The Present and Future of Refrigeration, Power Generation and Energy Storage

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Introduction

- low efficiency use of fossil fuels and the large emission of CO₂
- serious energy shortage and environment pollutions

the use of renewable energy is becoming possible as a substitute for the fossil fuels

some scientists have even imaged that fully renewable could be reached in 2030
ALTERNATIVE ENERGY

THE POWER OF RENEWABLE ENERGY

Wind, water and solar technologies can provide at least 40 percent of the world’s energy by 2030, eliminating all fossil fuels.

BY 2030

A PATH TO SUSTAINABLE ENERGY

In December leaders from around the world will meet in Copenhagen to try to agree on cutting back greenhouse gases in line with the Kyoto Protocol. The U.S. government is not expected to sign a new agreement to limit greenhouse gases, but even if it does not, there is a growing consensus that a transformation to sustainable energy is possible, and that it is in the interest of the planet.

A year ago former vice president Al Gore issued a green plan to transform America with 100 percent carbon-free electricity within 10 years. As the two of us have tried to restate the feasibility of such a plan, we found that America has a large and diverse set of renewable options, which are often overlooked. In this article we will discuss and evaluate these options.

Scientists have been building to this moment for at least a decade, analyzing various pieces of the puzzle. Most recently, a 2009 Stanford University study laid out a system according to their impact on global warming, pollution, water supply, biodiversity, wildlife and other concerns. The very best options were wind, solar, geothermal, tidal and hydropower projects—options that are driven by wind, water or sunlight. In fact, we refer to them as "WWSG"—nuclear is not an option.

Our plan calls for millions of wind turbines, water machines and solar installations. The numbers are large, but the scale is not an issue: incredible technology has achieved massive
Contents

- Introduction
- Refrigeration
- Power generation
- Energy storage
- Discussions
Refrigeration – current status

Electricity powered: Vapor Compression (VC) Cooling System

- The most widely adopted and a relatively mature refrigeration method
- High energy consumption
- COP of room air conditioner (AC): 3
- COP of water chiller system: 4 – 6
Refrigeration – current status

 Thermal powered: Absorption Cooling System

- Energy-saving & Environmental-friendly
- COP of LiBr-water absorption chiller:
  - 1.2 - 1.4 (double effect, 150°C); 0.4 - 0.7 (single effect, 75-90°C)
- COP of ammonia-water absorption chiller:
  - >1.0 (GAX cycle, 180°C); 0.6 (100°C higher)
Refrigeration – current status

Thermal powered: Adsorption Cooling System

- Energy-saving & Environmental-friendly
- COP of silica gel-water adsorption chiller: 0.35 -0.6 (with 60-80°C hot water)
Conventional VC system: realize cooling + dehumidification under low evaporation temperature

This air handling method leads to:

- Low evaporation temperature (5-7°C) is required to meet the need of dehumidification
- In big-scale system, a re-heating process is required to meet the need of supply air, which results in the waste of energy
Refrigeration – future

Temperature and Humidity Independent Control (THIC) Cooling System realize **cooling + dehumidification** within different sub systems

**Dehumidification sub-systems**

**VC sub-systems**
Refrigeration – future

Temperature and Humidity Independent Control (THIC) Cooling System

- Higher evaporation temperature, from the current 5-7°C to 15-20°C.
- Compared to VC systems, THIC systems can save 25%-50% electrical consumption, COP increases by about 40-60%. But may need high regeneration temperature!
Isothermal & Cool Dehumidification

Enlarged dehumidification

Cool dehumidification

The same relative humidity output

Δx

ΔT

dehumidification process
A unified solution

Conventional THIC Units

- Sensible heat H.X.
- Latent heat handling by desiccants

Unified

Desiccant H.X.

- Liquid spray desiccant H.X.
- Desiccant coated H.X.

Refrigerant evaporation-sensible cooling
Desiccant-Latent load

Condensing heat powered dehumidification

Sensible Load
Latent Load

Refrigeration inside tube
Dehumidification Outside tube

Conventional heat pump
Dehumidification-evaporation cooling
THIC heat pump
THIC heat pump with a unified solution

Outdoor air
AHU output air

含湿量 (kg/kg)
100
%RH
温度 (°C)
Refrigeration – future

Desiccant Direct Contact VC Heat Pump Air Conditioner System (THIC)

- Small volume and low initial cost compared to conventional THIC system.
- 45-60°C condensing heat can be used. If the AC units have 40-50% latent heat, then the COP can be nearly doubled (5.0).
Refrigeration – future

Two Temperature Level Control VC System (THIC)

- Evaporator is divided into two levels (5°C and 15°C for example).
- The level with lower evaporation temperature for dehumidification, the level with higher evaporation temperature for cooling.
- COP is higher than those with a 5°C evaporation temperature.
Solar powered Cooling System (absorption + adsorption)

- Evacuated tube collectors (>85 °C) for single effect chiller
- Plate type solar collectors (70-75° C) for two-stage system
- For a double effect system, it is more reasonable if solar heating could reach 150 °C, auxiliary fossil fuel could be used economically for cooling.
- Small scale absorption chillers coupled with solar collector technology is still a problem.
- Currently large scale solar cooling seems to be reasonably economic for solar cooling power above 200kW.
Refrigeration – future

- Solar powered Cooling System (absorption + adsorption)

- Solar adsorption: lower regeneration temperature (60-90°C), both plate type and evacuated tube solar collector designs can be utilized

- 20 kW Absorption Chiller
  COP about 0.6

- 5kW adsorption chiller:
  Cooling COP is about 0.5
  Solar COP is 0.2 - 0.25
Refrigeration – future

Renewable source heat pumps

- Various renewable energy driven: ground source, water source, air source
- Operate efficiently in cold winter

Ground-Source Heat Pump System

COP heating and cooling could be 30% increased
Air source heat pump water heater

(102 unites) applied in Shanghai Daan Real estate, Nov. 2008

Annual COP about 4 to produce 55~60 °C hot water
A residential heat pump energy centre is developed recently to solve the demand conflict between water heating (all year around) and air conditioning (in summer).

This system can change current energy consumption mode for buildings (a boiler for heating, an air conditioner for cooling and a gas/electric water heater for hot water supply).

A heat pump energy centre can meet all requirements in some climate regions.

The system could be extended for use in a swimming pool.
Heat Pumps – Air source floor heating

Library of Shanghai Jiao Tong University
Installed in Nov. 2010

Indoor floor heating

Outdoor heat pump system
Heat pump for Indoor swimming pool energy supply system
Average COPs of multi-function air source heat pump water heater used for heating shower water under different ambient temperature conditions

(Inlet water temperature: from city water temperature to 52 °C)
Average COPs of multi-function air source heat pump water heater used for heating swimming pool under different ambient temperature conditions

(Inlet water temperature entering heat pump: 35 °C; A plate heat exchanger exists between heat pump and pool water for anti corrosion; Pool water temperature: 27 °C)
Contents

- Introduction
- Refrigeration
- **Power generation**
- Energy storage
- Discussions
Demand are connected to distribution networks passively and uncontrollably.
Both demand and distribution generation are directly connected to the terminal use.

Energy sources could be solar PVs, solar thermal power plant, CCHPs, wind turbines, fuel cells, electric batteries and etc.
In conventional system, central power stations provide electricity for an entire region and most homes have to use natural gas to provide domestic heating.

In PV+CHP system, nature gas: for a CHP unit to supply electricity and heat.

For burning the same natural gas, 84% efficiency of the PV+CHP system and 35% efficiency for conventional power plants.
Micro CCHP/CHP

Biogas CHP/CCHP + Solar PV or Wind energy

Could be another option! Optimized high efficiency control is necessary!
Solar PV driven air conditioning

Technical performance

<table>
<thead>
<tr>
<th>System performance</th>
<th>Index</th>
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<tbody>
<tr>
<td>Cooling capacity</td>
<td>0.1～7 kW</td>
</tr>
<tr>
<td>Heating capacity</td>
<td>0.12～9 kW</td>
</tr>
<tr>
<td>Solar-electric efficiency</td>
<td>12.5%</td>
</tr>
<tr>
<td>Inverter efficiency</td>
<td>80.2%</td>
</tr>
<tr>
<td>Electric COP of AC</td>
<td>3～4.1</td>
</tr>
<tr>
<td>System Solar COP</td>
<td>0.3～0.41</td>
</tr>
</tbody>
</table>

System

- PV array
- Battery
- Inverter DC/AC
Mini distributed D.C. system for a house or apartment

- The system mainly consists of PV array and the batteries.
- The electricity generated by PV array will be conveyed to the batteries, which will supply the DC directly.
- In addition, the DC can be converted to AC with an AC inverter for some special applications.
With the cost reduction of Solar PV and Wind Turbine, distributed mini power system might be a future power.

Battery, PVs, Wind, Fuel Cells and etc..

Residential Appliances could be all DC Powered.
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- Introduction
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- Energy storage
  - Electrical storage
  - Thermal storage
- Discussions
### Electrical storage-current status

- **Batteries**: high-energy-density, low-power-density technology.
- **Supercapacitors**: high-power-density, low-energy-density technology

<table>
<thead>
<tr>
<th></th>
<th>Lead-acid</th>
<th>Nickel-cadmium</th>
<th>Sodium-sulphur</th>
<th>Sodium-nickel chloride</th>
<th>Lithium-ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demonstrated upper limit power rating</td>
<td>Ten of megawatts</td>
<td>Ten of megawatts</td>
<td>Megawatt scale</td>
<td>Hundreds of kilowatts</td>
<td>Tens of kilowatts</td>
</tr>
<tr>
<td>Specific energy (Wh/kg)</td>
<td>35-50</td>
<td>45-80</td>
<td>100</td>
<td>115</td>
<td>160</td>
</tr>
</tbody>
</table>
Electrical storage-future

- **The Lithium-ion battery:**
  - highest energy density $400 \text{kWh/m}^3$.
  - used in the small portable electronic equipments and hybrid vehicles

- **NaS (Sodium Sulphur) batteries:**
  - high energy efficiency 89–92%
  - made from inexpensive and non-toxic materials
  - Now could be commercialized in Japan and China with several tens MW recently
Electrical storage-future

Batteries integrated with renewable energy power generation systems

- In sunshine day, the PV array will generate electricity for the terminal use and part of the electricity will be stored in the battery.
- In the night, the battery will supply electricity for the terminal use.
Electrical energy storage system used in a future smart grid

- The system consists of a lithium-ion battery array coupled to SVC Light and control system.
- When the grid is under fault conditions, the electricity can be supplied to the customers by the storage system.
The common method of thermal energy storage

- (a) sensible heat energy storage
- (b) latent heat energy storage using phase change material (PCM)
- (c) thermochemical energy storage
Energy density of different thermal energy storage technologies

(a) Sensible heat
(b) Latent heat (EG+Paraffin)
(c) Chemical reaction
Building for Solar Air Heating Systems with sensible heat storage

Solar air heating systems with pebble bed energy storage

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector area</td>
<td>473.2</td>
<td>m²</td>
</tr>
<tr>
<td>Heating area</td>
<td>3458</td>
<td>m²</td>
</tr>
<tr>
<td>Collector efficiency</td>
<td>≥40</td>
<td>%</td>
</tr>
<tr>
<td>Energy saving per year</td>
<td>772262</td>
<td>MJ</td>
</tr>
<tr>
<td>Solar fraction predicted</td>
<td>49.4</td>
<td>%</td>
</tr>
</tbody>
</table>

Schematic diagram

Solar collector | Air duct and fan | Pebble | Indoor air outlet
Experiment test result in 2010 Dec

System energy gain

Daily solar fraction

Solar fraction in Dec

Comparison test of different heating room
Partitioned water tank

Horizontally partitioned water tank for large-scale solar powered system
Hybrid energy storage system

Integrated-collector-storage solar water heater with fins inside the wax

Composite phase change heat storage materials
## Thermal storage-future

### Integrated building with energy storage

<table>
<thead>
<tr>
<th></th>
<th>Walls</th>
<th>Roof</th>
<th>Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Solar Heating</td>
<td><img src="image" alt="Diagram" /> With daytime solar radiation</td>
<td><img src="image" alt="Diagram" /> With daytime solar radiation</td>
<td><img src="image" alt="Diagram" /> With daytime solar radiation</td>
</tr>
<tr>
<td>Active Heating</td>
<td><img src="image" alt="Diagram" /> With solar collector system</td>
<td><img src="image" alt="Diagram" /> With nighttime cheap electricity</td>
<td><img src="image" alt="Diagram" /> With nighttime cheap electricity</td>
</tr>
<tr>
<td>Night Cooling</td>
<td><img src="image" alt="Diagram" /> With nighttime ventilation</td>
<td><img src="image" alt="Diagram" /> With nighttime ventilation</td>
<td><img src="image" alt="Diagram" /> With nighttime ventilation</td>
</tr>
</tbody>
</table>

Integrated building envelopes with PCM energy storage
Thermal storage-future

Integrated building with energy storage

Open adsorption energy storage system on district heating net in Munich
Solar seasonal energy storage

Solar assisted ground-coupled heat pump seasonal energy storage
Thermal storage-future

Solar seasonal energy storage

a. in cooling mode

b. in heating mode

Solar seasonal energy storage using liquid-gas absorption chiller and latent heat storage in cooling and heating mode

Operation principle of energy storage using adsorption system
Thermal storage-future

Integrated energy storage and energy upgrade

(a) Energy storage process; (b) Energy release process; Energy storage process: A-B-C-D; Energy upgrade process: D-E-F; Combined cooling and heating production: D-H-I

Integrated energy storage and energy upgrade using solid-gas thermochemical sorption system
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Cooling could be more efficient

- independent temperature and humidity control
- new configurations and system integration make the system compact and reliable
- future air conditioning system could have a COP over 5
- Solar cooling
- renewable source heat pumps
Building integrated power system or distributed energy system

- smart system
- renewable energy integrated with the central grid network
- D.C. power system for residential application
Discussions

Electrical storage

- Electric battery related to electric vehicles could be a future battery considered for residential uses

- The low power density, high cost and efficient charge time are the bottlenecks for their application.

Thermal storage

- Supply thermal battery in kwh with high heat charge and release rate, and high power density
Thanks for your attention!