Thermodynamic assessment of APR1400 integrating the liquid air energy storage

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Contents

Current energy trends

- IRENA report suggested renewable energy portion to increase up to 2/3 of world energy share by 2050
- Increased supply from renewables, especially solar PV
- Conventional power such as NPPs forced to lower their load during peak demand due to negative pricing (duck curve)

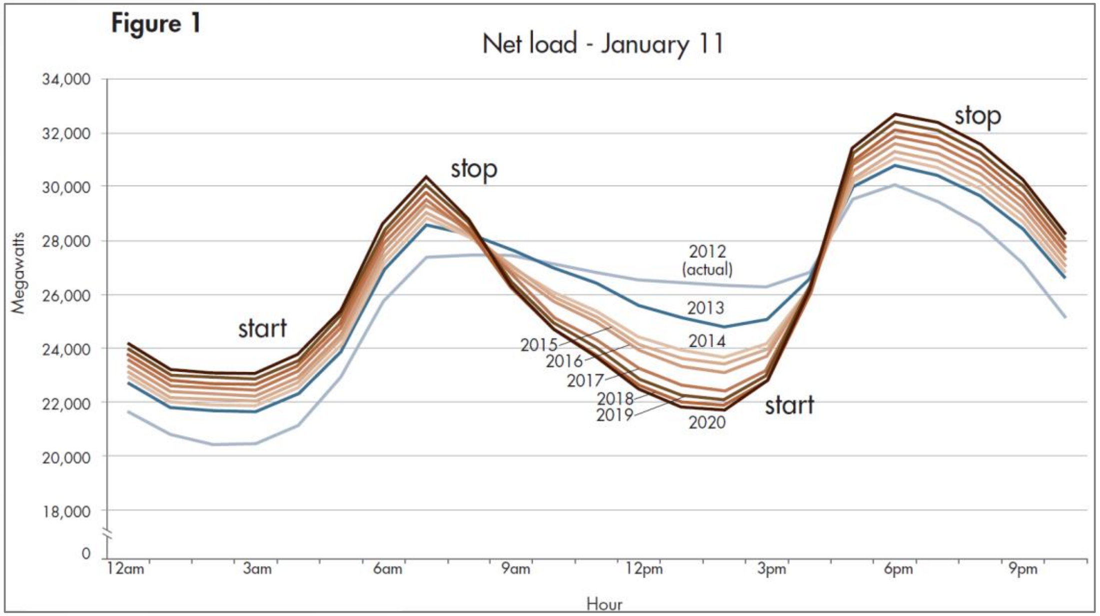


Fig. Net load curve for January 11 from 2012-2020
(Reference: National Renewable Energy Laboratory Report 2015)

Duck curve analysis

- First ramp of 8,000MW upwards in the morning
- Sun comes up around 7am → conventional replaced by solar (max overgeneration at 1pm)
- Sun sets from 4pm → solar generation ends, steepest ramp (~11,000MW/hr)

Ramping flexibility requirements

1) Reduce power during overgeneration period due to solar
2) Ramp up and react quickly

Nuclear plant issues

- Load-shifting generation is more cost-beneficial for nuclear, since it will sell at negative price at overgeneration
- Main issue is to improve the generation strategy to fit the increasing supply of renewables
- Two options: 1) load-following NPP or 2) integrating NPP with ESS to load-follow
- Load-following NPP cannot be done on primary side without economic, regulatory component integrity concerns
- Economic gain achieved when more power is generated during high electricity prices

** IAEA APR1400 Report says:

(Status report 83 - Advanced Power Reactor 1400 MWe (APR1400))

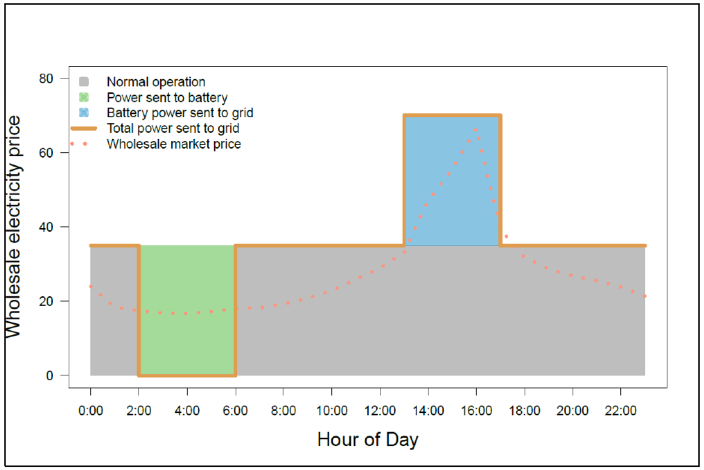
APR1400 is designed to be used for various operating modes not only for the base load full power operation but also for a part load operation such as the load following operation. **A standard 100-50-100% daily load follow operation has been considered in the reactor core design** as well as in the plant control systems.

In addition, various load maneuvering capabilities are considered in the design such as up to **10% step change in load, +/- 5%/min ramp load changes**. Also, it has the house load operation capability during a sudden loss of load up to 100% (full load rejection) in which plant control systems automatically control the plant at 3~5% power level without causing any reactor trips or safety system actuations.

The frequent changes in the load affect strongly on the aging of certain operational components and reduction in the load factor, causing problems in both economic and safety aspects. (Lokhov, 2011)

Nuclear Integration with ESS

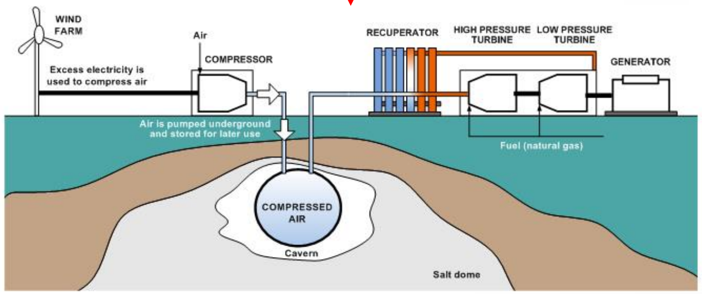
- Integrating ESS to nuclear has been researched by several research institutes including INL
- INL suggested *"CAES, TES as most suitable; Li-ion batteries or vanadium redox batteries also possible with lowered prices"*
- Integration options should be explored for conventional PWRs in Korea
- CAES or PHS cannot be expanded due to geological constraints
- One of the options is liquid air energy storage, which combines both CAES and TES



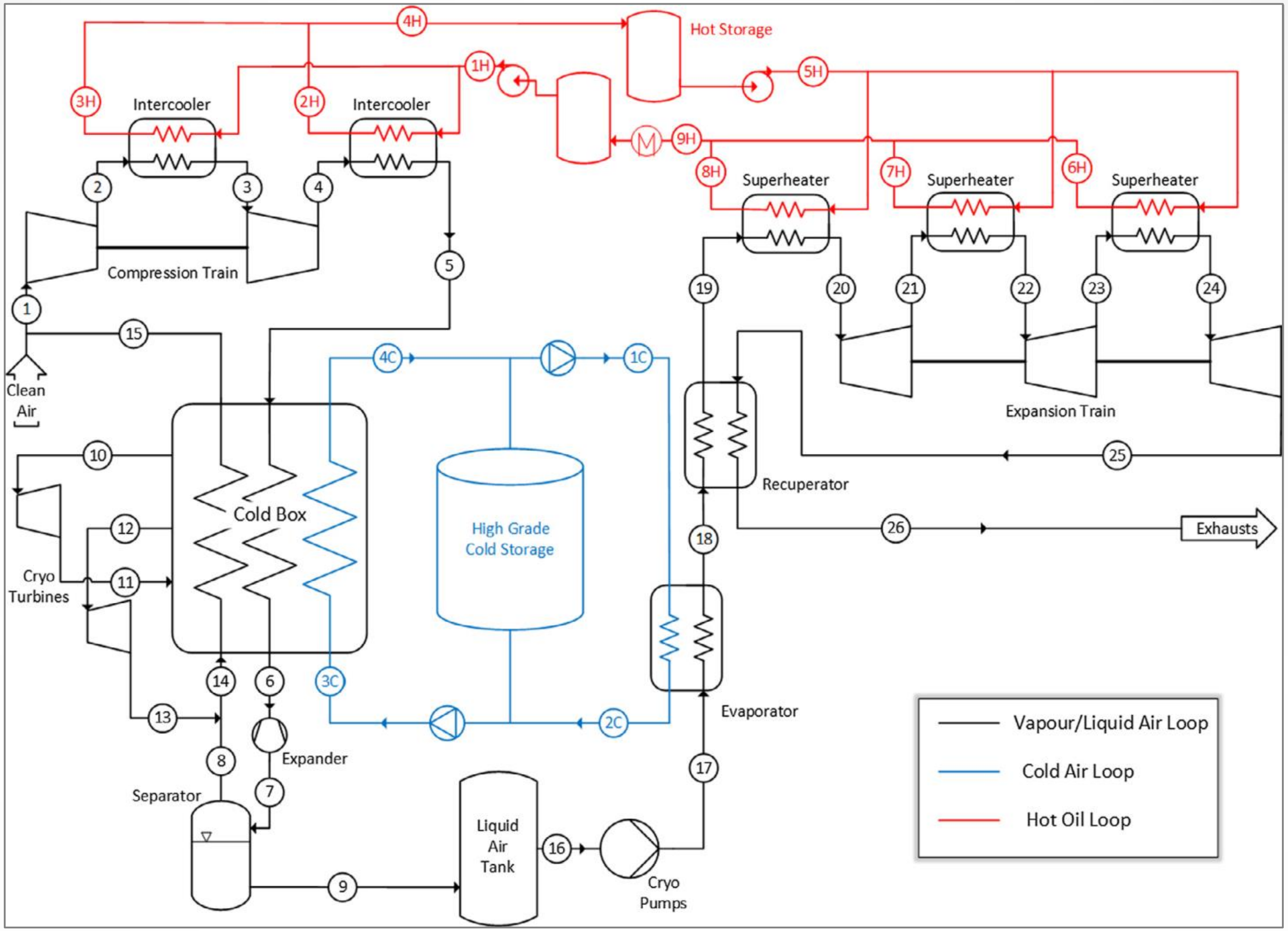
Technology Characteristics	PSH	CAES	Flywheels	Super-capacitors	SMES	Li-ion	Vanadium Redox
Environmental Impact	6.39	6.39	8.89	8.61	7.50	5.83	8.33
Technology Maturity	10.00	10.00	10.00	7.78	7.78	10.00	10.00
Geographic Availability	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cost Requirements	1.00	1.00	0.00	0.00	0.00	1.00	1.00
Cost Difference ($)	6.00E+06	8.50E+06	-1.00E+07	-3.00E+07	-3.00E+07	0.00E+00	6.00E+06
Space Requirements	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Weight Requirements	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Potential Additional Storage Capacity (kWh)	5.00E+11	2.00E+12	2.00E+13	2.50E+09	4.96E+08	7.50E+10	1.00E+10
Potential Additional Power Capacity (kW)	5.00E+11	5.00E+11	1.00E+15	5.00E+11	5.00E+11	7.50E+11	1.50E+11
Application Compatibility Factor	1.00	1.00	0.00	0.00	0.00	0.50	0.50
Levelized Cost of Storage, Lower-End ($/MWh)	188	192	276	NA	NA	321	248
Levelized Cost of Storage, Upper-End ($/MWh)	274	192	989	NA	NA	658	927
Favorable Policy Conditions	YES						
Market Variability	HIGH						

Figure 41. Stoplight chart with selected electricity storage technologies for Scenario 1.

Developer Inputs	*Value*
Required Energy Storage (MWh)	4000
Required Power (MW)	1000
Available Space (m^3)	Unlimited
Available Weight (kg)	Unlimited
Budget ($)	$10M
Project Timeline	11-15 years
Technology Proximity	Very Close
Geographic Availability	Elevation Change, Water Source, Evacuated Salt Cavern
Desired Application	Energy Arbitrage
Location	California



Liquid Air Energy Storage (LAES)



LAES principle: Charge (liquefaction) – storage (liquid air, thermal storage) – discharge (open Rankine cycle)

Why LAES?

- High energy density: 120-200Wh/L (vs. 0.5-1.5Wh/L for PHS, 3-6Wh/L for CAES, 200-500Wh/L for Li-ion)
- Can be deployed at large scale – LAES GigaPlant (200MW/1.2GWh) vs. Tesla Battery Farm (100MW/129MWh)
- No geological constraints: easy to expand for grid-scale application
- Technologies available on the shelf (air liquefaction, cryogenic turbomachinery, power cycle)
- Easy to integrate with waste heat or cold
- Fast response time (100s from startup to load set point)

30+ years lifetime
with mature components

Lowest cost
at utility scale

60% efficiency
in standalone configuration

70%+ efficiency
by utilising **waste heat or cold**

Ready to deploy
with an established supply chain

Zero emissions
and benign materials

Can be built
anywhere

Large-scale
GW and GWh

Table 3
Results of STOR trials.

	Time	% of call time
Response time (from start up to achieving load set point)	100 s	NA
Total time on call	2160 min	100%
Time spend generating	245 min	10.6%
Recovery time, when the plant is unavailable for generation (i.e. shutting down and start up time prior to synchronisation to the grid)	108 min	5%
Time spend on standby (available for generation)	1800 min	84%
Unplanned outage	7 min	0.3%
Availability (total time either on standby or generating)	2045 min	94.6%
Reliability (time either available or on planned shutdown)	2153 min	99.7%

Issues with LAES Nuclear Integration

- Li et al. (2014) suggested a preliminary design of NPP-LAES
- Charging for 8 hours, discharging for 1 hour using 100% steam bypass
- Round-trip efficiency: $\eta_{RT} = \frac{Increased\ energy\ output\ of\ discharge\ mode}{Energy\ consumed\ in\ storage\ mode}$, about 71% while net output power is 687MW (2.7 times NPP power)
- Design constraints on the interface heat exchanger
- Safety issues regarding interface HX temperature transients
- 100% steam bypass to LAES may cause rapid steam turbine transients

Research Objectives: To design thermodynamically NPP-LAES system for APR1400, considering reasonable conditions for NPP

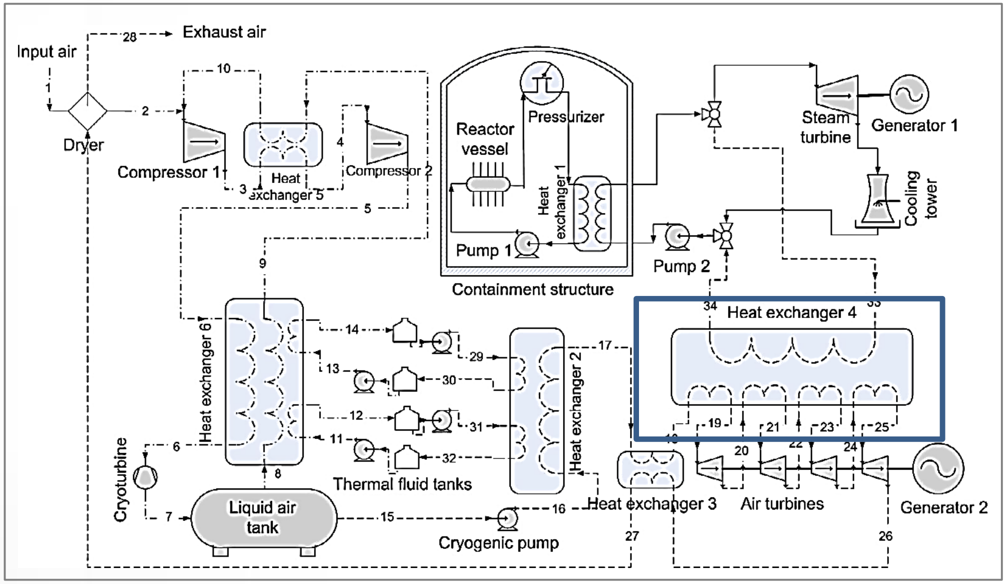


Fig. Schematic of NPP-LAES system suggested by Li et al. (2014)

Table 3
Performance summary of the key components.

Components	Power/heat loads (MW)	Exergy loss (MW)	Exergy loss ratio (%)
Energy storage mode			
Compressor 1	40.03	3.96	10
Heat exchanger 5	1.11	0.07	87
Compressor 2	39.83	3.99	10
Heat exchanger 6	59.71	3.74	8
Cryoturbine	3.12	0.43	12
Energy release mode			
Cryogenic pump	19.18	5.77	30
Heat exchanger 2	439.79	38.76	10
Heat exchanger 3	133.02	2.012	10
Heat exchanger 4	807.91	78.45	20
Air turbines	706.69	62.81	8
Net power consumption in energy storage mode (MW)		76.74	
Net power output in energy release mode (MW)		687.51	
Round trip efficiency (%)		71.26	

Design conditions of NPP-LAES

- The system was designed so that the primary side would not be affected, and the secondary side would not undergo drastic change (10% steam bypass)
- Secondary side merge point temperature should match the inlet of steam generator
- Main focus is to calculate the energy discharge cycle, while energy storage cycle operates as an air liquefaction plant (energy storage mode information obtained from Li et al. (2014))
- The hot side of the air evaporator is assumed to be connected to the cold recovery storage of the energy charging cycle

Design parameters	Values
Reactor thermal output	3983 MW_{th}
Plant efficiency	35.1%
Steam temperature	285°C
Feedwater flow rate	2261 kg/s
Feedwater temperature	232°C
Steam pressure	6.9 MPa
Ambient temperature	25°C
Percentage of steam bypass flow	10%
Isentropic efficiency of air turbines	90%
Isentropic efficiency of cryogenic pump	70%
HX pinch temperature	5 K
LAES storage mode work consumption	76.7 MW
LAES storage mode production rate	150 kg/s

Table. Design parameters of the APR1400 integrating the LAES

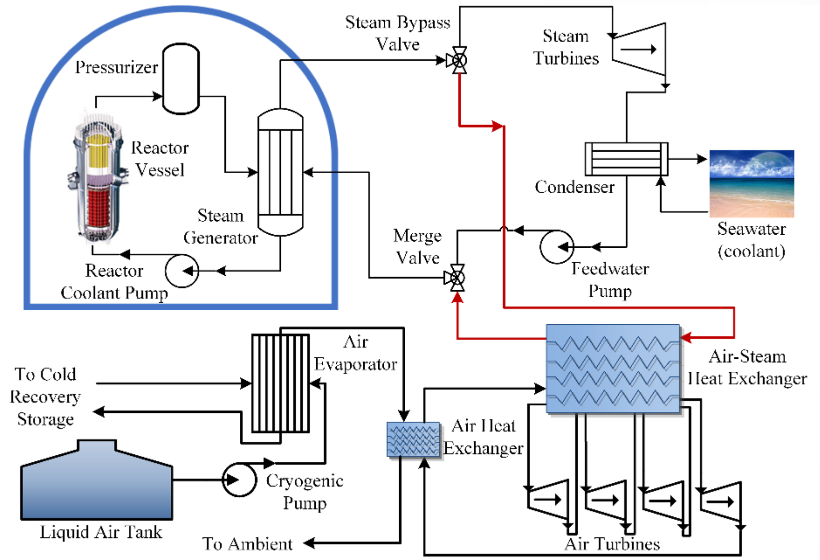


Fig. Schematic of APR1400 integrating the LAES system (discharge cycle)

Design code methodology

- Thermodynamic calculation performed by the in-house KAIST-CCD code utilizing properties from NIST REFPROP
- Air modelled from properties as mixture (N_2 78%+O_2 21%+Ar 1%)
- Calculation runs until the outlet temperature of liquid air at the exit converges within a low error bound satisfying the energy balance in the air-steam heat exchanger
- Round-trip efficiency of the system: $\eta_{RT} = \frac{W_{discharge} - r \cdot Q_{NPP} \cdot \eta_{NPP}}{W_{storage}} \cdot \left(\frac{\dot{m}_{LAES,prod}}{\dot{m}_{LAES,discharge}}\right)$

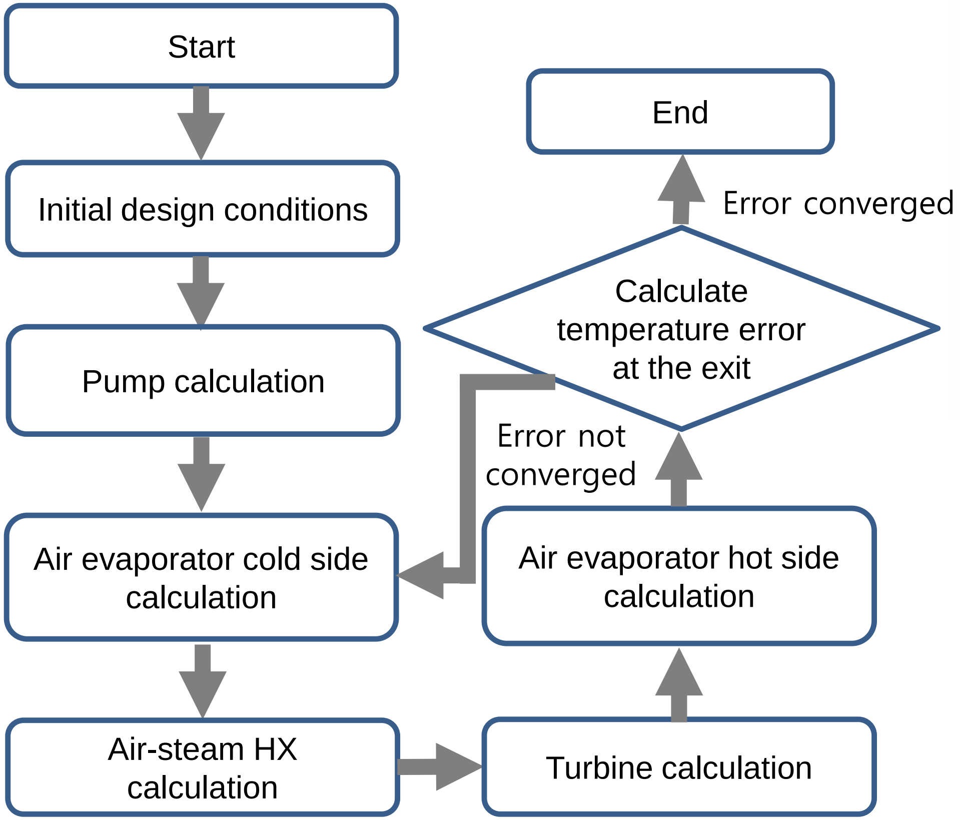
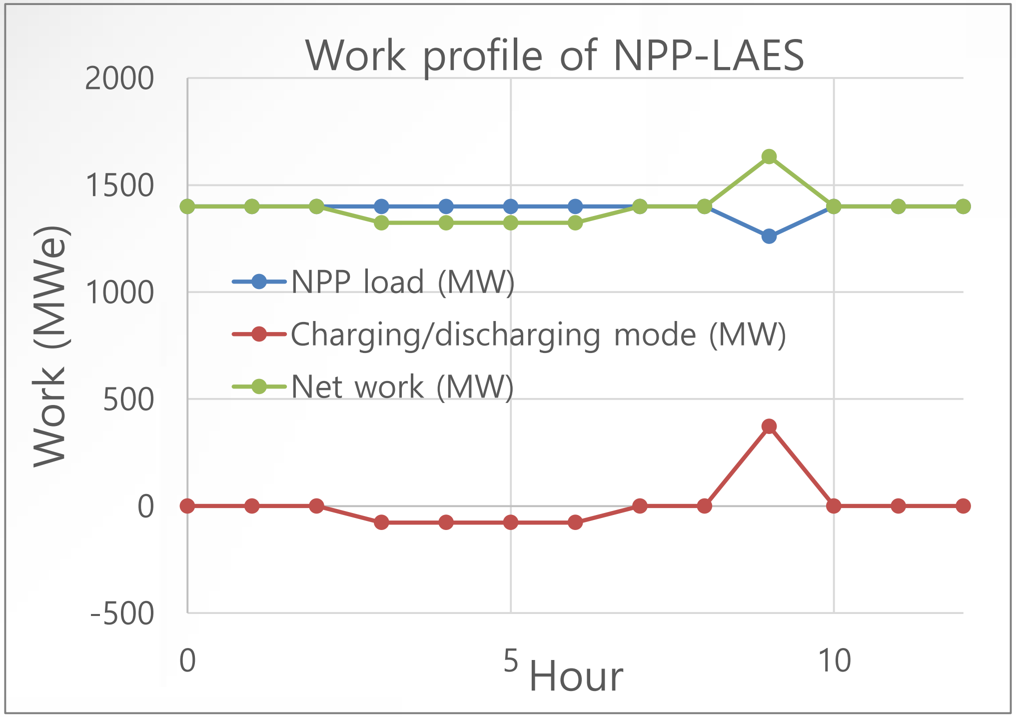


Fig. KAIST-CCD code algorithm for NPP-LAES design

Design analysis and results



- Steady state points for the NPP-LAES system are obtained
- 4.2 hours of charging leads to 1 hour of discharging at 2.7 times the NPP reduced power (140MW → 372MW)

Design results	**Values**
LAES maximum pressure	15 MPa
Number of turbines	4
Turbine work	387 MW
Pump work	15 MW
Round trip efficiency	71.4%
Air mass flow rate	635 kg/s

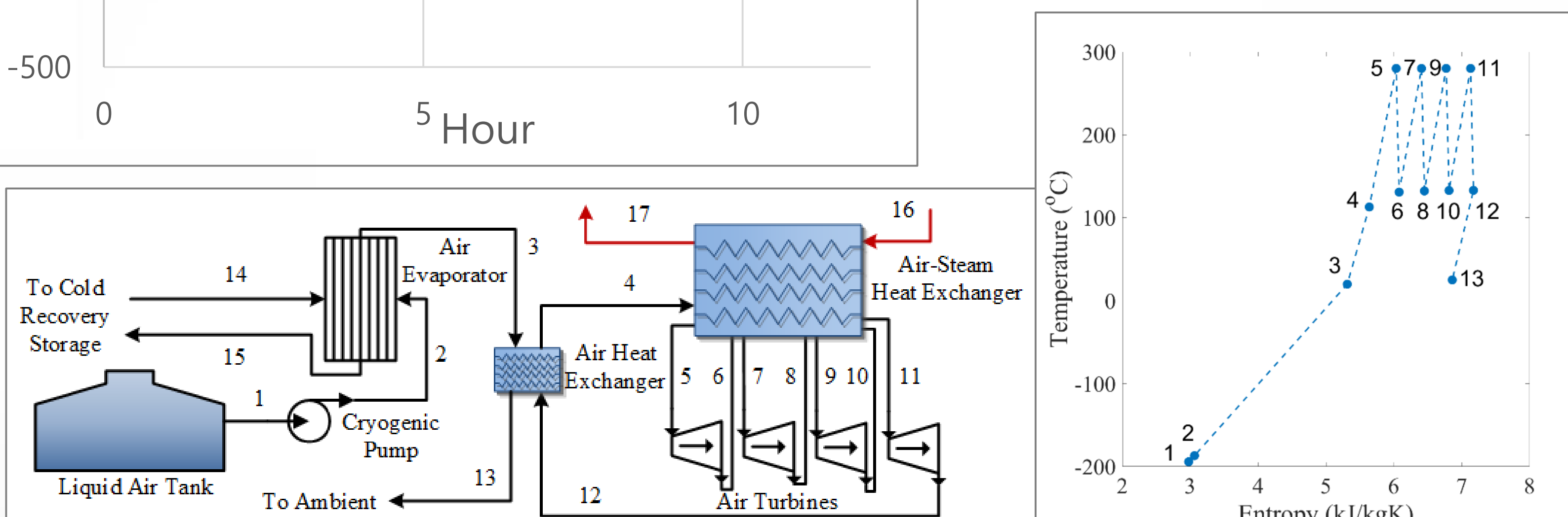


Fig. T-s diagram of the NPP-LAES system (left) and point schematic for discharging cycle (right)

Design sensitivity analysis

- Number of turbines and operating maximum pressure have been observed in sensitivity analysis
- As the number of turbines increase, the round-trip efficiency increases and mass flow rate decreases
  → Favorable trend for enhancing performance
- Trade-off between allowable limit for pressure and cost associated should be studied

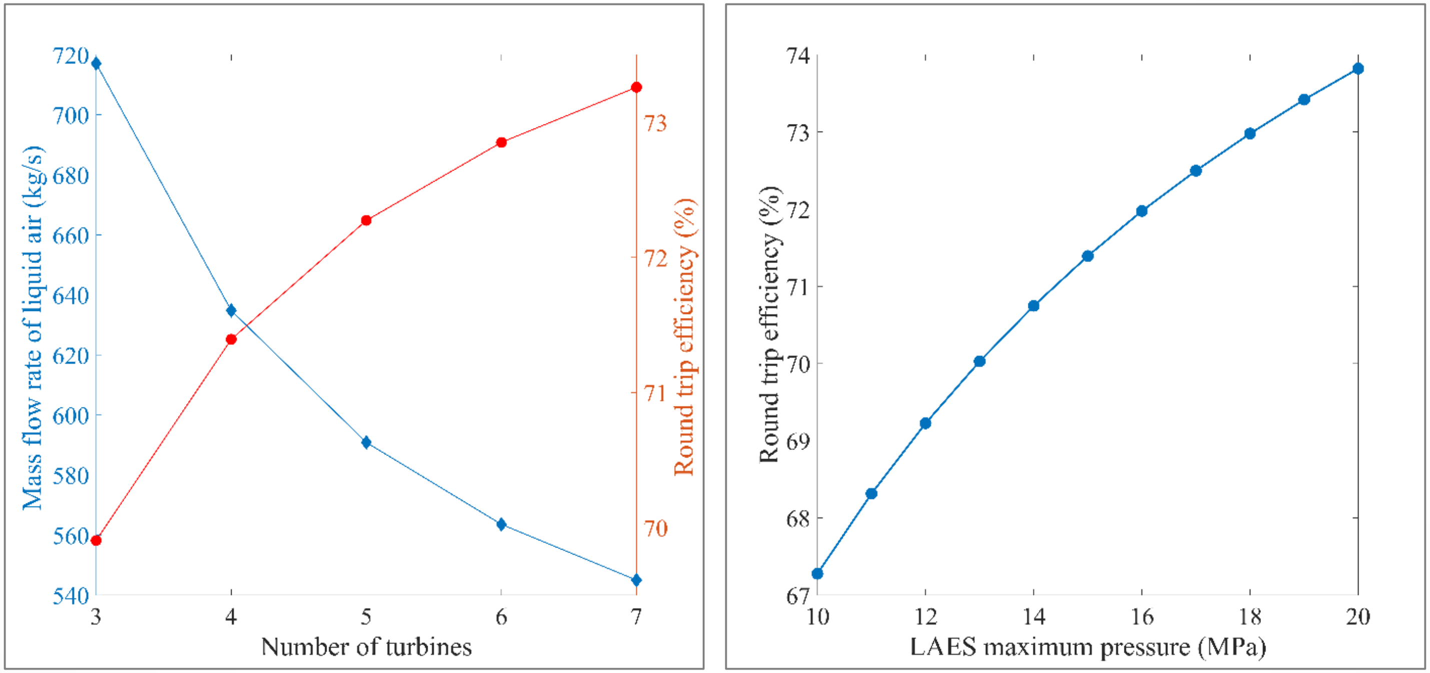


Fig. Performance of integrated system w.r.t. number of turbines (left) and maximum pressure (right)

Conclusions

1. Nuclear integration with grid-scale energy storage systems may enhance the economic competitiveness.

2. Integrating the APR1400 with the LAES under the objective of minimizing primary side temperature changes is studied thermodynamically. The design code is formulated to examine results for the proposed system.

3. Bypassing 10% of the steam flow (100%-90% load) before entering the steam turbines can ramp up the power generation by nearly 2.7 times, with round-trip efficiency of nearly 71%. Also, the maximum pressure can be increased to enhance the round trip efficiency, as long as the design limitations allow.

Future Work

1. Thermodynamic modelling of the NPP-LAES system should be further optimized with different layouts.

2. The performance changes during steam cycle transients should be investigated with respect to varying load conditions.

3. Variation of potential heat sources, condenser heat or feedwater stream in the steam cycle, can be considered for further heat integration.

4. Transient analysis of integrated LAES-NPP to determine safety margins, temperature transients at the steam generator inlet should be performed using system codes (e.g. GAMMA+).

5. Interface heat exchanger design should be conducted to investigate design capabilities.

6. Preferential boiling of liquid nitrogen over stored time will be investigated to observe any potential factors of performance deterioration.

References

1. IRENA (2018), Global Energy Transformation: A roadmap to 2050, International Renewable Energy Agency, Abu Dhabi.
2. Denholm, Paul, et al. Overgeneration from solar energy in California. A field guide to the duck chart. No. NREL/TP-6A20-65023. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2015.
3. Lokhov, Alexey. "Technical and economic aspects of load following with nuclear power plants." NEA, OECD, Paris, France (2011).
4. Li, Yongliang, et al. "Load shifting of nuclear power plants using cryogenic energy storage technology." Applied energy 113 (2014): 1710-1716.

Thank you

Questions are welcome

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