycle analysis considering chemical reactions ・Modeling and numerical simulation of turbulent combustion process	H. Watanabe ○Y. Takata A. Yamada

Milestones (1)



Milestones (2)



Milestones (3)

	2017-2020 (short)	2021-2030 (mid)	2031-2050 (long)
HMT-1: Phase change heat transfer	Development of boiling surface with onset of boiling at less than 2K in ΔT_{sat} and with CHF by 2.5 times higher than copper surface	Measurement of heat transfer characteristics of micro liquid layer in boiling and evaporation process by making use of thermoreflectance method	Clear Understanding of liquid-vapor heat transfer from nano to macro scale
	Clear understanding of wettability effects in liquid-vapor phase change	Clear understanding of heat transfer performance and pressure drop of new refrigerants in evaporator and condenser	
HMT-2: Adsorption	Accumulation of adsorption isotherm and kinetics data of natural or low GWP refrigerant onto functional adsorbents	Atomic scale understanding of adsorption phenomena for functional adsorbents	Development of HMT enhancement technique for adsorption heat exchanger
	Clear understanding of adsorption/desorption process of functional adsorbents	Establishment of adsorption kinetic enhancement technique Adsorbed phase thermodynamics	

Milestones (4)

	2017-2020 (short)	2021-2030 (mid)	2031-2050 (long)
TES-1: Waste heat-driven adsorption heat pump/ refrigeration system	Clarification of the best suitable adsorbent and refrigerant combination for adsorption heat pump and refrigeration systems	Demonstration of systems and optimization of operating conditions Second law-based optimization of hybrid heat pump and power cycles	Development of rapid adsorption/desorption heat exchanger using activated carbon based composite adsorbent
TES-2: Vapor compression heat pump/ refrigeration system using new refrigerants	Development of heat pump system for a wide range of temperature using new HFO refrigerants	Design criteria and performance prediction technique for heat pump/refrigeration with new refrigerants Entropy and exergy analyses	Development of prototype heat pump system with ultimate COP

Milestones (5)

	2017-2020 (short)	2021-2030 (mid)	2031-2050 (long)
TES-3: High Efficiency Power Generation System	Conceptual design of power generation system with high efficiency and low CO_2 emission using coal and imported low carbon H_2	Development of elementary processes and units including Combustor, Reductor and Gas separator Numerical simulation technique for turbulent combustion process	Pilot scale plant of power generation system (1MWt)
	Understanding of turbulent-chemistry interaction in turbulent reacting flows by experimental and numerical examination Development of basic database for modeling Development of turbulent combustion models and validation on a fundamental configuration (DNS, LES)	LES modeling and simulation of turbulent combustion in turbulent reacting flows and validation on a larger scale problem Multi-physics modeling on interaction of fluid-structure Massively parallel computing on a large-scale target to confirm applicability to a practical scale problem	Multi-physics simulation on interaction of fluid-structure Massively parallel computing on a practical-scale problem to directly contribute to industries

Ultimate Targets (1)

		Ultimate targets	Current Benchmarks	Technology/Application
Area1: Thermophysical properties (TP)	**TP-1:** High Pressure Hydrogen	• Clear understanding of thermophysical properties of hydrogen from cryogenic temperature to 500°C and up to 100MPa with an accuracy of ±2%	• PVT up to 100MPa and 500°C by HYDROGENIUS • Viscosity up to 100MPa and 400°C by HYDROGENIUS • Thermal conductivity up to 100MPa and 500°C by HYDROGENIUS	• Hydrogen property data base for hydrogen station and infrastructure
	TP-2: New refrigerants	• Development of equation of state for new HFO refrigerants and their mixtures • Elucidation of heat transfer characteristics for new HFO refrigerants and their mixtures	• PVT, critical point and vapor pressure of HFO refrigerants by Higashi et al. at Iwaki Meisei Univ.	• Vapor compression heat pump/ refrigeration system (contribute to TES-2)
	TP-3: Thermal transport in nanoscale	• Multiscale analysis of thermal transport in and around nanomaterials • Elucidation of thermal transport at complex interfaces	• Measurement of thermal conductivity of carbon nanotube(CNT) by T-junction technique by Zhang, Takahashi and Fujii. • Measurement of heat conduction at simple interface by TDTR method developed by Cahill	• Highly efficient thermal transport device

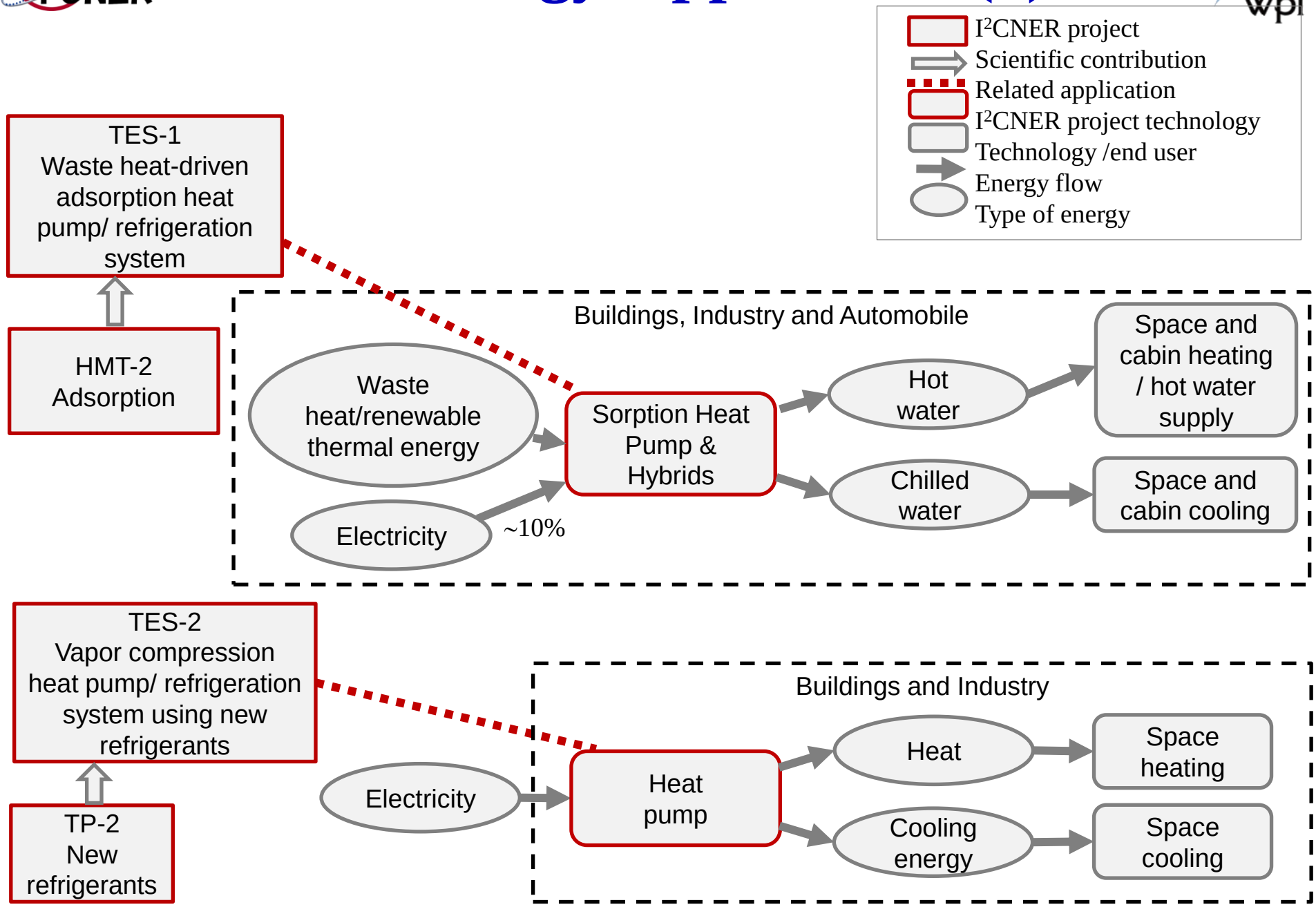
Ultimate Targets (2)

		Ultimate targets	Current Benchmarks	Technology/Application
Area 2 : Heat/Mass Transfer (HMT)	**HMT-1:** Phase change heat transfer	• Elucidation of wettability and structure effects in liquid-vapor phase change phenomena	• Mixed-wettability boiling surface by Takata et al.	• Heat loop tube (i.e. for data center)
	HMT-2: Adsorption	• Cooling capacity per adsorbent bed: 1.5 kW/L, for example, ethanol-activated carbon system: (Specific cooling effect 900 kJ/kg x packing density 0.3 kg/L)/(adsorption time 180s) • Thermodynamic models and data for adsorbed phase (u, h, s, c_p, c_v etc.)	• AQSOA®-Water system: 0.5 kW/L by Mitsubishi Plastics • No data on the adsorbed phase thermodynamic properties	• Waste heat-driven adsorption heat pump/ refrigeration system • Hybrid cycle heat pump system using vapor compression and waste heat (contribute to TES-1)
Area 3 : Thermal Energy Systems (TES)	**TES-1:** Waste heat-driven adsorption heat pump/ refrigeration system	• HP systems with large specific heating/refrigeration power • Raise COP toward 0.9 at heat source temperature level of 80℃ • Hybrid cycle with COP higher than vapor compression cycles	• COP 0.6@60℃ by Maekawa MFG (adsorption heat pump) • About 6.5 COP at compressor level (mechanical heat pump)	• Waste heat-driven adsorption heat pump/ refrigeration system • Hybrid cycle heat pump system using vapor compression and waste heat
	TES-2: Vapor compression heat pump/ refrigeration system using new refrigerants	• COP 10 on the basis of electricity input using non-GWP refrigerant • Performance enhancement using entropy- and exergy-based system analyses	• COP 6.5 on the basis of primary energy by air-conditioning/refrigeration makers	• Vapor compression heat pump/ refrigeration system
	TES-3: High Efficiency Power Generation System	• Thermal efficiency and CO_2 emission 65%/300g-CO_2/kWh	• Thermal efficiency and CO_2 emission IGCC:40%/700g-CO_2/kWh	• High Efficiency Power Generation System using coal and imported low carbon H_2

Role & Contribution through Technology

- The role of this division toward CNS is to create
  1. Heat mass transfer devices to reduce energy loss in heat transfer in the applicable field such as data centers, contributing to energy saving for air conditioning
  2. Efficient waste heat / renewable thermal energy driven heat pump, contributing to efficiency increase and energy saving for heating and cooling applications where waste heat / renewable thermal energy air are available such as factory and automobile
  3. High efficiency vapor compression heat pump, contributing to efficiency increase and energy saving for air conditioning in all sectors

Technology/Application (1)



Technology/Application (2)