Integration of Pumped-Heat-Electricity-Storage into Water / Steam Cycles of Thermal Power Plants

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BACKGROUND
- Pumped Heat Electricity Storage (PHES)
- PHES versus batteries
- Which storage?
Background – Alstom Concept
Pumped Heat Electricity Storage

- Distributed electricity storage
- Propane working fluid
- Liquid medium thermal storage
- Reversible cycle and components
Rapid changes in battery technology and cost reduced the attractiveness of original concept.
Which storage?

- **UPS Power Quality**
  - PHES for distributed Electricity storage
  - D-PHES Standalone for centralized application

- **T&D grid support/Load shifting**
  - Flow batteries
  - NaS battery
  - Advanced lead-acid
  - NaNiCl2 battery
  - Li-ion battery
  - Lead acid battery
  - NiCd
  - N/MH

- **Bulk power management**
  - CAES
  - Pumped hydro

- **Battery/Supercap/Flywheels**
  - High-power flywheels
  - High-power supercap

- **Power Levels**
  - 1 kW
  - 10 kW
  - 100 kW
  - 1 MW
  - 10 MW
  - 100 MW
  - 1 GW
I-PHES
Integrated Pumped Heat Electricity Storage
- Principle
- Motivation
- Concepts
I-PHES Principles

HP making use of excess of electricity

Existing / New power plant
SPP, CCPP

Charging sequence

Discharging sequence

$P_{el, in}$
Heat pump
Heat storage

High temperature concept

Low temperature concept

$P_{el, out}$
Motivation to improve utilization of power plant

- Utilization of existing fleet
- Increase utilization factors of existing plants
- Frequency support
- Renewable back-up capacity
- Differentiation to energy storage market
- High flexibility
- Lean and fast
- Easy product development
- Easy systems integration
- Large scale storage
- Start time (cold) ~ 10 min
- Turn down capability 0-100%
- Net LHV efficiency +0.2 to 0.5% pts
- Additional net power ~+5%
- Realistic Net Round Trip Efficiency > 60%
- Capacity > 20MWe
- Price < 0.024 EUR/kWh produced
- Easy systems integration

Power Plant Operation Optimization

- Energy Storage with reduced CAPEX and OPEX
- Fuel savings
- Emissions reduction
- Emissions -4 to 6%
- Fuel savings ~0.5%

CERA-IHS market predictions
Why HP integrated in power plants?

There are at least two main power generation issues that HP in PP can address:

- Installed over-capacity, due to intermittent nature of wind and solar
  - Example for Germany in 2014

<table>
<thead>
<tr>
<th></th>
<th>Installed capacity (GW)</th>
<th>Peak production (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind+Solar</td>
<td>73.8</td>
<td>-</td>
</tr>
<tr>
<td>Thermal</td>
<td>103</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL</td>
<td>176.8</td>
<td>~85</td>
</tr>
</tbody>
</table>

No additional generation capacity

- Reduced thermal plants utilization
  - Gas example for Germany in 2014

Existing plants to be used more

Source: Prof. Dr. Bruno Burger, Fraunhofer Institute for Solar Energy Systems ISE
Target for Round-Trip efficiency > 60% reduces the scope of investigation into high-efficiency WSC.

Maximum theoretical RTE

$RT_{net\ eff} = WSC_{net\ eff} \times COP$

Steam temp. has a minimal impact on RTE.

**Scope of investigation**

ISO RTE 60%

30% 35% 40% 45% 50% 55% 60% 65% 70%

Max steam temperature - °C

300 350 400 450 500 550 600

Carnot eff.
Gross WSC eff.
CCPP
Coal plant
Indust. WSC
COP CO2 heat pump

**COP**

300 350 400 450 500 550

70% 65% 60% 55% 50% 45% 40% 35% 30%

**Carnot eff.**

74.0% 73.5% 73.0% 72.5% 72.0% 71.5% 71.0% 70.5% 70.0%

**WSC efficiency**

To high WSC efficiency

Round Trip Efficiency - %

60 65 70 75 80 85 90 95 100

Max steam temperature - °C

300 350 400 450 500 550 600

**Maximum RT efficiency achievable**

Scope of investigation

**CCPP KA26-1**
Cycle - Subcritical
HP Temp. °C 565
Rating power MW$_{gross}$ 172
Net efficiency % 41.5%

**Coal plant**
Cycle -
HP Temp. °C 540
Rating power MW$_{gross}$ 888
Net efficiency % 46.4%

**Ind. WSC Altamira**
Cycle - Subcritical
HP Temp. °C 540
Rating power MW$_{gross}$ 102
Net efficiency % 32.4%

**RP800 Ultra-Supercritical**
Cycle -
HP Temp. °C 600
Rating power MW$_{gross}$ 888
Net efficiency % 46.4%
Charging cycle configuration: Recuperated Heat Pump Cycle

- Fluids: CO2, air, argon
- CO2 compressor investigated by Industria de Turbo Propulsores
- Thermal Energy Storage: molten salt, thermal oil, pressurized water

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature</td>
<td>$T_\infty$</td>
<td>$15^\circ C$</td>
<td>$T_{20}$</td>
</tr>
<tr>
<td>Temperature range of the provided heat</td>
<td>$T_{HP3} \leftrightarrow T_{HP4}$</td>
<td>predefined</td>
<td>boundary condition dependent on I-PHES concept and reference WSC parameters</td>
</tr>
<tr>
<td>Terminal temperature difference of heat exchangers</td>
<td>$\Delta T_{HEX}$</td>
<td>5K</td>
<td></td>
</tr>
<tr>
<td>Evaporator temperature difference</td>
<td>$\Delta T_{Eva}$</td>
<td>15K</td>
<td>CO2 heat pump only</td>
</tr>
<tr>
<td>Upper HP pressure level</td>
<td>$p_{\max} = p_{HP3} = p_{HP4} = p_{HP5}$</td>
<td>variable / subject to optimization</td>
<td>$\leq p_{\max,limit} = 200bar$</td>
</tr>
<tr>
<td>Lower HP pressure level</td>
<td>$p_{\min} = p_{HP1} = p_{HP2} = p_{HP6}$</td>
<td>variable / subject to optimization</td>
<td>$\leq p_{\min,limit} = P_{\text{CO2}}(T_{\infty} - \Delta T_{Eva}) = 34.85 bar$ (CO2 heat pump only) $\geq p_{\min,limit} = 1 bar$</td>
</tr>
<tr>
<td>Isentropic compressor efficiency</td>
<td>$\eta_c$</td>
<td>0.8</td>
<td>conservative estimate (mainly responsible for irreversibilities within the HP cycle)</td>
</tr>
<tr>
<td>Isentropic turbine efficiency</td>
<td>$\eta_T$</td>
<td>0.9</td>
<td></td>
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</tbody>
</table>
High-temperature I-PHES concept
Simple configuration

- Similar RT efficiencies for all fluids ~63%
- Expansion in wet region for CO2 cycle
- W/O Expander RTE ~60%
- High risk for CO2 compressor

No benefit with CO2
High-temperature I-PHES concept
More complex configurations

- Extract additional low-temperature heat from the HP cycle
- Exploit (right picture) the lower thermal potential created by the HP process
- Only feasible with CO2 due to strong dependency of the specific heat capacity of CO2 on temperature
- Benefit negligible (<+1% pts) for a complex realization
Low-temperature I-PHES concept
Integration into the preheating train

- When integration temperature decreases, CO2 HP is more efficient than air/argon HP
- Low temperature integration allows to achieve relatively high RTE ~56-58% (<200°C)
Alternative concepts studied
Series connection of heat pump & electric heater

System flexibility much higher (grid service and start-up)

Power-to-Heat = X Heat Pump & (1-X) Electric Heater

RTE = 50-60% still realistic!
I-PHES
INITIAL VALUE
PROPOSITION
- Potential applications
- Increase capacity factor
- Reduce plant cycling
## Potential applications

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Applications</th>
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<tbody>
<tr>
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<td>Electricity to electricity storage</td>
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<tr>
<td>Centralised</td>
<td><img src="" alt=" " /></td>
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<tr>
<td>Coal</td>
<td><img src="" alt=" " /></td>
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<tr>
<td>CCPP</td>
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<tr>
<td>Nuclear</td>
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<tr>
<td>Solar</td>
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<tr>
<td>Stand-alone storage new build</td>
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<tr>
<td>Decentr.</td>
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<tr>
<td>Industrial Steam turbine</td>
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<tr>
<td>Stand-alone co-located with wind/PV</td>
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**Back-up capacity**: Capacity credit is the amount of power that can reliably be expected to produce at the times when demand for electricity is highest (International Energy Agency definition).

**Power boost**: additional power produced with heat from storage (>100% load), WSC running overloaded

**Flexibility**: Supporting power plant start-up, WSC warming up while compensating renewables fluctuations
Initial value proposition

Value for a storage business
Lowest costs for daily cycles (2<hours of storage<6), together with ACAES

Value for existing power plants
Increased capacity factor of existing power plants (CCPP specific)
- Extend service business for under-utilized power plants
Reduce power plant cycling and related material fatigue

A CAES: Adiabatic Compressed Air Energy Storage
HP in PP: Heat pump integrated in a Power Plant
Initial value proposition

Increasing capacity factor of existing Power Plants

Example of calculation: German spot market 2013

Assumptions:
- Electricity spot price in charging: 20 €/MWh
- Natural gas price cost: 9 €/mmBTU (~30 €/MWh_th)
- CO2 costs: 10 €/Ton
- I-PHES O&M costs: 0.2 cent€/kWh
- CCPP O&M costs: 0.2 cent€/kWh
- I-PHES efficiency: 60%
- CCPP efficiency: 55%

Results:
- Initial CCPP cf*: 8%
- Final capacity factor*: 40%
- Capacity factor* gain: +32% pt

*time-based capacity factor
Initial value proposition

Reduced plant cycling

- No start/stop cost
- Net-zero electricity exported to the grid in charging mode
- Ability to provide frequency support provision in both charging and discharging mode

- No cycling/part-load cost
SUMMARY
Summary

- HP with CO2 at low temperature represents a low cost/risk solution for preheating train integration, still achieving high RTE.

- High temperature will make air HP more attractive: equivalent RTE as CO2 HP, low risk, cheaper.

- CCPP application requires matching high temperature HP: an alternative concept with a series connection of HP & electric heater.

- Further work on system design and integration:
  - CO2 compressor below 200°C, >20MWe
  - Control, dynamic and operation with WSC
  - Sizing in regard with power plant integration.