

Multi-energy liquid air energy storage powered by geothermal energy from an abandoned exploitation well – A techno-economic analysis

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Abstract

Liquid air energy storage is a promising thermo-mechanical electricity storage technology that can simultaneously deliver different energy streams, such as electricity, cooling, and heating. Yet, when operated in multi-energy mode, its commercial deployment remains constrained by limited round-trip efficiency and weak economic performance. This study proposes and techno-economically evaluates a novel integrated multi-energy LAES system coupled with 1) the low-grade geothermal heat from abandoned exploitation wells during discharging and 2) different industrial energy valorisation pathways, including direct waste heat utilization during the dehydrogenation of liquid organic hydrogen carriers, organic Rankine cycle, absorption chiller and clean dry air supply. The results show that bidirectional heat recovery and multi-output operation significantly enhance system performance. While stand-alone LAES remains economically unfeasible under all electricity tariff scenarios, exhibiting high LCOS of 0.97 USD/kWh_e and no viable discounted pay-back period, integrated configurations achieve LCOS values below 0.15 USD/kWh_e and a discounted pay-back period of 13.7 years. Among the investigated options, the configuration integrating direct waste heat utilization and clean dry air demonstrates the highest robustness to electricity price uncertainty. Furthermore, exploiting the horizontal extension of abandoned wells enables zero-emission geothermal heat recovery, offering a viable pathway for both well revitalization and electrical energy storage utilization.

Keywords

Liquid air energy storage (LAES), Carnot battery, Electrical energy storage, Geothermal, Organic Rankine cycle, Absorption chiller, Wafer fabrication.

1. Introduction

Clean energy supply and electrification are central to the shift to a net-zero emissions future energy system [1]. Hence, electricity – the backbone of future net zero integrated energy systems – should increase its share in the global final energy use from 20% to 50-70% by 2050, mainly via low-emission sources such as solar and wind power. To accommodate the increasing shares of

renewables and secure power system flexibility, the rapidly evolving global energy mix requires a broad portfolio of options, including energy storage and hydrogen [2].

Liquid air energy storage (LAES) is a promising electrical energy storage technology that recently gained growing popularity. By using air as both the energy storage medium and the working fluid, LAES proves to be a low-cost, high-energy density, and eco-friendly technology well-suited for medium to large-scale applications without locality constraints like pumped hydro or compressed air energy storage technologies. The working principles of an LAES system are illustrated in **Fig. 1**: air is liquefied by electricity during the charging stage, stored in a liquid air tank during the storage stage, and regasified for power production during the discharging stage. The waste heat from air compression and waste cold from air regasification during charging and discharging, respectively, are stored using thermal energy storage (TES) technologies to augment the round-trip efficiency (RTE). Hence, one main bottleneck to the current deployment of LAES is represented by the high energy consumption during the liquefaction cycle (charging stage), undergoing the compression of air at relatively high pressures to achieve adequate liquid air yield. In particular, the recovery process of the air compression heat in the discharge phase is crucial to obtain acceptable RTE values. Thus, one key to ensuring the high efficiency of an LAES system is to realize higher temperature compression and compression heat storage (usually 180 – 400 °C), despite only a fraction of the compression heat being needed for the discharging stage, and around 20%–45% of the compression heat may be surplus.

Nomenclature			
h	Enthalpy [kJ/kg]	SEAC	Single-effect absorption chiller
k	Conductivity [W/mK]	TES	Thermal energy storage
m	Mass flow rate [kg/s]	<i>Greek symbols</i>	
Q	Thermal power [kWth]	μ	Utilization factor [-]
T	Temperature [°C]	η	Efficiency [-]
t	time [h]	<i>Subscripts</i>	
W	Electrical power [kWe]	amb	Ambient
<i>Acronyms</i>		ave	Average
ABC	Absorption chiller	BM	Bare Module
AEW	Abandoned exploitation well	C	Compression
CAPEX	Capital cost [USD]	ch	Charge
CDA	Clean dry air	CP	Cryogenic pump
COP	Coefficient of Performance [-]	CT	CryoTurbine
CTES	High grade cold storage	d	Discharge
DEAC	Double-effect absorption chiller	des	Desorber
DPBP	Discounted Pay-back period [year]	eva	Evaporator
DU	Direct Utilization	f	Fluid phase
ET	Electricity tariff [USD/kWhe]	i	Discount rate
HGWS	High grade warm storage	in	Inlet
HTF	Heat transfer fluid	iso	Isentropic
LAES	Liquid air energy storage	l	Liquid phase
LCOS	Levelised cost of storage [USD/kWhe]	lat	Latent
LOHC	Liquid organic hydrogen carrier	out	Outlet
NPV	Net Present Value [USD]	pp	Pinch Point
OPEX	Operational Cost [USD]	s	Storage
ORC	Organic Rankine cycle	SH	Superheater
RTE	Round trip efficiency	th	Thermal
SC	Specific consumption [kWh/kg]	wf	Working fluid

One of the most interesting features of LAES technology is that it can be operated as a poly-generation, or multi-energy system, simultaneously producing electricity (from the generator), heat (from the air compression), and cooling energy (from either the regasification process or the turbine outlet). Notably, heating and cooling represent more than 50% of global energy end use [3]. Energy systems integration – including coordinating the operation and planning of energy systems across various pathways and geographical scales [4] – is crucial for innovative energy technologies like LAES to become commercially viable and competitive [5]. In a multi-energy asset, LAES serves not only to generate electricity but also to provide heating and cooling to external systems. This setup can involve integrating LAES with district heating and cooling networks or directly into buildings to meet thermal energy demands by repurposing waste heat or cold from LAES operations [6].

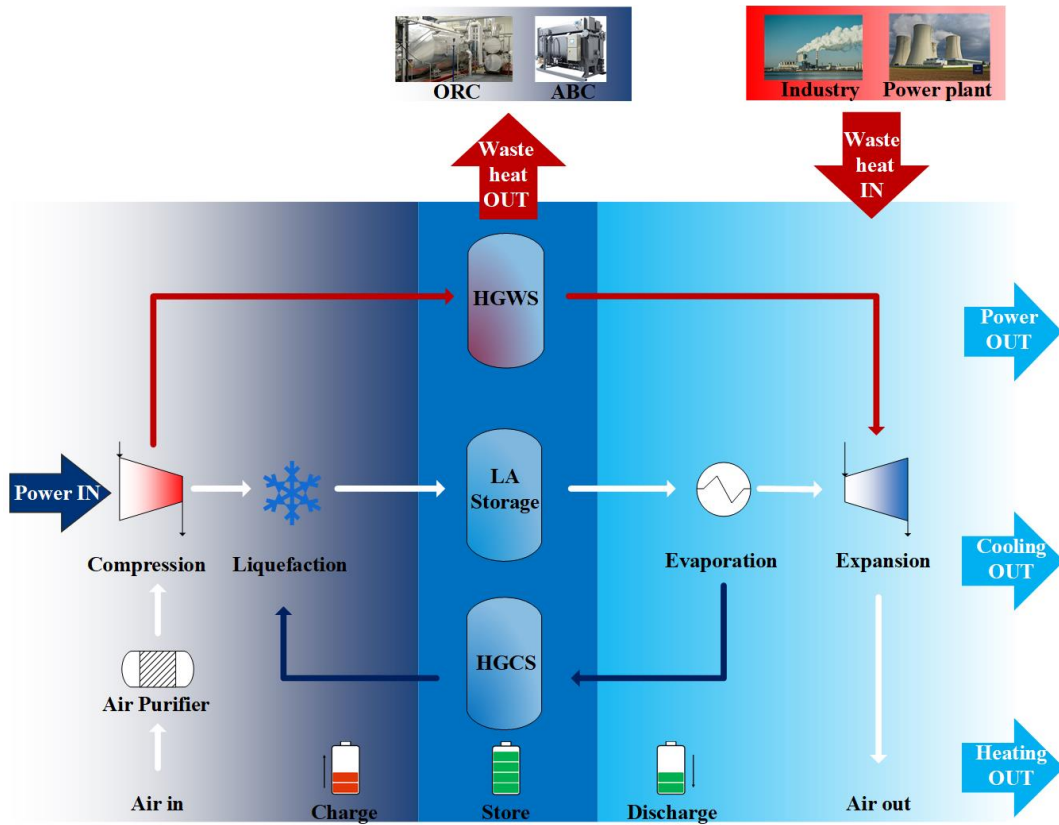


Fig. 1. The working principles of a liquid air energy storage (LAES) system integrating different waste heat recovery technologies and external heat/cold sources. Adapted from Ref. [7].

Studies have also shown that properly utilizing the excess waste heat through integration with other processes improves overall energy efficiency. A series of medium-to-low temperature powering and cooling technologies, such as organic Rankine cycle (ORC), absorption chiller (ABC), Kalina cycle (KC), and thermo-electric generator (TEG), has been studied in the literature. For example, She et al. [8] integrated an LAES with an ORC. A higher exergy efficiency and round-trip efficiency (RTE) of 9-12 % were achieved. Nabat et al. [9] proposed a combined KC and TEG hybridization. The RTE increased to 61.6% at the optimum charging and discharging pressures. All of the studies indicate that integration with external heat users can improve overall performance of all subsystems leading to cost-saving and emission reduction.

Nevertheless, although LAES generates substantial compression heat, several studies have avoided the additional investment associated with high-temperature thermal energy storage (HTES) and diathermic oil systems by directly employing external high-temperature heat sources to support air expansion during discharge. More broadly, because LAES is inherently thermo-mechanical, it can provide multiple energy outputs while also integrating external waste heat or

cold sources in a bi-directional manner. To improve the techno-economic performance of LAES, various hybrid configurations have therefore been explored, using external cold sources to support air liquefaction or external heat sources to enhance discharge-stage efficiency.

Recent studies carried out by Kim et al. [10] and Tafone et al. [7] investigated the coupling of LAES with the hydrogen supply chain, focusing on techno-economic assessments of waste-cold recovery from liquid hydrogen regasification. Their analyses demonstrate that exploiting cryogenic cold from hydrogen infrastructure can significantly enhance LAES performance and deliver system-level benefits within broader energy planning frameworks.

On the heat integration side, Briola et al. [11] proposed using the waste heat from natural gas power production processes (around 1250 °C) for LAES discharging and achieved a maximum storage efficiency (a self-defined indicator) of 2.173. Cetin et al. [12] combined LAES with a single flash geothermal power plant with a stream of geothermal energy at 180 °C supplied to the LAES discharging stage. The RTE of LAES was 46.7%, but the integrated energy system reached an efficiency of 24.4%, significantly higher than that of a conventional geothermal power plant, which is usually around 12% [13].

Using external heat for LAES can also bring extra benefits. Storing the compression heat can take about 4 -10% of the CAPEX of a standalone LAES system. The system CAPEX can be reduced with similar or higher RTE by completely using external heat sources and removing the high-temperature heat storage. However, the compression heat in these studies was neither utilized nor stored. Moreover, most studies used high-grade external heat sources that are enough even for direct power generation. Despite the enormous amount of waste heat generated around the globe, most low-grade waste heat sources are rarely utilized. Among them, oil and gas wells in the United States co-produce around 25 billion barrels of fluid at temperatures of 80 °C – 150 °C [14]. Once abandoned, approximately 30 million abandoned exploitation wells (AEWs) around the globe still have the potential to produce massive amounts of geothermal heat below 150 °C [15]. If not properly treated, AEWs cause significant environmental hazards. Geothermal exploitation not only saves the treatment cost of around 0.1 – 1.6 million USD per well [16], but also avoids the costs of drilling, which takes half of the CAPEX of a conventional geothermal power plant. However, direct electricity production using the AEW geothermal energy suffers from an efficiency of as low as around 5% [17], making the integration of a cryogenic temperature cold sink a viable option to realize high-efficiency power production from AEW.

In the general context of long-duration storage solutions for renewables penetration enhancement, AEWs represent a valuable opportunity for LAES, whose widespread deployment remains constrained by relatively low round-trip efficiency and weak economic competitiveness when operated as a stand-alone system. Indeed, addressing these limitations requires moving beyond isolated storage concepts toward integrated, site-specific solutions that can exploit locally available resources. In this regard, AEW inherent geothermal potential can be harnessed to support LAES operation during the discharge phase, while their existing infrastructure reduces the need for new drilling investments. In this way, AEW-integrated LAES systems offer a pathway to translate global grid flexibility requirements into practical, location-specific energy solutions.

In a previous study [15], the authors designed a two-stage organic Rankine cycle using AEW geothermal heat (110 °C) as the heat sink and liquified natural gas regasification (around -160 °C) as the cold sink. A significantly higher efficiency of 24% was obtained. Similarly, the discharging stage of liquid air in an LAES is another ideal cold sink, with the expansion temperature to be as low as -190 °C. If using LAES as the power cycle, the generally wasted AEW geothermal heat can be an ideal heat source for power production and high-efficiency electricity storage. In this case, the reduced heat source temperature during the expansion may also reduce the outlet temperature of the heat transfer fluid, making it possible to provide cooling to co-located cold energy users.

On the excess heat side, with the geothermal energy from the AEW serving the expansion heat demand of the discharging stage, the high-grade waste heat during the compression process is unexploited, and therefore, it can all be used for higher-value applications. Since its temperature

is considerably higher than AEW, the waste heat can be either employed for: i) electricity production via organic Rankine cycle (ORC), increasing thus the RTE of LAES; ii) cooling production via absorption chiller (ABC), increasing thus the utilization ratio of LAES. Alternatively, direct heat supply to industrial needs can avoid the conversion loss from heat to electricity and then back to heat.

Therefore, in this study, we evaluate three different strategies for waste heat recovery: 1) RTE enhancement through electricity production via ORC implementation; 2) Utilization ratio enhancement through cooling production via ABC implementation, and 3) direct use of waste heat through a co-located dehydrogenation plant for liquid organic hydrogen carriers (LOHCs). LOHC is among the three most promising technologies for long-distance hydrogen transportation since it is potentially cheap, safe, and easily manageable [18]. The LOHC concept employs a liquid organic compound to react with H_2 during hydrogenation [19]. The product is transported to users potentially via traditional oil vessels. During dehydrogenation, the LOHC decomposes and H_2 is released. This process is highly endothermic and can take 70% of the levelized cost of the whole process. According to Hank et al. [20], waste heat integration for dehydrogenation can increase the LOHC pathway efficiency by 16 – 18%, and the temperature level of LAES compression heat matches well with a series of LOHCs, including the toluene/methylcyclohexane (TOL/MCH) cycle, which requires a dehydrogenation temperature of 250 – 450 °C [18]. Since LAES compression heat is usually stored at temperatures between 300°C to 400°C [21], this range perfectly encompasses and exceeds the temperature range required for LOHC dehydrogenation, allowing for direct or slightly upgraded use. Industrial waste heat, on the other hand, is usually lower than 150°C except for geographically limited processes such as cement manufacturing [22], making them less suitable for direct usage without significant effort of temperature upgrading or co-location.

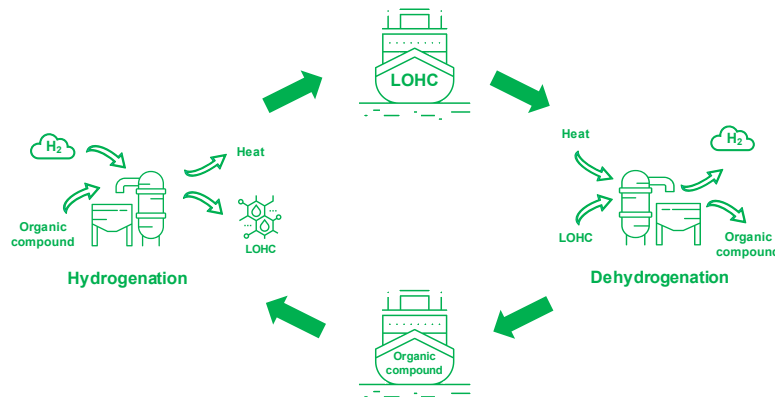


Fig. 2. LOHC supply chain concept.

In addition, coupling LAES with AEW enables the expansion exhaust air to be delivered at temperatures compatible with compressed or clean dry air (CDA) applications. CDA is extensively used in semiconductor manufacturing facilities to operate pneumatic equipment, control valves, and maintain clean processing environments [23]. However, conventional CDA production involves energy-intensive air treatment, including deep dehumidification to dew points of -20 °C or lower, making it one of the largest electricity consumers in wafer fabs and accounting for approximately 20% of total power demand, with even higher consumption in humid regions such as Southeast Asian countries [23]. In contrast, air processed within the LAES liquefaction cycle already undergoes rigorous purification, resulting in very low moisture and CO_2 content, the dryness and cleanliness of the LAES outlet air, on the other hand, is qualified enough to serve as the CDA for wafer fabs [7]. By utilizing the geothermal heat from AEWs for the expansion stage, we can deliver this inherently ultra-dry and clean air at temperatures and pressures directly compatible with wafer fab requirements. This approach eliminates the massive electricity penalty

associated with standalone dehumidification units, turning a waste stream into a critical industrial utility.

In summary, rather than treating LAES as a standalone technology, it has been reimagined as a polygenerative hub where the concept of bi-directional heat recovery is central to the integration strategy of the work. On one side, LAES provides high-grade heat for industrial users or for waste heat recovery purposes. On the other, LAES absorbs low-grade geothermal heat during the discharge phase. When complemented by additional services—such as heating, cooling, and clean dry air for the semiconductor sector—the system evolves into a versatile, multi-energy platform. Together, these combined synergies substantially improve utilization, energy productivity, and economic viability.

2. System description

The configuration of the multi-energy stand-alone LAES system, taken as reference, is presented in **Fig. 3**, which clearly highlights the different phases of the energy storage system's operation. In the figure, dark blue thick arrows represent the cooling load provided to the district cooling user.

The system consists of five core subsystems: i) charge phase for air liquefaction, ii) liquid air storage, iii) high temperature thermal energy storage (HGWS), iv) a cryogenic thermal energy storage (HGCS) and v) a discharge phase based on direct air expansion.

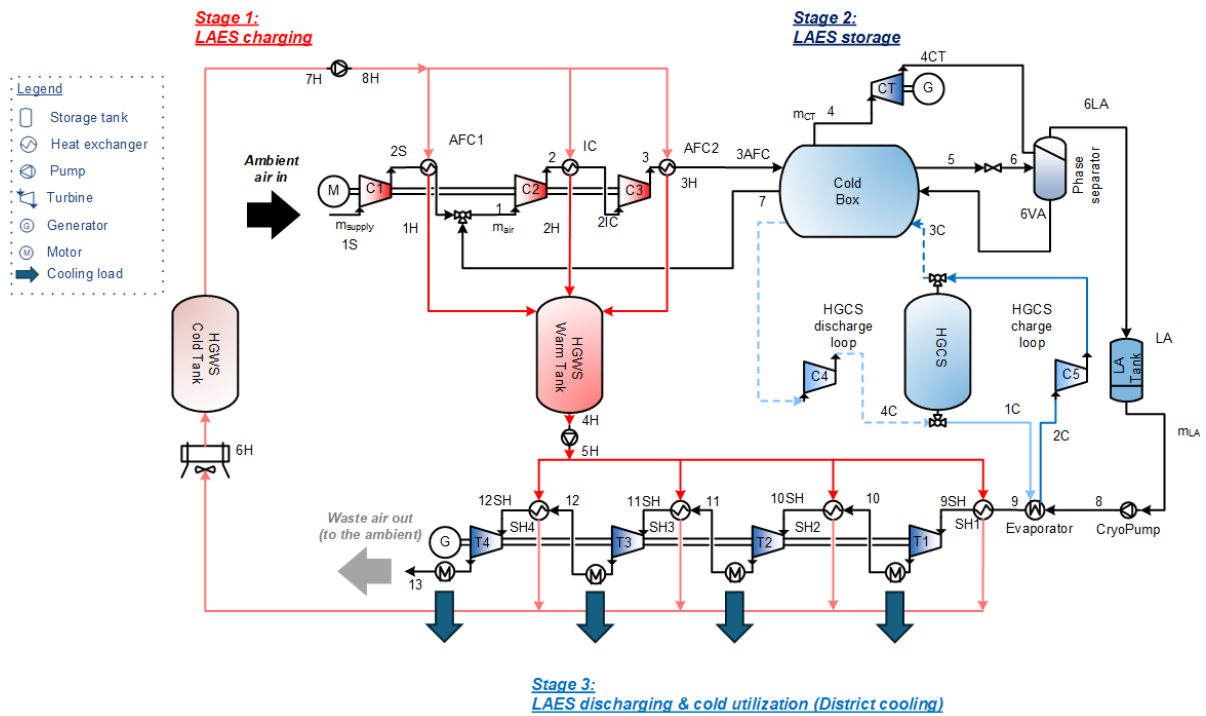


Fig. 3. Multi-energy stand-alone LAES process flow diagram.

During charging, ambient air is liquefied using a Kapitza cycle, where three intercooled compression stages—powered by off-peak electricity—raise the air to high pressure before it enters a multi-stream cold box heat exchanger. Inside the cold box, part of the air expands through a cryogenic turbine (CT), producing work via generator G and reaching cryogenic temperatures, while the remaining fraction is throttled across a Joule–Thomson valve to the storage pressure. Liquid air is then drawn from a phase separator and stored in pressurized tanks, while the non-liquefied stream (6VA) precools the incoming high-pressure air through recuperation. The compression train also releases significant high-grade heat, which is captured by a diathermic fluid in a two-tank HGWS system.

During discharging—operated during peak-demand periods—the stored liquid air is pumped (CryoPump), evaporated, and expanded through a multi-stage, reheated turbine train using the thermal energy accumulated in the HGWS, feeding electricity back to the grid. At the turbine outlet, the cold air is used to provide the required cooling load to the district cooling user. Simultaneously, the cold released during evaporation is stored in the HGCS packed-bed unit, which subsequently cools the inlet air during the next charging cycle to improve round-trip performance. Nitrogen and Therminol 66 serve as the heat-transfer fluids in the HGCS and HGWS loops, respectively.

The integrated multi-energy LAES-AEW system (**Fig. 4**) retains the core architecture of the stand-alone LAES system, while introducing significant modifications.

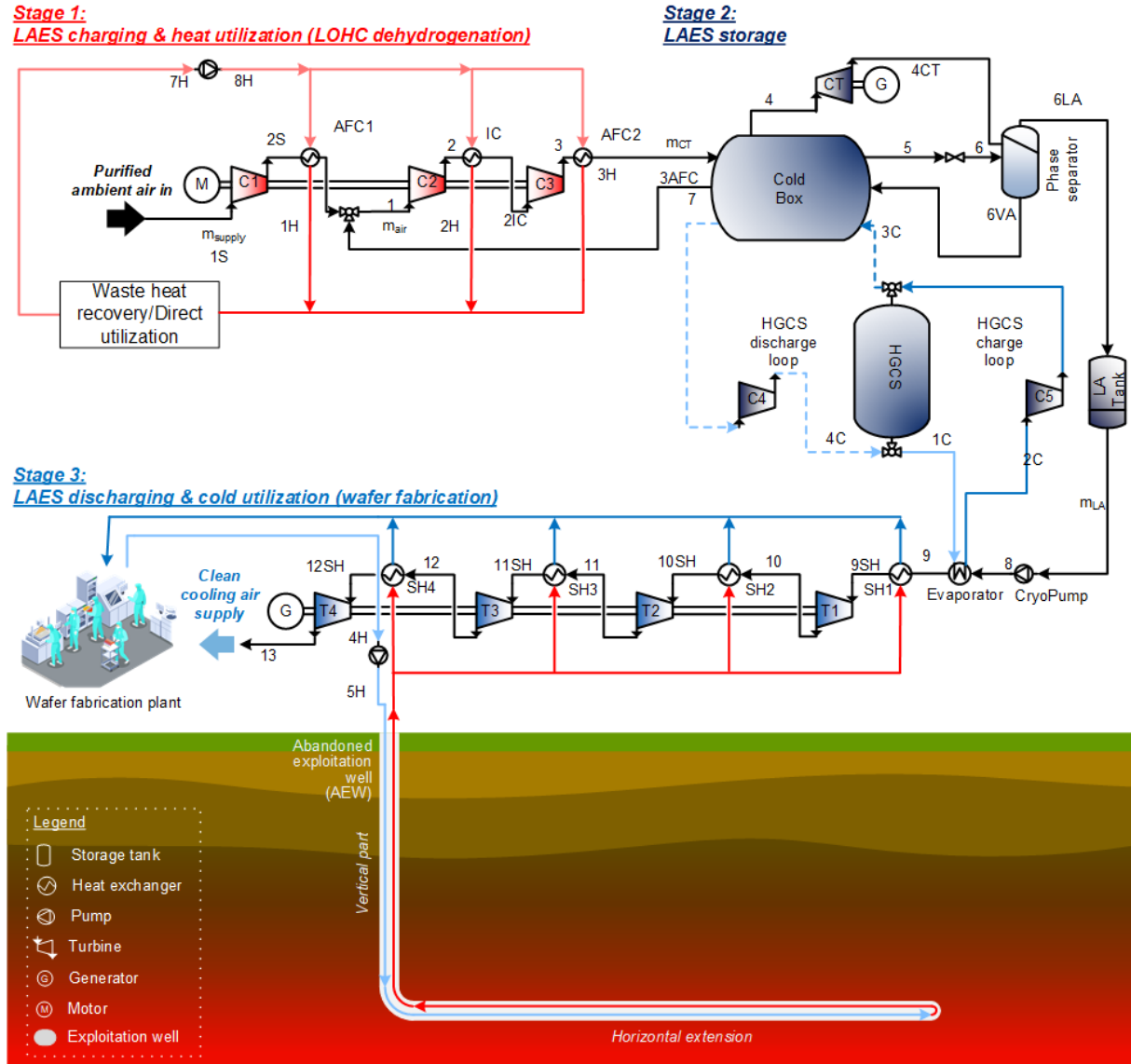


Fig. 4. Integrated LAES-AEW process flow diagram process.

At Stage 1 (LAES charging & waste heat utilization – ORC/ABC/LOHC dehydrogenation), after the ambient air is purified and dried, it enters the cascade compressor unit C1-C3 to increase the pressure. During this period, the heat generated by the compressor's work is taken away by the cooling water and used for a waste heat recovery system (ORC evaporator/ABC generator), or for the preheating of MCH in a TOL/MCH-based LOHC dehydrogenation plant before it enters the dehydrogenation reactor.

At Stage 2 (LAES storage), the compressed air is routed into the cold box, where it is progressively cooled before undergoing expansion in the turbine CT, producing mechanical work that is converted into electricity by the generator G. The resulting cryogenic stream is partially liquefied and directed to the liquid air storage tank (LA), while the remaining gaseous fraction is recirculated to the cold box to support the regenerative cooling process. At Stage 3 (LAES discharging & cold utilization for wafer fabrication), the liquid air is pressurized by the cryopump, evaporates in the evaporator, and expands in several stages of turbines to produce electricity. The primarily untapped low-grade geothermal energy from AEW is used for air expansion. The cold outlet heat transfer fluid (water) and the CDA at the turbine outlet are directly provided to a wafer fab for its cooling demand and manufacturing processes.

3. Mathematical models

The technical analysis is conducted using MATLAB R2025a, where dedicated routines were implemented to simulate the various components and subsystems of both the stand-alone and integrated multi-energy LAES configurations. All component models adopted in this study were previously developed and validated in the authors' earlier works. The machine learning model developed by Xiao et al. [15] for the AEW simulation is used to simulate the outlet water temperature of the AEW geothermal energy exploitation. The thermodynamics model developed by Tafone et al. [24] is used to simulate the performance of the LAES subjected to the waste heat supply from the AEW. The steady-state organic Rankine cycle implemented in Tafone et al. [7,25], is used to simulate the organic Rankine cycle exploiting the waste heat from the air compression process. The absorption chiller model is simulated using SorpPump, an open-source thermodynamic solver framework [26]. For the LOHC dehydrogenation plant, it is assumed that the compression heat is used to replace high temperature heat pumps for MCH preheating. For the wafer fab, cooling and CDA are supplied to save the operational cost of the cooling units, air purifiers, and air dehumidifiers. Assumptions and design parameters used in the models are listed in **Table 1** and **Table 2**.

The mathematical models for the individual LAES components have been thoroughly detailed in previous publications by the authors and will therefore not be repeated here. The mathematical models of the newly integrated subsystems—namely the AEW, ORC, and ABC modules—have been reported in **Appendix A1**. Readers are referred to Refs. [15][25][27] for the complete models formulation of the AEW, the ORC and the ABC, respectively.

Table 1. LAES and ORC mathematical assumptions

Parameters	Value
T_{amb} , Air inlet temperature (°C)	25
T_{AEW} , AEW outlet temperature (°C)	110
t_{ch} , Charge time (h)	6
t_d , Discharge time (h)	3
p_{ch} , Charge pressure (bar)	119
p_d , Discharge pressure (bar)	145
p_s , Storage pressure (bar)	7.8
$\eta_{iso,P}$, Cryo-pump isentropic efficiency (%)	80
ΔT_{EVA} , Evaporator cold end temperature approach (°C)	5
ΔT_{SH} , Superheater hot end temperature approach (°C)	10
$\Delta T_{PP,CB}$, Cold box pinch point approach (°C)	2

Table 2. ORC and ABC mathematical assumptions.

Parameters	Value
$\eta_{iso,ORC,P}$, ORC pump isentropic efficiency (%)	80
$\Delta T_{EVA,ORC,PP}$, ORC evaporator pinch point temperature difference (K)	5
$\Delta T_{COND,ORC,PP}$, ORC condenser pinch point temperature difference (K)	5
$\Delta T_{EVA,ABC,PP}$, ABC evaporator pinch point temperature difference (K)	5
$\Delta T_{ABS,ABC,PP}$, ABC absorber pinch point temperature difference (K)	8
$\Delta T_{SHEX,ABC,PP}$, ABC SHEX pinch point temperature difference (K)	8
$\Delta T_{DESO,ABC,PP}$, ABC desorber pinch point temperature difference (K)	8
$\Delta T_{COND,ABC,PP}$, ABC condenser pinch point temperature difference (K)	5
$\eta_{iso,ORC,P}$, ABC solution pump isentropic efficiency (%)	95
$c_{min,sol,ABC}$, Minimal solution concentration difference (%)	5

3.1. Techno-economic analysis

A comprehensive techno-economic assessment is conducted to quantify the economic performance of the integrated energy system. The underlying assumptions, definitions, and economic parameters adopted in this analysis are summarized in **Table 3**. The total investment cost of the LAES plant is estimated using the module costing approach [28], whereby the bare module cost (C_{BM}) of each component is first calculated and then updated to present-year values using the Chemical Engineering Plant Cost Index (CEPCI) to account for inflation from the reference year X:

$$CAPEX_{LAES} = \sum C_{BM,i} \left(\frac{CEPCI_{2022}}{CEPCI_X} \right) \quad (1)$$

A more exhaustive description of the empirical correlations and methods implemented to assess the capital cost of each LAES component and the related assumptions can be found in Ref.[7]. A system lifetime of 35 years is assumed for the overall plant. Component-level replacement of shorter-lived units such as ORC systems (25 years) and absorption chillers (up to 30 years) is not explicitly modeled and is considered a second-order effect within the scope of this system-level analysis.

Table 3. Assumptions for the techno-economic analysis

Parameters	Value	Unit	Reference
<i>Lifetime</i>	35.00	year	[29]
$ET_{off,peak}$	0.21	USD/kWh _e	[30]
ET_{peak}	0.47	USD/kWh _e	[30]
n_{cycle}	365.00	Cycle/year	Assumption
$OPEX_{LAES,Power}$	12.03	USD/kW _e /year	[7]
$OPEX_{LAES,Energy}$	0.0029	USD/kWh _e /year	[7]
$OPEX_{ORC}$ (%CAPEX)	2.50	%	[7]
<i>Clean dry air specific consumption (SC_{CDA})</i>	0.15	kWh _e /m ³	[23]
$CEPCI_{2023}$	797.90	-	[31]
i	5.00	%	Assumption

To estimate the capital cost of the AEW renovation, the following correlation, developed by Xiao et al. [15], has been implemented as:

$$CAPEX_{AEW} = \alpha_{other} SIC_{GEO,eq} P \frac{\eta_{world,ave}}{\eta} \quad (2)$$

where $\alpha_{other} = 31\%$ is the share of the other costs in a conventional geothermal plant, $SIC_{GEO,eq}$ [USD/kW_e] is the average specific investment cost (SIC) for small geothermal projects (less than 1 MW_e) in the IRENA renewable power generation costs report [32], $\eta_{world,ave}$ is the worldwide average efficiency of geothermal plants, and η is the overall efficiency of the AEW geothermal plant.

The capital cost of the absorption chiller was estimated through a thorough market survey conducted for 23 single and double effect absorption chillers within two decades, including the quotations the authors received. Based on this analysis, the following correlation has been implemented to retrieve the specific investment cost (SIC) expressed in USD/kW_e as a function of the cooling power output of the ABC unit as expressed in Eq.(9):

$$SIC_{ABC} = 4420 (\dot{Q}_c)^{-0.342} \quad (3)$$

The capital cost of the organic Rankine cycle is estimated using an empirical correlation proposed by Xiao et al. [15], derived from market survey data collected over the past decade. This correlation relates the specific investment cost (SIC), expressed in USD/kW_e, to the net electrical output of the ORC unit, as defined in Eq. (10).

$$SIC_{ORC} = -678 \ln(\dot{W}_{net,CRC}) + 6725.4 \quad (4)$$

The first law analysis was implemented to compute the main performance indices of the LAES, namely the liquefaction specific consumption (SC_{LAES}) and the round-trip efficiency (η_{RT}) computed as:

$$SC_{LAES} = \frac{\int_0^{t_{ch,LAES}} \dot{W}_{net,ch} dt}{\int_0^{t_{ch,LAES}} \dot{m}_{LA} dt} \quad (5)$$

$$\eta_{RT} = \frac{\int_0^{t_d} \dot{W}_{net,d} dt + \int_0^{t_d} \dot{W}_{net,ORC} dt}{\int_0^{t_{ch}} \dot{W}_{net,ch} dt} \quad (6)$$

where $\dot{W}_{net,ch}$ and $\dot{m}_{LA}$ are the instantaneous net power consumption and liquid air production during the LAES charge phase, respectively, and $\dot{W}_{net,d}$ and $\dot{W}_{net,ORC}$ are the instantaneous net power production during the LAES discharge phase and the ORC operation, respectively.

Due to the polygenerative capability of LAES, an overall efficiency (η_o) has also been defined taking into account both the thermal (cooling and heating) and the electrical output:

$$\eta_o = \frac{\int_0^{t_d} \dot{W}_{net,d} dt + \int_0^{t_d} \dot{W}_{net,CRC} dt + \int_0^{t_{ch}} \frac{\dot{Q}_{th}}{COP_H} dt + \int_0^{t_d} \frac{\dot{Q}_c}{COP_C} dt}{\int_0^{t_{ch}} \dot{W}_{net,ch} dt} \quad (7)$$

where $\dot{Q}_{th}$ and $\dot{Q}_c$ are the instantaneous thermal and cooling power production, during the LAES charge and discharge phase, respectively.

The levelized cost of storage (LCOS) represents the discounted ratio between the total lifetime costs of an electricity storage system and the cumulative electrical energy delivered over its operational lifetime. The delivered electricity is evaluated on an annual basis (n) across the total lifetime N (years) and discounted using an interest rate i (%):

$$LCOS = \frac{CAPEX + \sum_{n=1}^N \frac{EC}{(1+i)^n} + \sum_{n=1}^N \frac{OPEX_{O\&M}}{(1+i)^n} - \sum_{n=1}^N \frac{Rev_{CDA}}{(1+i)^n} - \sum_{n=1}^N \frac{Rev_{Cooling}}{(1+i)^n} - \sum_{n=1}^N \frac{Rev_{Heating}}{(1+i)^n}}{\sum_{n=1}^N \frac{E_d}{(1+i)^n}} \quad (8)$$

where $CAPEX$ [MUSD] is the capital cost of the system; EC [MUSD] is the electricity cost required to charge the LAES, calculated as a function of the electricity tariff and the round-trip efficiency; $OPEX_{O\&M}$ [MUSD] represents the operation and maintenance costs of both LAES and ORC; Rev_{CDA} [MUSD] is the revenue derived from clean dry air sale; $Rev_{Cooling}$ [MUSD] is the revenue associated with the cooling service; $Rev_{Heating}$ [MUSD] is the revenue associated with the heating service; E_d [kWh_e] is the electricity produced during the discharge phase.

The net present value (NPV) of the investment describes the economic feasibility of the project by taking into consideration the $CAPEX$, the yearly Cash Flow (CF_n) the discount rate and the lifetime of the system:

$$NPV = \sum_{n=1}^N \frac{CF_n}{(1+i)^n} - CAPEX \quad (9)$$

The discounted pay-back period ($DPBP$) is computed by evaluating the number of years ($DPBP$) to achieve a NPV value of zero:

$$DPBP = \{N \mid NPV = 0\} \quad (10)$$

4. Results and discussion

The objective of this section is to comparatively assess the performance of the multi-energy stand-alone LAES and the integrated configurations to evaluate their technical and economic performance. **Table 4** reports the seven study cases under investigation, defining a specific code for each configuration assessed.

Table 4. Case studies nomenclature and description.

Nomenclature	Configuration description
SA LAES	Stand-alone LAES
LAES-AEW-DU	Integrated LAES with AEW and direct utilization of the waste heat.
LAES-AEW-DU-CDA	Integrated LAES with AEW, direct utilization of the waste heat and clean dry air utilization.
LAES-AEW-ORC	Integrated LAES with AEW and organic Rankine cycle.
LAES-AEW-ORC-CDA	Integrated LAES with AEW and organic Rankine cycle, with clean dry air utilization.
LAES-AEW-ABC	Integrated LAES with AEW and absorption chiller.
LAES-AEW-ABC-CDA	Integrated LAES with AEW and absorption chiller, with clean dry air utilization.

4.1. Energy performance analysis

Table 5 summarizes the key technical parameters of both the stand-alone and integrated multi-energy LAES systems. To ensure a consistent basis for comparison, the two configurations are designed with identical storage capacity and discharge power, while differences in performance arise from the system integration and operating strategies.

Table 5. Technological parameters of the multi-energy integrated and stand-alone LAES systems

Items [unit]	SA LAES	LAES-AEW-DU	LAES-AEW-DU-CDA	LAES-AEW-ORC	LAES-AEW-ORC-CDA	LAES-AEW-ABC	LAES-AEW-ABC-CDA
$\dot{W}_{net,d}$ [kW _e]	410.72	410.72	410.72	410.72	410.72	410.72	410.72
$\dot{Q}_c$ [kW _e]	97.85	59.71	59.71	59.71	59.71	425.77	425.77
$\dot{Q}_{th}$ [kW _{th}]	-	466.25	466.25	-	-	-	-
η_{RT} [%]	44.84%	44.84%	44.84%	55.95%	55.95%	44.84%	44.84%
η_o [%]	47.01%	85.36%	85.36%	57.62%	57.62%	76.94%	76.94%
SC [kWh _e /kg _{LA}]	0.25	0.25	0.25	0.20	0.20	0.25	0.25
SP [kWh _e /kg _{LA}]	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$\eta_{el,ORC}$ [%]	-	-	-	13.79	13.79	-	-
COP_{ABC} [-]	-	-	-	-	-	1.11	1.11
T_{WH} [°C]	222.91	222.91	222.91	222.91	222.91	222.91	222.91
p_{WH} [bar]	1.50	1.50	1.50	1.5	1.5	1.50	1.50
$\dot{m}_{WH}$ [kg/s]	1.22	1.22	1.22	1.22	1.22	1.22	1.22
$\dot{m}_{LA}$ [kg/s]	0.51	0.51	0.51	0.51	0.51	0.51	0.51
HTF LAES charge	Therminol 66	Therminol 66	Therminol 66	Therminol 66	Therminol 66	Therminol 66	Therminol 66
HTF LAES discharge	Therminol 66	Water	Water	Water	Water	Water	Water

The results clearly demonstrate that all integrated configurations outperform the stand-alone LAES system in terms of global energy utilization, but the mechanisms of improvement differ depending on the integration pathway. Overall, the combination of AEW heat recovery, enhanced thermal management, and multi-energy outputs leads to higher system utilization, improved energy productivity. The performance enhancements can be better understood by examining three key dimensions: i) overall efficiency indicators; ii) thermal and cold energy outputs and iii) subsystem performance (i.e. ORC and ABC).

The ORC-based configurations (LAES-AEW-ORC and LAES-AEW-ORC-CDA) show the most pronounced enhancement in round-trip efficiency, increasing from 45% (stand-alone) to 56 %. This nearly 11 %-point gain stems from the extra 91 kW_e electrical power produced by the ORC, which offsets part of the charging power requirement and decreases the liquefaction specific consumption from 0.25 to 0.20 kWh_e/kg_{LA}, as shown in **Table 5**. This demonstrates that the ORC provides not only an incremental power boost but also a more effective valorization of the compression heat, which would otherwise remain unused.

The absorption chiller configurations also exhibit higher overall energy efficiency compared to the stand-alone LAES with an overall LAES efficiency increased from 47 % to 77 % due to the extra cooling power produced by the cascaded ABC. Indeed, the cascaded ABC system converts the available temperature glide of the thermal oil stream into a total useful cooling capacity of 348.4 kW_{th}, comprising 251.6 kW_{th} from the DEAC stage and 96.8 kW_{th} from the SEAC bottoming stage. When evaluated using the combined performance metric defined in Eq. (COP_{eff}), the cascaded configuration achieves an effective COP of 1.11. This value is used directly in the integrated LAES-AEW system analysis to represent the overall thermal-to-cooling conversion performance of the absorption subsystem. To maintain focus on system-level integration, all intermediate cycle characteristics, including COP sensitivity to desorber temperature, the distribution of heat extraction across individual DEAC and SEAC passes are presented in the **Appendix A2**. From the pure electrical efficiency perspective, the round-trip efficiency does not

change (η_{RT} stays at 44.84%) but the system gains substantial thermal productivity, raising the share of useful energy outputs by transforming waste heat into value-added cooling. This supports the idea that integrating an ABC is primarily beneficial for transforming waste heat into value-added cooling, especially when aligned with cooling-dominated users.

In the waste heat direct utilization (DU) cases, the round-trip efficiency remains unchanged, but the overall efficiency increases significantly from 47 % to 86 %. Here, efficiency gains arise from direct heat sale or utilization, not from increased electrical output. This confirms that the DU pathway enhances revenue and energy valorization, but does not change the thermodynamic core of the LAES cycle.

4.2. Economic performance analysis

The techno-economic assessment reveals several noteworthy trends regarding the performance of the integrated LAES–AEW systems relative to the stand-alone LAES configuration. The techno-economic results computed assuming the methodology presented in Section 3.1 are firstly shown in **Fig. 5**, providing the calculated *CAPEX* for all the systems. The economic results unexpectedly reveal that the *CAPEX*s of the stand-alone and the integrated systems without ORC and ABC are almost identical, with the integrated system showing a slightly lower *CAPEX*. A closer examination of the *CAPEX* breakdown explains this behavior. In the integrated configuration, cost reductions associated with the hot thermal energy storage and charging infrastructure are sufficient to compensate for the additional investment required for AEW refurbishment, resulting in a slightly lower total *CAPEX* despite the high cost of the well renovation.

In addition to *CAPEX* considerations, the integrated systems achieve higher revenues compared to the stand-alone system (**Fig. 6**). The highest total revenue of the integrated system (LAES-AEW-DU-CDA) is almost 3 times that of the standalone system (0.22 vs 0.60 MUSD), with heating and CDA generating the largest revenues. The revenue from cooling, on the other hand, is considerably small compared to the other sources. Notably, as shown in **Table 6**, the inclusion of AEW heat utilisation leads to significant improvements in net cash flow (CF_{net}). Whereas the stand-alone LAES system generates negligible annual cash inflow (0.003 MUSD), the AEW-integrated systems increase net cash flow by up to two orders of magnitude. For instance, CF_{net} reaches 0.16 MUSD in the direct-utilisation case (LAES-AEW-DU) and rises to 0.38 MUSD when the clean dry air (CDA) stream is also monetized. These gains occur regardless of changes in round-trip efficiency, highlighting the economic value of integrating external energy services such as thermal energy sale and CDA delivery.

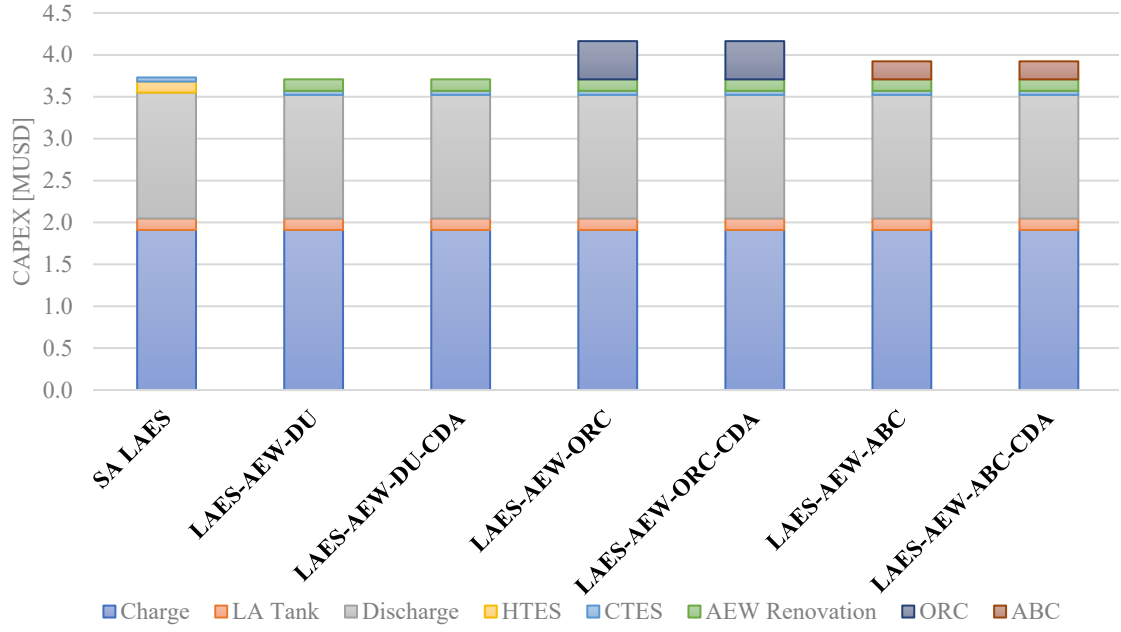


Fig. 5. CAPEX comparison in the integrated and standalone LAES configurations.

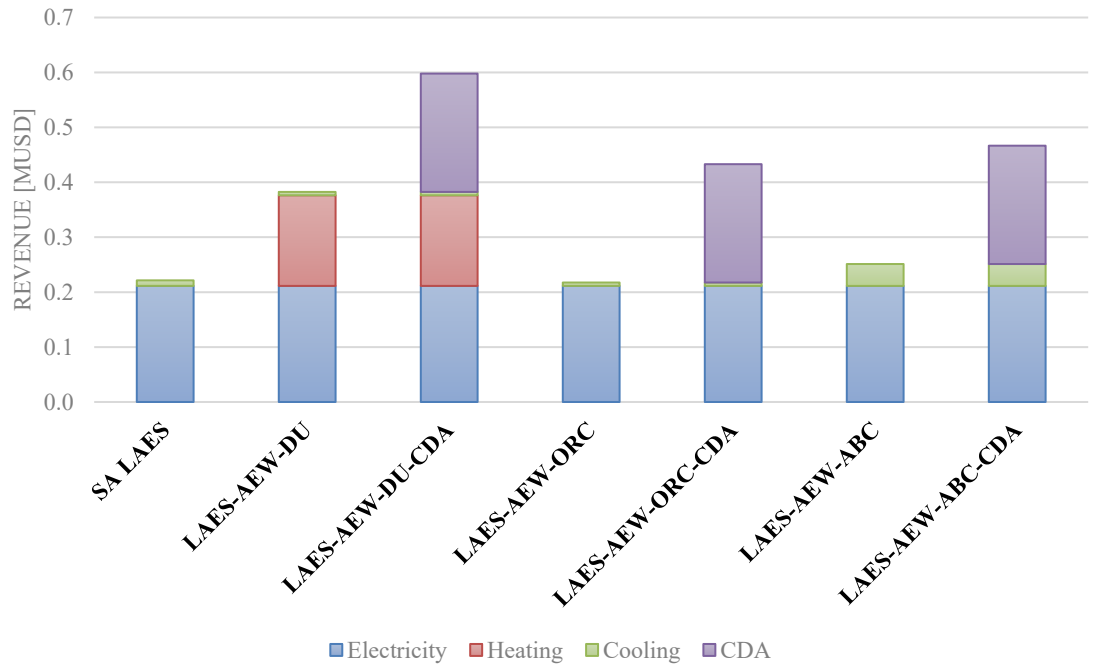


Fig. 6. Revenue comparison of various sources in the integrated and standalone LAES configurations.

Table 6. Net cash flow and Net present values of integrated and stand-alone LAES systems.

Items [Unit]	SA LAES	LAES-AEW-DU	LAES-AEW-DU-CDA	LAES-AEW-ORC	LAES-AEW-ORC-CDA	LAES-AEW-ABC	LAES-AEW-ABC-CDA
CF _{net} [MUSD]	0.003	0.164	0.379	0.029	0.245	0.028	0.243
NPV [MUSD]	-3.688	-1.029	2.499	-3.688	-0.161	-3.470	0.058

The ORC-enhanced systems provide an additional 91 kW_e of electric output, improving round-trip efficiency from 45 % to 56%. However, this notable 11-point % increase in performance alone is insufficient to achieve economic viability, as the ORC-only system remains characterised by negative NPV. Despite being negative, profitability is improved when the ORC is combined with CDA utilization, indicating that multi-output revenue stacking is essential for ORC-based integration to become competitive. A similar trend is observed for the ABC cases, where increased cooling revenue alone does not guarantee economic feasibility. The CDA stream again proves decisive in shifting the system toward positive NPV.

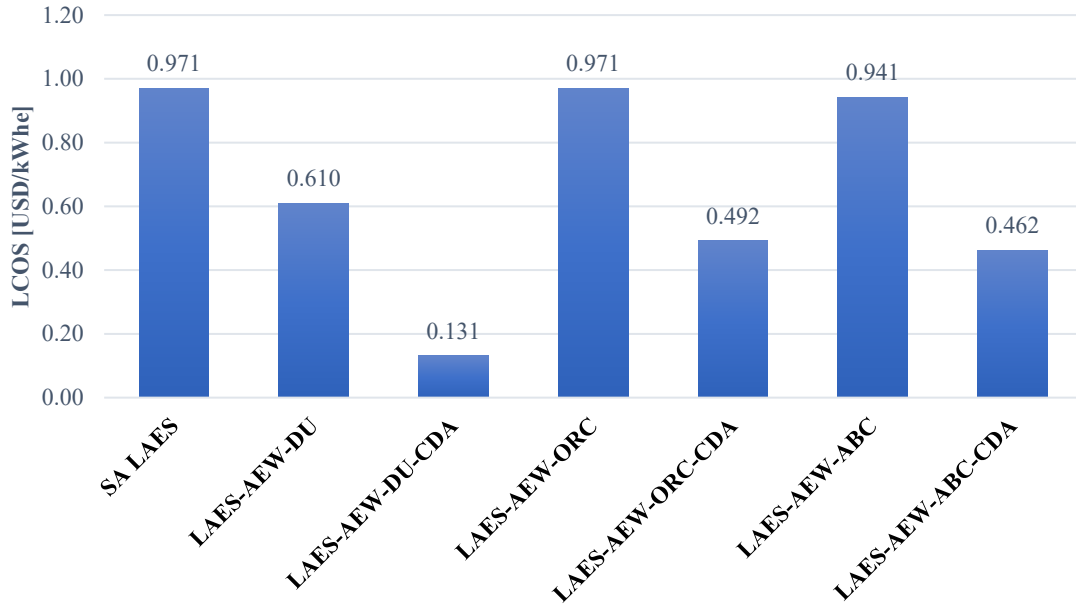


Fig. 7. *LCOS* comparison of the integrated and standalone LAES configurations.

The levelized cost of storage (*LCOS*) reflects the combined impact of *CAPEX*, *OPEX*, and revenues across the different configurations (**Fig. 7**). The stand-alone LAES exhibits an *LCOS* of 0.971 USD/kWh_e, whereas the integrated systems, with higher revenues, show substantial reductions—down to 0.610 USD/kWh_e in the DU case and an exceptionally low 0.131 USD/kWh_e when CDA is also provided. In **Fig. 8**, Discounted payback periods (*DPBP*) show similar trends. The stand-alone LAES system does not recover its investment within the project lifetime, confirming its economic non-viability. Among the integrated configurations, only those incorporating CDA achieve a feasible discounted payback: the integrated DU-CDA system achieves a positive *DPBP* of 13.7 years, while, among the other configurations, only ABC-CDA achieves a positive *DPBP* of 33.7 years. These results confirm that CDA, along with the revenue coming from the delivery of heating power, is the most influential revenue source, determining whether the integrated system becomes economically viable. These results are in agreement with previous authors' work [7] and favourably economically compare with other LAES hybrid configurations proposed in literature, as shown in **Table 7**.

Table 7. Techno-economic comparison of the current work with literature data.

Reference	η_{RT} [%]	<i>LCOS</i> [USD/kWh _e]	Configuration
Current work	44.8	0.131	LAES integrated with AEW
Tafone et al. [7]	67.6	0.125	LAES integrated with LH ₂ regasification
Georgiu et al.[33]	55.0	0.3-0.4	LAES integrated with waste heat
Li et al.[34]	110.3	0.090	LAES integrated with solar power plant
Liu et al. [35]	73.5	0.156	LAES integrated with nuclear power plant
Park et al.[36]	51.0	0.183	LAES integrated with nuclear power plant

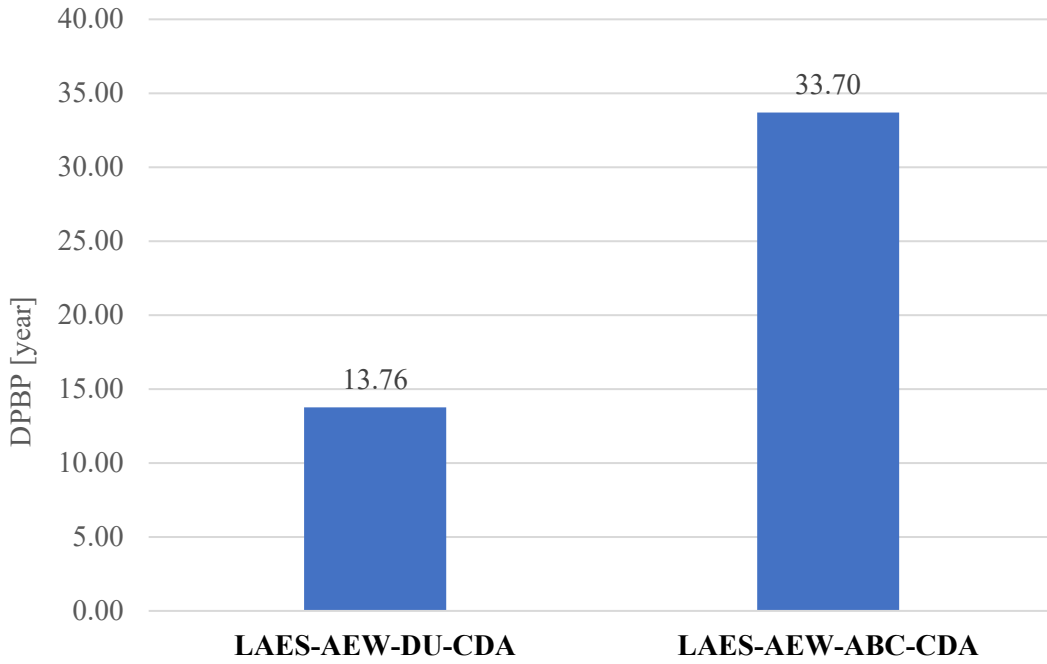


Fig. 8. Discounted PBP comparison of the integrated LAES configurations. Only configurations exhibiting a finite and economically feasible discounted PBP are included.

4.3. Sensitivity analysis case studies

The current section evaluates the performance of the stand-alone and integrated LAES configurations by varying the electricity tariffs at which LAES is charging and dispatching electricity and the industrial demand of the clean dry air, whose revenue, as shown in the previous section, is an important pillar for the economic feasibility of the LAES integrated configuration. Three cases have been selected for this analysis: the stand-alone LAES and the integrated LAES system showing feasible discounted pay-back periods (LAES-AEW-DU-CDA and LAES-AEW-ABC-CDA).

In order to better understand the trends of the KPIs under examination (*LCOS* and *NPV*), the results of the sensitivity analysis involving both the electricity tariffs, and the clean dry air demand are plotted in terms of performance heat maps. **Fig. 9-Fig. 13** show the *NPV* and the *LCOS* at utilization factors of the clean dry air of 20%, 40 %, 60% and 80%. Electricity tariffs at peak and off-peak periods are varied as well between 0.30-0.54 USD/kWh_e and 0.06-0.30 USD/kWh_e, respectively.

As already highlighted in the previous sections, the first thing to note is the significant influence of the clean dry air revenue at every electricity tariff considered. As shown in **Fig. 9** and **Fig. 10** for the integrated LAES-AEW-DU-CDA system, *LCOS* values decrease markedly with increasing CDA utilization. At low utilization factor ($\mu_{CDA} = 0.2$), *LCOS* remains relatively high ($\approx 0.37\text{--}0.60$ USD/kWh_e) and is strongly sensitive to electricity tariff spreads. As μ_{CDA} increases to 0.6–0.8, *LCOS* drops significantly, reaching minimum values below 0.15 USD/kWh_e under favorable tariff conditions. This highlights the dominant role of CDA monetization in offsetting operating costs, rather than electricity arbitrage alone. Moreover, at low clean dry air utilization levels, the *LCOS* is primarily governed by the off-peak electricity tariff, while the impact of peak electricity prices remains comparatively limited, as also evidenced in **Fig. 13a** for the stand-alone LAES case ($\mu_{CDA} = 0$). This phenomenon is further enhanced for the LAES-AEW-ABC-CDA in **Fig. 11** where

the dependence on the electricity off-peak tariff alone is caused by the electricity cost becoming predominant over the other cost components at higher values of the electricity off-peak tariff. Indeed, in these scenarios, the revenues from heating/cooling delivery outweigh those from clean dry air: as a consequence, the peak electricity tariff has little impact on the *LCOS*. Conversely, at higher utilization factors of the clean dry air, the decline in *LCOS* becomes more pronounced, as it strongly depends on both electricity off-peak and peak tariffs. However, in this case study, the ABC-based configuration exhibits systematically higher *LCOS* values compared to the DU-case for equivalent μ_{CDA} levels, reflecting the additional CAPEX and energy losses associated with the absorption chiller.

Comparable patterns are also observed for the net present value, although additional drivers must be considered. At low clean dry air utilization levels, NPV remains highly sensitive to variations in both off-peak and peak electricity prices. As the utilization factor increases, the influence of off-peak tariffs becomes less pronounced relative to peak prices. This behaviour arises because revenues from clean dry air progressively dominate the overall cash flow and are more strongly linked to peak electricity tariffs, outweighing contributions from electricity arbitrage and heat supply. As a result, the NPV increases markedly at higher utilization levels.

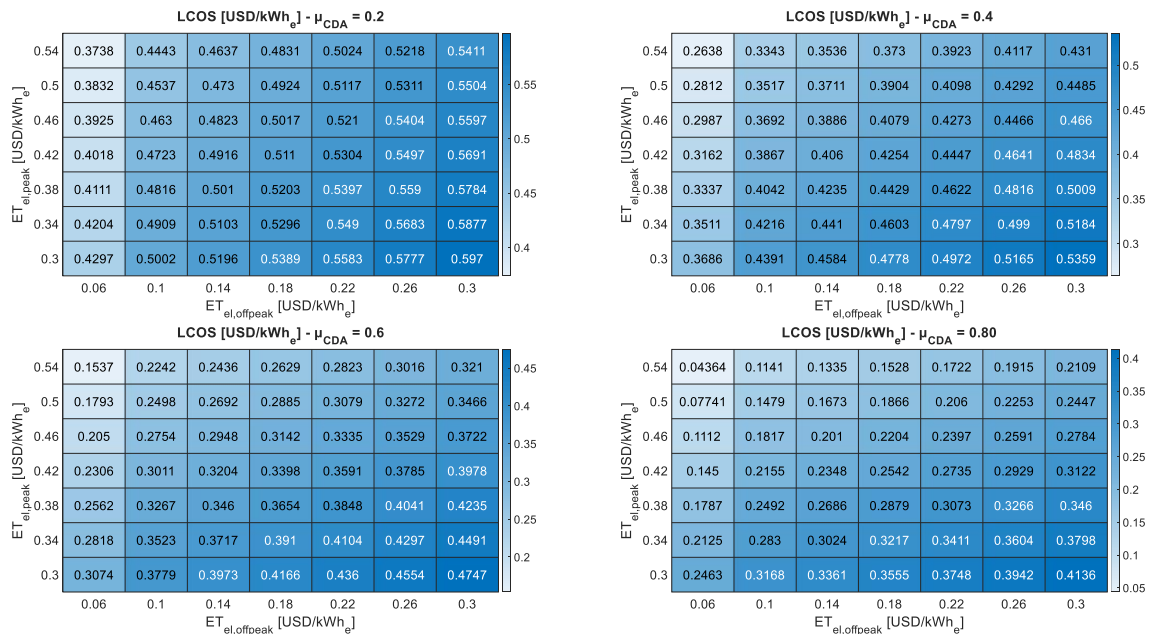


Fig. 9. *LCOS* performance heat maps. Integrated LAES-AEW-DU-CDA case study.

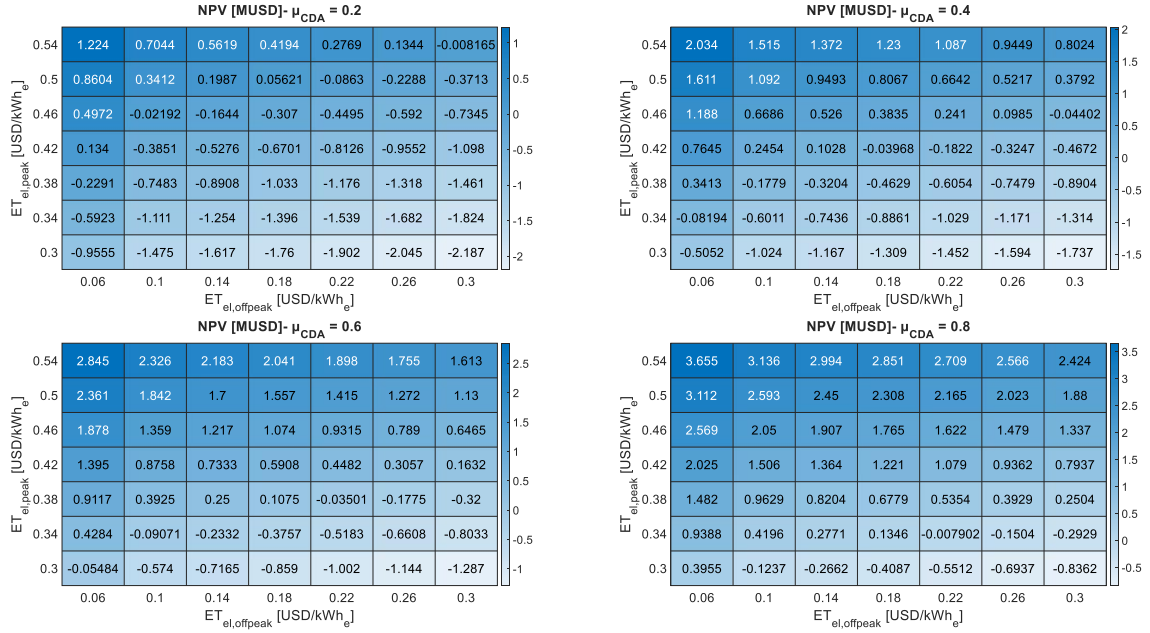


Fig. 10. NPV performance heat maps. Integrated LAES-AEW-DU-CDA case study.

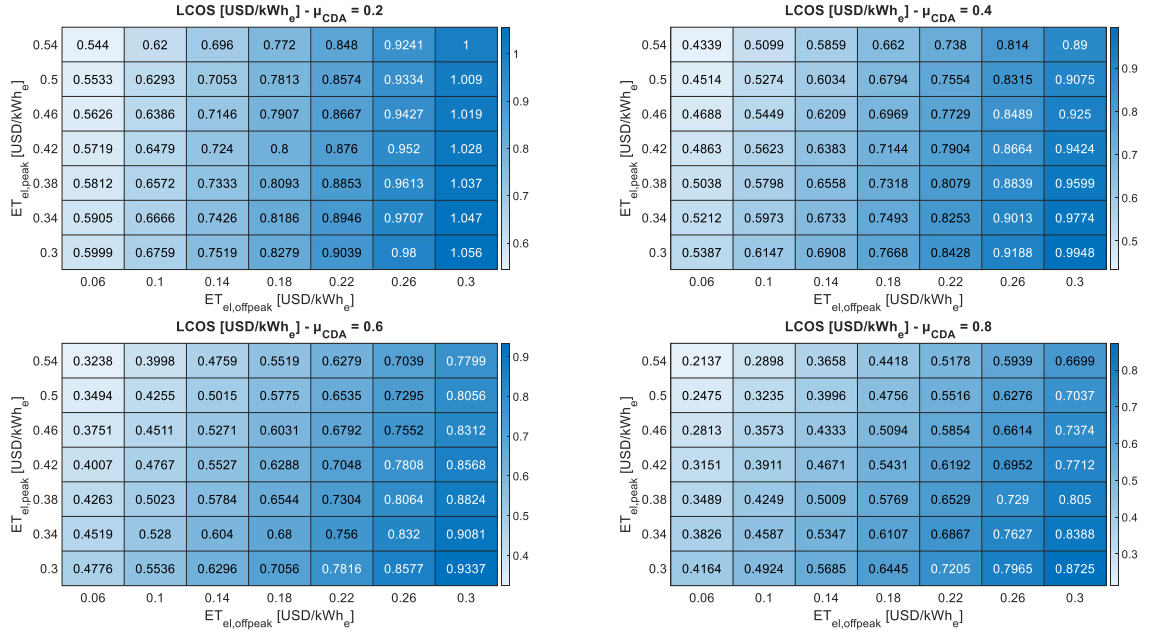


Fig. 11. LCOS performance heat maps. Integrated LAES-AEW-ABC-CDA case study.

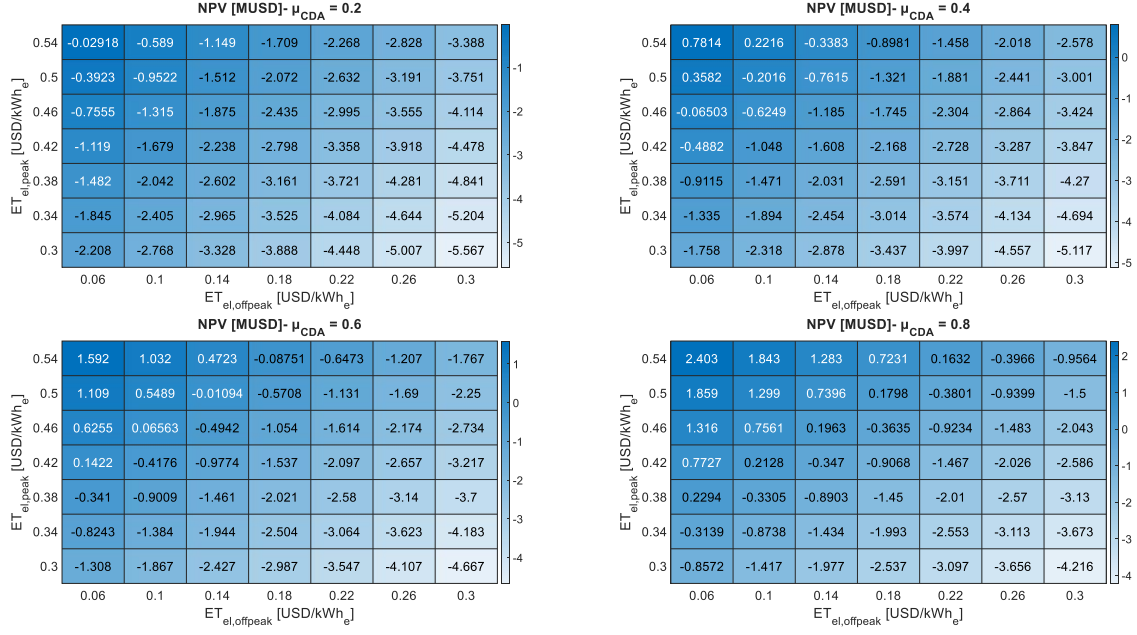


Fig. 12. NPV performance heat maps. Integrated LAES-AEW-ABC-CDA case study.

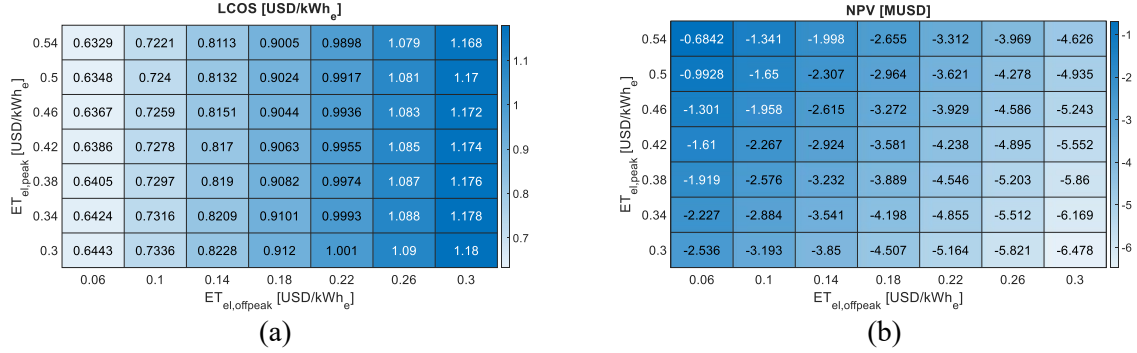


Fig. 13. LCOS (a) and NPV (b) performance heat maps. Stand-alone LAES case study.

Furthermore, a sensitivity analysis on the discount rate (i) was carried out in the range of 3–8% to evaluate its impact on the economic performance of the investigated configurations. The results are summarized in **Fig. 14** and **Fig. 15**.

As expected, increasing the discount rate negatively affects all economic indicators. For the stand-alone LAES, the NPV remains negative across the entire range, with only marginal variation (from −3.67 MUSD to −3.70 MUSD), confirming its economic infeasibility. In contrast, the integrated configurations show a stronger sensitivity to the discount rate. For the LAES-AEW-DU-CDA system, the NPV decreases from 4.44 MUSD at 3% to 0.71 MUSD at 8%, while remaining positive under all conditions, indicating robust economic viability. The LAES-AEW-ABC-CDA configuration exhibits a more pronounced dependence, with NPV shifting from 1.30 MUSD at 3% to −1.09 MUSD at 8%, highlighting a narrower economic margin.

A similar trend is observed for the LCOS, which increases with the discount rate for all systems. The stand-alone configuration shows consistently high LCOS values (0.85–1.18 USD/kWh_e), whereas the integrated systems maintain significantly lower costs. In particular, the LAES-AEW-DU-CDA configuration exhibits the lowest LCOS (0.011–0.334 USD/kWh_e), confirming its superior economic performance.

Overall, although the discount rate influences the absolute values of the economic indicators, the relative ranking of the configurations remains unchanged, with the LAES-AEW-DU-CDA system consistently outperforming the other options.

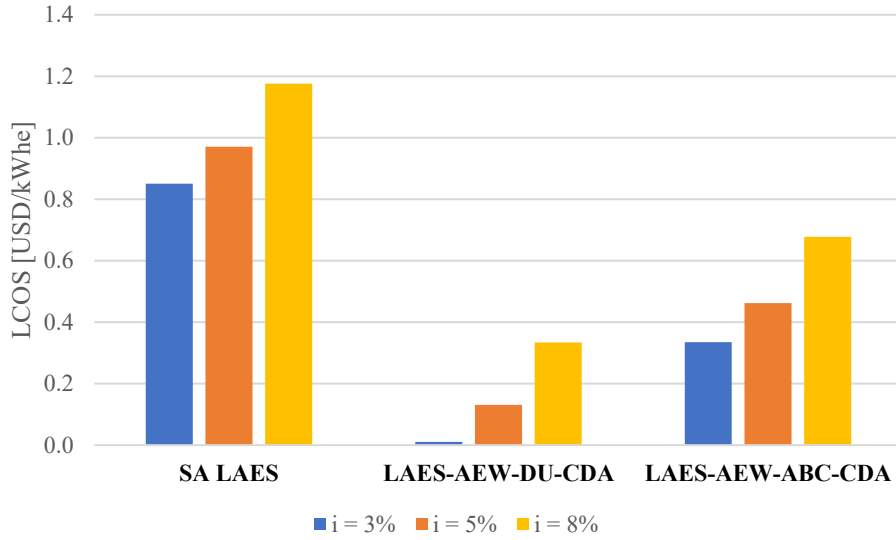


Fig. 14. LCOS as the discount rate varies for stand-alone and hybrid LAES configurations.

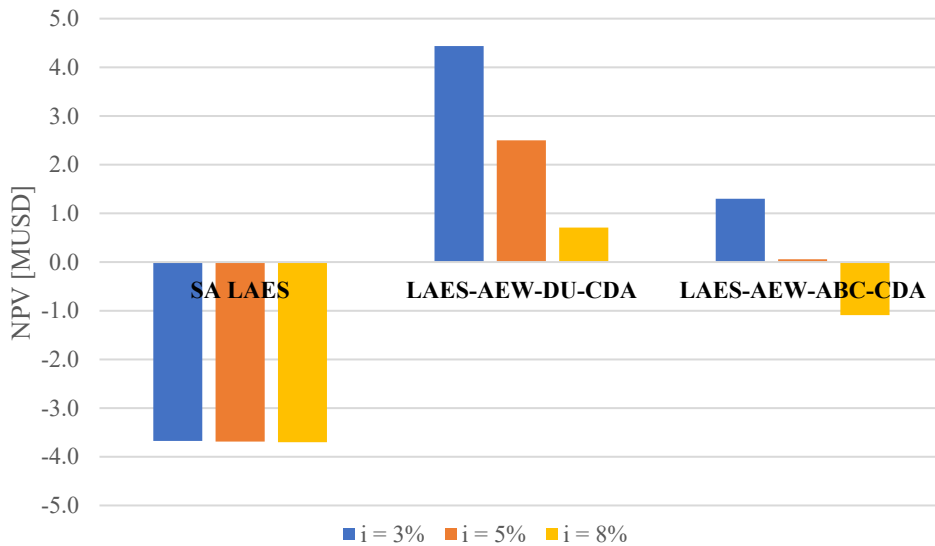


Fig. 15. NPV as the discount rate varies for stand-alone and hybrid LAES configurations.

5. Conclusions

This study proposed and designed a novel integration of LAES with AEW geothermal exploitation and wafer fabrication clean dry air (CDA) production. The system takes advantage of the otherwise untapped waste heat from abandoned exploitation wells to enhance the efficiency of the LAES discharging process. The techno-economic results provide several novel insights into the role of multi-energy integration in improving the viability of LAES systems. A key finding is that thermo-economic feasibility is governed less by round-trip efficiency improvements and more by the ability to create sustained, high-value revenue streams.

First, AEW integration produces notable reductions in both CAPEX and OPEX. The removal of HTES units offset the AEW renovation cost, contradicting the assumption that geothermal

integration necessarily increases investment. Furthermore, operational costs decline due to lower electrical consumption during charging. These findings collectively demonstrate that AEW integration provides a structural cost advantage even in cases where electrical efficiency remains unchanged.

Second, and more significantly, the discounted payback period analysis reveals the decisive role of clean dry air as an economic driver. All systems lacking CDA yield negative NPV, indicating that they never recover their investment within the analysis horizon. In contrast, CDA-enabled systems achieve discounted payback periods ranging from 13.7 to 33.7 years. This underscores a central novelty of the present work: profitability is not solely dictated by thermodynamic performance, but by the provision of multi-vector energy services, where industrial-grade air emerges as a high-value product with strong market relevance, such as in wafer fabrication.

Third, the study demonstrates that traditional metrics of LAES performance—such as round-trip efficiency—do not reliably predict economic feasibility. The ORC case, for example, exhibits the highest round-trip efficiency (55.95%), yet remains economically unattractive unless CDA revenue is included. Conversely, the DU-CDA configuration, which shows no increase in round-trip efficiency, delivers the lowest LCOS and shortest discounted payback, illustrating that revenue stacking outweighs thermodynamic gains in determining financial viability.

These findings position LAES not merely as a long-duration storage technology, but as a multi-output energy platform capable of delivering electricity, heat, cooling, and industrial utilities. This integrated perspective represents a significant departure from conventional LAES studies, highlighting a new paradigm in which system-wide co-valorization of external energy and material streams is the key enabler of economic feasibility.

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CRedit author statement

Alessio Tafone: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Lizhong Yang:** Methodology, Software, Data curation, Writing- Original draft preparation. **Anurag Chidire:** Visualization, Investigation Software, Writing - Original Draft. **Benjamin Kanz:** Data curation, Supervision. **Tobias Massier:** Supervision, Funding acquisition. **Roberto Pili:** Writing- Reviewing and Editing. **Fei Xiao:** Methodology, Software, Supervision. **Alessandro Romagnoli:** Supervision.

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