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Feasibility of liquefied nitrogen energy storage in cities

Yong Yuan[1], Li Zhu[2], Menghao Huang[1], Jiaolong Zhang[1*]

[1]College of Civil Engineering, Tongji University. Siping Road 1239, Shanghai 200092, China
[2]CCCC Second Highway Engineering Co., Ltd.Keji Road 33, 710065 Xi'an. China

[*]**Correspondence to:** Jiaolong Zhang, Email: Jiaolong_Zhang@tongji.edu.cn

Abstract: Energy storage is a critical component of the modern electrical system, alongside power plants, grids, and users. Many methods of storing electrical power have made significant progress. This paper presents a perspective on storing electrical energy in cities in the form of liquid nitrogen and its associated thermal energy byproducts. Statistics on city electrical consumption indicate that commercial services account for more than 50% of total usage, with Heating Ventilation Air Conditioning comprising 50% of this power consumption, both on a daily and seasonal basis. This highlights the potential for electrical consumption to manifest as cold energy in summer and thermal energy in winter. To address this, a liquid nitrogen energy storage and release (LN-ESR) system is proposed, capable of storing large quantities of both cold and thermal energy. The stored cold energy can be released during summer to regulate building air temperature, while the resulting expanded gas could drive a gas turbine to generate electricity. In winter, the thermal energy can be used to heat buildings. A preliminary techno-economic analysis is presented, comparing the LN-ESR system with conventional compressed air energy storage (CAES) and evaluating its feasibility for underground storage applications.

Keywords: Liquid Nitrogen Energy Storage (LN-ESR), Cold and thermal energy utilization, Urban energy consumption, HVAC electricity demand, Underground energy storage

1. Introduction

Energy storage plays a significant role in daily life and industry. Whether it is a power bank used to recharge a mobile phone or a Pumped storage power station operating in conjunction with a nuclear power plant, energy storage has become a new trend in resource regulation. Nowadays, the electrical system is considered an interaction system comprising the source, grid, storage, and user, rather than simply a relationship between source and user. Researchers have summarized the energy storage technologies [1], and perspective development of the classified forms [2, 3].

At present, the widely studied and used types of energy storage systems are as follows: (1) Mechanical energy storage, which converts electrical energy into mechanical potential energy, such as pumped storage power station (PSPS) or named as Pumped Hydraulic Station (PHS) pumping water from low to high reservoirs to store gravitational potential energy, or compressed air energy storage (CAES), which compresses air in a closed container to store potential energy, or flywheels, which store rotational potential energy; (2) Electrochemical energy storage, such

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as various types of batteries or supercapacitors, which store electricity directly; (3) Thermal energy storage (TES), in which energy is stored by heating a medium with high heat capacity or using change materials; (4) Chemical energy storage, most notably hydrogen production by water electrolysis or methane synthesis; (5) Other forms of energy storage, such as superconducting coils or plasma, which are promising but still at the conceptual device stage.

Table 1 shows the comparison of energy density and capacity of the four typical types of energy storage technologies. It indicates that although the PSPS has a large capacity, its energy density is too low. The energy density of both lithium battery energy storage power station and liquid hydrogen is high, but their capacity is not large enough. CAES can reach the 100 mega-watt level, which is suitable for large-scale energy storage requirements, at moderate energy density.

Table 1. Characteristics of typical energy storage technologies

EST	M-ED(Wh/kg)	V-ED (Wh/L)	Capacity (MW)	Features
CAES (300 atm)	40-60	50-100	100~1000	Long life, low cost, suitable for large-scale energy storage
Lithium battery (Li-ion)	150-250	250-700	10~100	High energy density, but high cost and limited lifespan
Liquid hydrogen (H_2)	33,000	2360 (70 L/kg)	~10	Very high mass energy density, but low bulk density
PSPS	0.1-0.3	0.5-1.5	>1000	Dependent on the terrain, the energy density is extremely low

Note.1)EST: Energy storage technology; 2) M-ED: Mass energy density; 3) V-ED: Volumetric energy density; 4) CAES: compressed air energy storage; 5) PSPS: Pumped storage power station.

Energy storage is not only a societal demand but also a goal for engineers. Recently, chemical energy storage, such as lithium batteries, has become increasingly popular due to its high density and efficiency. Hundreds of mega-watts of lithium battery storage power stations have been built in many places around the world. However, it is not uncommon for lithium batteries for mobile phones, or lithium battery mopeds and cars to catch fire and fails [4]. Fire and explosions accidents of lithium battery power stations cannot be controlled manually. Consequently, the safety of lithium battery storage power stations has always been questioned.

The power capacity of PSPS typically reaches the 100-gigawatts high and has few devastating accidents. It has been favored by the industry for decades [5]. However, the construction of energy storage power stations is limited by geographical conditions, and land resources. Most cities lack suitable construction conditions. Furthermore, when electricity is transmitted back to a PSPS located in a remote area, power losses are inevitable due to the energy consumption of multiple transmission stages.

Originating in the 1970s, CAES technology using caverns as energy storage media has a power generation capacity of several hundred mega-watts [6], but is less energy efficient and requires fuel replenishment to drive turbines [7]. In addition, the stability of storage caverns and potential air leakage are important concerns [8]. CAES power generation technology mainly consists of three stages: air compression, storage, and release. Air compression and turbine power generation through air release are mature technologies. Compressed air can be stored in steel tanks (pipes), abandoned mines, or salt caverns. However, large-capacity, high-density storage media and sufficient access space are essential for implementing CAES in urban areas, which are usually unavailable.

Cities are the main centers of energy consumption and fluctuation. Industrial production and daily life require large amounts of electricity during the day, while electricity consumption is relatively low at night. Regulating indoor air temperature in both summer and winter increases electricity consumption, whereas demand is relatively stable in spring and autumn. This paper argues that it is possible to develop a safe, high-density, large-capacity, and distributed critical gas energy storage technology, based on urban infrastructure construction. Such technology would enable efficient storage and release of energy to meet peak demands of Heating, Ventilation, and Air Conditioning (HVAC) systems, as well as generate electricity for nearby urban buildings. To this end, two changes are proposed: (i) compressing air to a critical state to produce liquid nitrogen as a high-density energy storage medium; and (ii) constructing relatively large-capacity energy storage spaces within urban underground facilities such as shafts. Both technologies are mature individually, and the key challenge lies in their integration. Herein, this paper first presents the conceptual design of the energy storage system which is comprised of compressing air to obtain liquefied nitrogen (and byproduct). The subsequent analysis addresses the storage requirements of 100 MW liquid nitrogen and the approaches for storing waste heat produced during nitrogen production process. Then following section gives concepts on the corresponding storage container and shaft construction scale. Brief technical and economic analysis of the system is also provided. It is argued that the prospective technology presented here can form a new energy storage industry chain, with potential applications in grid peak regulation and in providing emergency power supply for end users in the event of grid outages.

2. Compressed air energy storage - power generation system

The power generation system of CAES consists of three modules as displayed in Figure 1: air compression and condensation, high-pressure storage, and refueling turbine. The first and last modules are mature industrial technologies, while high-pressure storage represents the core of the system.

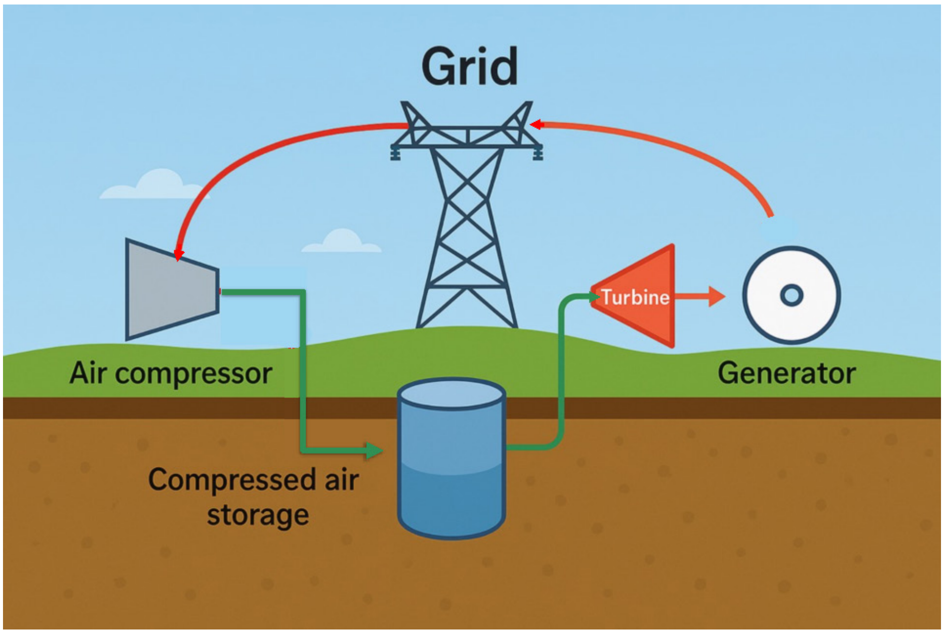


Figure 1. Concept of CAES electric generating system

With the development on this concept, several types of the energy storage-regenerate system have evolved: Compressed Air Energy Storage (CAES), Advanced Adiabatic Air Energy Storage (AA-CAES), Liquefied Air Energy Storage (LAES), and Supercritical Compressed Air Energy Storage (S-CAES). Their developments are summarized in the following subsections, respectively.

2.1 Compressed Air Energy Storage (CAES)

Air storage mainly relies on underground salt caverns, abandoned mines or hard rock caves to store compressed air. Air storage pressure ranges from 4 to 8 MPa. The pressure is limited by geological conditions, and the stability of the geological formation is required. The risk of air leakage from the storage needs to be strictly monitored. When releasing energy, it is necessary to refuel (natural gas) to heat the air. Fluctuations in air pressure within the storage cavern affect the efficiency of power generation. Typical application cases include the Huntorf power station in Germany (air pressure 5.5~7.0 MPa) and the McIntosh power station in the United States (air pressure 7.5 MPa) [6].

2.2 Advanced Adiabatic Air Energy Storage (AA-CAES) [9,10]

AA-CAES has been developed for above ground high-pressure vessels or new gas storage structures. Air storage pressure ranges from 10 to 15 MPa, with multi-stage compression applied during the charging process. Heat storage technology is employed to recover compression heat, thereby eliminating the need for external refuelling. Increasing storage pressure can significantly enhance energy density. Potential air storage units include steel pressure vessels, composite air tanks, and artificial chambers. A typical case is the 100 MW demonstration project in Zhangjiakou, China, where the gas storage pressure is 12 MPa, and the energy storage efficiency has been improved to 60%~70%. In the case of the ALA-CAES project in Switzerland, gas is stored in decommissioned tunnels at pressures of up to 10 MPa. Another project is located in Jintan County, Jiangsu Province, where salt formations at a depth of 800–1000 m and a thickness of about 200 m have been developed into caverns with storage capacities ranging from 10,000 to 300,000 m^3. The compressed air, stored at pressure of 7~12 MPa, is expected to generate

10MWh in the first phase [11].

Zhang et al. [12] proposed and analyzed a CCES system based on the Brayton cycle, using hot water as the heat storage medium. Under typical transcritical operating conditions, the round-trip efficiency is 60% and the energy density is 2.6 kWh/m^3. For typical supercritical operating conditions, a round-trip efficiency of 71% can be achieved, with an energy density of 23 kWh/m^3. This system has a high round-trip efficiency and an energy density comparable to those of CAES systems, thermoelectric (or electrothermal) energy storage systems, and other CCES systems.

2.3 Liquefied Air Energy Storage (LAES) [13]

The Highview Energy Company and the University of Brighton are developing and industrializing LAES technology [14]. A 350 kW/2.5 MWh experimental platform was built in the UK in 2012, and the team began constructing a 5 MW/15 MWh demonstration project in 2014. They are now constructing a 50 MW/250 MWh energy storage power station in the United States, which is scheduled to begin operation in 2022 [15].

In 2017, the team from the Institute of Physics and Chemistry of the Chinese Academy of Sciences completed the construction of a 100kW low-temperature LAES (LT-LAES) demonstration platform at the Langfang pilot base, Hebei Province [16]. It has achieved good experimental results, with a cold storage efficiency of 90% and an overall system efficiency of up to 60%, reaching an internationally leading level. A 100kW mixed working fluid cold storage engineering verification platform was also built, which can conduct low-temperature cold storage experiments with various cold storage working fluids, and has completed mixed working fluid tests in the -160°C temperature range. Table 2 presents a comparison of the energy storage capacity of these three compressed air energy storage technologies.

Table 2. Typical case of CAES

Type	Pressure/MPa	Capacity/MW/MWh	Efficiency/%	Cases
CAES	5.5~7.0	290/580	42	Huntorf, German
AA-CAES	10~12	100 /400	65	Zhangbei, China
L-AES	0.1	50 /250	55~60	Highview, UK

2.4 Supercritical Compressed Air Energy Storage (S-CAES)

Carbon dioxide (CO_2) is an excellent candidate for working fluids in CAES systems due to its favourable physical properties. Specifically, carbon dioxide can reach its critical condition (31.3 °C, 7.38 MPa) or liquefy more easily than air, which has a critical point of -141 °C, 3.77 MPa. In addition, supercritical CO_2 (s-CO_2) possesses advantageous properties, such as low viscosity, high density, high thermal stability, non-toxicity and non-flammability, making it a safe and environmentally friendly choice for engineering applications. As a result, compressed carbon dioxide energy storage (CCES) systems have emerged as a viable alternative to CAES.

Zhang et al. [17] proposed a compressed liquid carbon dioxide energy storage system, replacing compressed air with liquid carbon dioxide as the working medium. They calculated the system efficiency and effective energy efficiency, analyzed system performance, and performed parameter analysis to assess the influence of various parameters. The results show that as the outlet pressure of the compressor, turbine and pump increases, the system efficiency and effective energy efficiency first increase and then decrease. However, the variation in system efficiency and effective energy efficiency caused by the pump outlet pressure is much less significant than the variation caused by the turbine outlet pressure and compressor outlet pressures.

2.5 Trends in compressed gas energy storage systems

The energy density of compressed air is a key parameter for its use as an energy storage or power medium, which determines the amount of energy stored per unit mass or volume. Table 3 compares the energy density differences between traditional CAES, L-AES, and SC-CAES. One can find that there is little difference in mass energy density between several technologies, but the volume energy density of SC-CAES is 5-6 times that of traditional CAES. The comparison Indicates the potential prospects of SC-CAES for large-capacity energy storage.

Recently, Zhang et.al [18] summarized the trends in various compressed gas energy storage (CGES) systems, including CAES and the newly developed Compressed Carbon Dioxide Energy Storage (CCES) systems. They also mentioned the concluding remarks from the Europe ADELE project on high-temperature (>400°C) CCES, then focused on the comparison between low-temperature (<200°C) CAES and CCES. A meaningful conclusion regarding the priority of optimization was proposed for the cold energy storage tank. They used the term Compressed

Gas Energy Storage (CGES) to include traditional CAES and its subdivisions:

- Adiabatic Compressed Air Energy Storage, A-CAES
- Advanced Adiabatic Compressed Air Energy Storage, AA-CAES
- Isobaric Adiabatic Compressed Air Energy Storage, AA-CAES
- Underwater Compressed Air Energy Storage, UW-CAES
- etc.

and newly developed CCES and its subdivisions:

- Thermoelectric Energy Storage, TEES (CO2)
- Integrated CCES
- Hybrid Thermal CCES
- High-temperature CCES
- Low-temperature CCES
- etc.

Obviously, liquid gas should be classified into other for it takes the phase change form as:

- Liquid Air Energy Storage, LAES
- Liquid Carbon dioxide Energy Storage, L-CCES
- Supercritical Compressed Air Energy Storage, SC-CAES
- Thermal Energy Storage, TES
- Supercritical Carbon dioxide Energy Storage, SC-CCES
- Transcritical Carbon dioxide Energy Storage, CCES
- etc.

In spite of these advances, it is not reasonable to transport electricity that has already been transmitted to the city back to locations with salt rock caverns, abandoned mining shafts, or laneways for energy and electricity generation. A wise decision is to explore new ways to achieve a distributed, high-intensity, large-capacity energy storage and release system, with high efficiency and long-term serviceability within a city.

Table 3. Energy density of typical CAESs

Type	MED(kJ/kg)	VED(kWh/L)	Remarks
CAES	150-200	0.05-0.1	Limited by compressor efficiency (approx. 70-85%)
L-AES	200-300	0.2-0.3	Liquefaction increases energy density, but requires additional cold energy recovery
SC-CAES	250-350	0.3-0.5	High pressure and high temperature (close to the critical point, complex technology)

Note. MED-Mass energy density; VED-Volume energy density.

3. Characteristics of urban electricity consumption

According to the Shanghai Statistical Yearbook 2024 [19], total electricity consumption in Shanghai rose to 184.9 billion kWh in 2023. Consumption is distributed among the secondary industry (45.5%), the tertiary industry (service sector, 37.1%), and residential usage (16.5%). Although the industrial share remains significant, the combined share of the service sector and residential usage—which are heavily influenced by seasonal temperature variations—still accounts for nearly 54% of total demand, driving the need for demand-side thermal management.

Recent data from the State Grid Shanghai Municipal Electric Power Company [20] further highlight the increasing impact of HVAC systems on grid stability. During the record-breaking summer peak in 2024, the city's power load reached a historic 40.30 GW. At this peak, the cooling load (air conditioning) contributed approximately 19 GW, or roughly 47% of the total load. This high proportion of temperature-dependent consumption exacerbates the "peak-valley" disparity, confirming the need for dual-purpose storage systems like LN-ESR, which can handle both electrical and thermal demands.

3.1 Data acquisition and processing

To investigate the specific load characteristics of the service sector, this study selected a representative commercial complex in Yangpu District, Shanghai (gross floor area approximately 150,000 m²) as a case study. The load data shown in Table 4 and Table 5 were obtained from the building's Energy Management System (EMS).

Sampling Method:The electrical load was monitored using smart meters at the main distribution board. The sampling period covered the entire calendar year of 2023 (January 1 to December 31). The data sampling frequency was set at 15-minute intervals to capture instantaneous peak fluctuations, resulting in 35,040 raw data points per metering channel.

Data processing steps: To ensure data quality and representativeness, the following processing steps were applied:

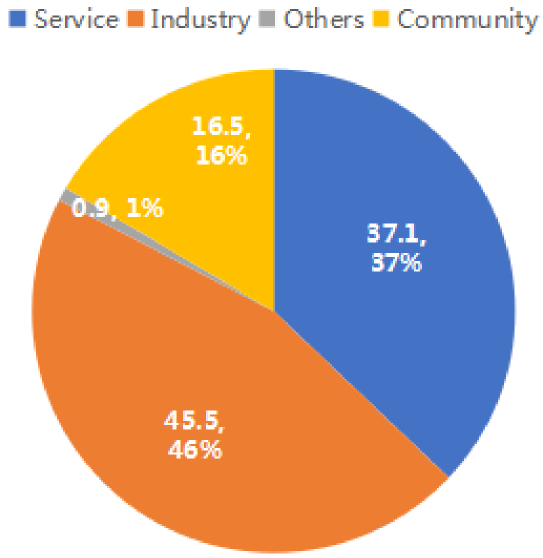
(1) Data cleaning: Raw data points with missing values or clear outliers (e.g., zero readings due to sensor maintenance) were removed and reconstructed using linear interpolation.

(2) Aggregation: The 15-minute interval data were aggregated into hourly average power (kW) to match standard grid dispatch intervals.

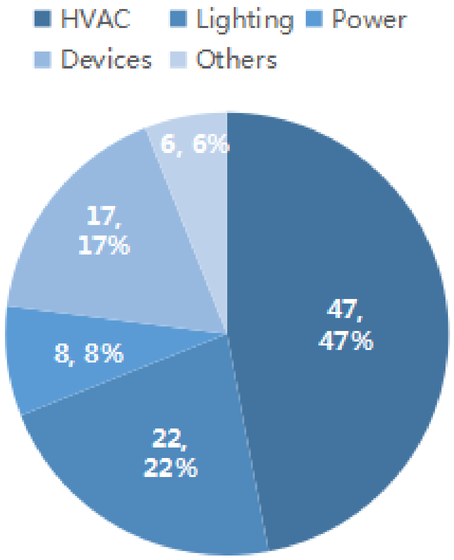
(3) Typical profile generation: The hourly load profiles

shown in Table 5 do not represent a single random day but are the average load of typical weekdays (Tuesday to Thursday) in representative months (April, July, October, and January), excluding weekend anomalies and extreme weather events.

Table 4 presents the monthly electricity consumption of a commercial center in Shanghai. The peak months are July and August in the summer, followed by December and January of the winter, due to HVAC demand. Electricity consumption during these periods is 30~40% higher than that in spring or autumn. This suggests that energy should be stored during spring and the autumn, and then used in summer and winter.



(a) Proportion of annual electricity consumption by sector (Shanghai, 2023)



(b) Composition of grid load during summer peak (Shanghai, 2024)

Figure 2. Attribute of city electricity consumption

Table 4. Monthly electricity consumption of a shopping mall (Shanghai)

Month	Monthly/mkWh	Daily(kW)	HVAC/(%)	Remarks
Jan.	3.20~3.50	4300~4700	35~40	Heating, New Year's promotion
Feb.	2.80~3.10	3800~4200	30~35	Closed during the Spring Festival
Mar.	3.00~3.30	4000~4400	25~30	Temperature rising
Apr.	2.50~2.80	3400~3800	20~25	The Lowest period
May	2.90~3.20	3900~4300	25~30	Air con. turns on sporadically
Jun.	3.80~4.20	5100~5600	40~45	Dehumidification during rainy season
Jul.	4.80~5.20	6200~6800	50~55	Peak consumption
Aug.	4.70~5.10	6100~6700	50~54	High temperature, summer vacation
Sept.	3.70~4.00	5000~5400	35~40	Temperature dropped
Oct.	3.10~3.40	4200~4600	25~30	National Day promotion
Nov.	2.60~2.90	3500~3900	20~25	The second trough
Dec.	3.60~3.90	4800~5200	35~40	Heating, promotions

Table 5. Hourly electricity load of a shopping mall (Shanghai) with season (kW)

Period	Spring/Apr.	Summer/Jul.	Autumn/Oct.	Winter/Jan	Remarks
00:00	800	1,200	850	1,000	Cold chain, security equipment
01:00-04:00	750~780	1,150~1,180	800~830	950~980	The lowest period
05:00	850	1,300	900	1,100	Cleaning
06:00	1,000	1,500	1,100	1,300	Lighting and elevator
07:00	1,500	2,000	1,600	1,800	Air con.
08:00	2,200	3,500	2,400	2,700	Business preparation
09:00	3,000	4,800	3,300	3,600	office open
10:00	3,800	6,200	4,000	4,400	Officially open
11:00	4,200	6,800	4,500	4,800	Customers during lunch
12:00	4,500	7,000	4,700	5,000	
13:00	4,300	6,900	4,600	5,200	
14:00	4,000	6,500	4,400	5,000	
15:00	3,800	6,200	4,200	4,800	
16:00	3,900	6,300	4,300	5,000	Passengers flow
17:00	4,200	6,600	4,600	5,500	
18:00	4,800	7,200	5,000	6,000	The highest peak
19:00	4,700	7,100	4,900	5,900	
20:00	4,200	6,800	4,600	5,600	
21:00	3,000	5,500	3,500	4,500	Partially closed
22:00	1,800	3,200	2,000	3,000	Closed, basic equipment
23:00	1,200	1,800	1,300	1,500	Nighttime troughs

There are two peaks in electricity consumption during the summer season, at 12:00 and 18:00, but only one peak in the winter season at 18:00, according to the statistics in Table 5. The difference between peak and valley electricity consumption is more than three times. This is mainly because energy is stored at night and released for use during the day.

It is clear that the service sector is the largest consumer of electricity in a city. The HVAC system is the biggest contributor to electricity consumption, both in terms of seasonal variation and daily changes. Regulation of HVAC consumption is mainly based on daily balance, mostly via making ice during night of summer. Limited actions are taken for seasonal regulation or for balancing heating in winter.

4. Liquefied nitrogen energy storage-release system

4.1 Production of L-N_2

Air contains 78% nitrogen and 21% oxygen. Using air as the raw material provides sufficient resources for liquid nitrogen production. At present, there are three established processes for nitrogen liquefaction: cryogenic air separation, pressure swing adsorption (PSA), and membrane air separation. The cryogenic air separation method relies on the different boiling points of liquid oxygen and liquid nitrogen, and involves compression, purification, liquefaction and distillation. The molecular sieve method is based on the principle of pressure swing adsorption. Membrane air separates oxygen and nitrogen by exploiting their different permeation rates under pressure. Table 6 compares these three technologies.

Compared with the cryogenic approach to producing liquid nitrogen, the production capacity of the other two types of processes is too low, although they have low energy consumption and require low investment in production equipment. Comparatively speaking, cryogenic air separation is suitable for large-scale industrial production, and its by-product such as liquid oxygen can also be obtained. In addition, wasted heat from the cooling process can be used to heat liquid nitrogen at the heat engine end.

Though this paper does not aim to investigate the cryogenic approach, it is still necessary to provide a general liquefying process to determine which products should be stored for energy storage and electric generation. A cryogenic nitrogen production system mainly consists of an air purification unit, compressed air buffer unit, oxygen and nitrogen separation unit, nitrogen buffer unit and other modules, as shown schematically in Figure 3.

- Pretreatment module: It is mainly composed of an air purification unit with a filter group, dryer, oil remover, and other components, to remove dust, water and oil from the air, preventing pipeline freezing at low temperatures;
- Pre-cooling unit module: The heat exchanger cools the purified air to 10–15°C using water or ammonia cooling;
- The air compressor(s) module: It composed of low-pressure and high-pressure air compression units. The heat generated during compression should be stored for later use in driving a turbine.
- Expansion refrigeration module: The counter-current heat exchanger cools the air to below -170°C, and the high-pressure air is further throttled and cooled to -196°C (77 K) by the expander. The released heat should be stored for use during the expansion recovering stage;
- Distillation tower module: It uses the boiling point difference to separate liquid nitrogen (N_2 77 K) and liquid oxygen (O_2 90 K). The high-pressure tower preliminarily separates nitrogen at the top, and oxygen-rich liquid air at the bottom. Further, condenses the nitrogen at the top of the low-pressure tower is further condensed to purify the liquid nitrogen to 99.999 purity. Both liquid oxygen and nitrogen can be transported through pipelines and stored separately in their respective tanks.

Although the liquid nitrogen production process is mature, from the perspective of an energy storage-power generation system, it is necessary to balance energy consumption and output. Therefore, to reduce the energy consumption of air purification and nitrogen separation, the gaseous nitrogen discharged after driving the turbine should be recovered and stored to supplement liquid nitrogen production when electricity consumption is low.

4.2 Concept design of LN-ESR system

The main consideration in developing a liquid nitrogen energy storage–release (LN-ESR) system is based on the following facts:

- The volume of nitrogen liquefaction is only 1/700 of that of gaseous, which can achieve the goal of high-density energy storage;
- The compressed air refrigeration at the compressor(s)-throttle process will generate heat. The additional heat of refrigeration can be stored, which can be used to assist the expansion of liquid nitrogen at the heat turbine end;, and drive the turbine to move the generator to generate electricity;
- After the cold energy of liquid nitrogen is released, the clean nitrogen can be refluxed to low-pressure storage to assist in refrigeration, reducing overall energy consumption.

The LN-ESR system proposed in this paper should not be regarded merely as a combination of CAES and liquid gas energy storage (L-GES) systems. As shown in Figure 4, the system can be divided into three portions: liquid nitrogen production (refrigerator), energy storage system, and energy release (heating/air-con and power generation). However, its composition is substantially different from previous L-AES or L-CCES. The refrigerator section produces liquid nitrogen (and by product oxygen), not just compressed air for driving the turbine. It follows the Routine:

1. Air filter –> 2. Air compressor(s) -> 3. Heat exchanger -> 5. Compressed air storage -> 6. Expander(s) -> 8. Distiller -> 9. L-N_2 tank.

The energy stored in the LN-ESR system should include not only the liquefied nitrogen (and liquid oxygen as by-product during refrigeration), but also the heat released during compressor air, the compressed air before distillation process, and the recycled clean nitrogen after the expander(s) used to run the generator. Therefore, systematic design is essential for a successful demonstration. From the perspective of large-capacity energy storage, it is necessary to determine the appropriate volume of liquid nitrogen storage to coordinate the process links between production, storage and energy release.

While stored compressed air serves only as an intermediate in L-N_2 production, it still contains the mechanical potential power of compressed air. Energy storage should be extended to include 5. compressed air, the thermal energy released during compression 4.Low-temperature thermal and liquefying process 7. High-temperature thermal, and 9. L-N_2 in the form of cold energy.

The turbine used for CAES to produce electricity usually run under the pushing pressure of 0.2~1 MPa (2~10 bar). It is suitable for the system of liquefied nitrogen when it recovers at normal temperature (25°C) which could get the pressure around 0.4 bar. There might be two types of energy releasing forms, which comprised as at four ways:

Type I. Directly compensating to HVAC system: in summer stored 9. cold energy exposure to building, or heating building in winter via extracting thermal from 4. Low-temperature container;

Type II. Generating electricity to grid or for the usage in a building: normal CAES system 5. Compressed air expansion via 11. Turbine to drive 12. Generator, can be auxiliaries with heating from 7. High-temperature thermal container; or Driving 13. Cryogenic turbine to run 12. Generator.

The coupling processes of pressure and temperature should be considered in the whole system. Such coupling links exist as in the operating pressure and temperature during nitrogen liquefaction, and as the storage heat released by compressed air and retrieval it, as well as the mode of gasification liquid nitrogen to cool a building by using its atmosphere thermal energy.

Furthermore, the LN-ESR system could make use of underground space for available land in the city is always limited. It is also necessary to put storage tanks and compressor(s) and turbine below underground, to prevent production noise and to provide safety spaces for high-pressure vessels and high-temperature tanks.

Table 6. Economic comparison of the three liquid nitrogen production processes

Compare items	Cryogenic	PSA	Membrane
Purity	99.999	95~99.9	95~99.5
Capacity (Nm^3/h)	≥1000	1~5000	1~500
Start-up time	Hours	Minutes	Seconds
Energy (kWh/Nm^3)	0.4~1.0	0.3~0.6	0.1~0.3
Investment (m¥/RMB)	1.0~100	~1.0	0.1
Maintenance	High	Medium	Low
Byproduct	Oxygen, argon	None	None

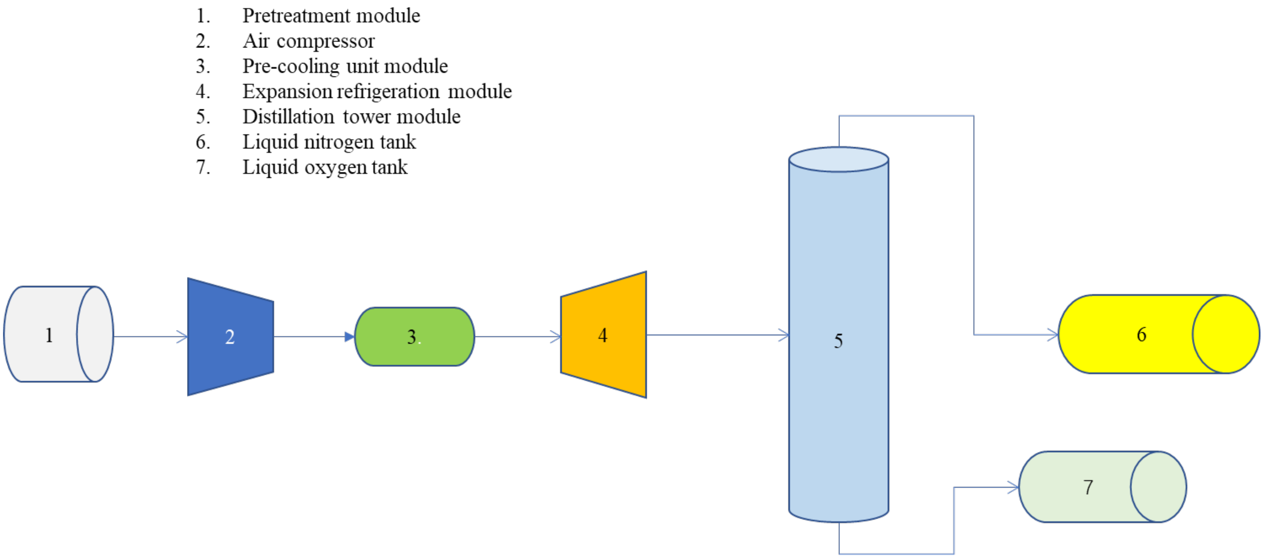


Figure 3. Cryogenic air separation

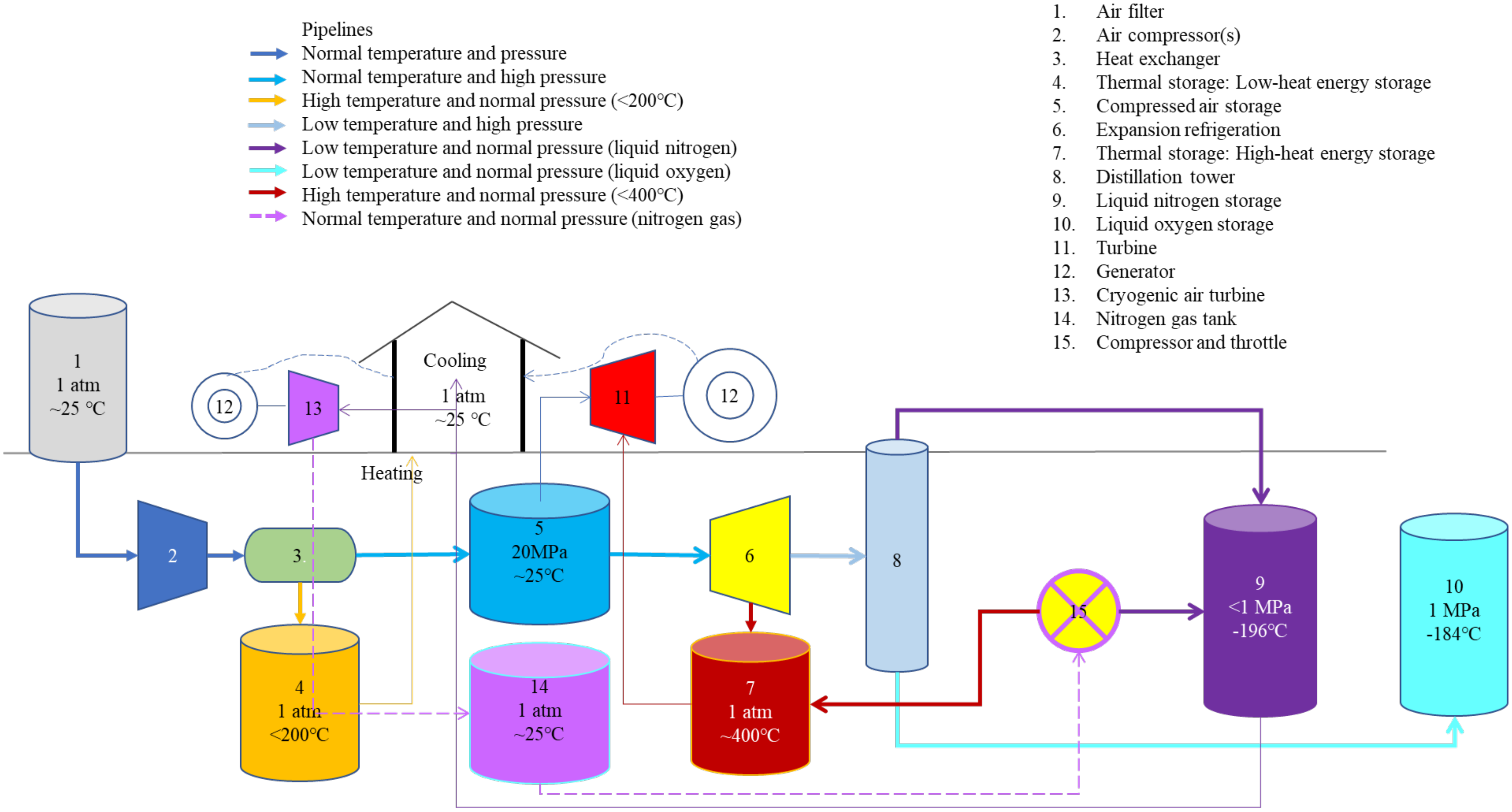


Figure 4. Concept of LN-ESR

4.3 Products storage

4.3.1 Liquid nitrogen/liquid oxygen storage

Liquefied nitrogen ($L-N_2$) storage tanks with a capacity exceeding 10,000 liters (10 cubic meters) for the food industry and medical care are classified as super-large storage tanks, which clearly cannot meet the requirements of urban energy storage. The liquefied storage of gas has been widely applied in liquefied natural gas (LNG). The 270,000 cubic meters storage tank at Zhuhai Jinwan 'Green Energy Port', with a height of 65.7 meters and a diameter of nearly 100 meters, stores 169 million cubic meters of natural gas, sufficient to meet the gas needs of 22 million residents for two months. The capacity of this storage tank is essentially on the same scale as the 220,000 cubic meters of caverns at the Jintan CAES demonstration power station.

The sandwich structure of LNG storage tanks is commonly used, comprising an inner tank, an outer tank, and an insulation layer. The inner tank is made of low-temperature resistant stainless steel (such as 0Cr18Ni9), which is in direct contact with LNG and is subjected to low temperature and pressure up to 0.8 MPa. The outer tank is usually made of carbon steel material as a protective layer to support the inner tank and isolate it from external environmental influences. The insulation layer is filled with pearlescent sand or elastic foam and vacuumed to reduce heat conduction. It should be noted that such large tanks stored above ground not only occupy urban space, but also require auxiliary brackets to maintain their stability for safety operation. The technology used to construct large LNG tank can also be applied to $L-N_2$.

Liquid nitrogen/oxygen can be stored at low pressure (~1.0MPa). As the pressure of liquid nitrogen in the tank will vary with usage when driving a turbine, a constant pressure storage system should be developed. To save land space, $L-N_2/O_2$ and thermal tanks can be stored underground by constructing shafts as shown in Figure 5. Shafts can be constructed using advanced vertical shaft machine (VSM) [21, 22]. The other advantages of underground storage are constant temperature characteristics of the geological formations, balanced outside pressure of the formation or water with respect to the inner pressure of the tanks, and safety isolation within still water under accident impacts or vibrations.

4.3.2 Thermal storage

Large-scale thermal energy storage (TES) technology is a key means to solve the spatio-temporal mismatch between energy supply and demand, and to improve energy recycling efficiency. Commonly used heat storage methods can be divided into three categories: sensible heat storage, latent heat storage, and thermochemical heat storage, as shown in Table 7.

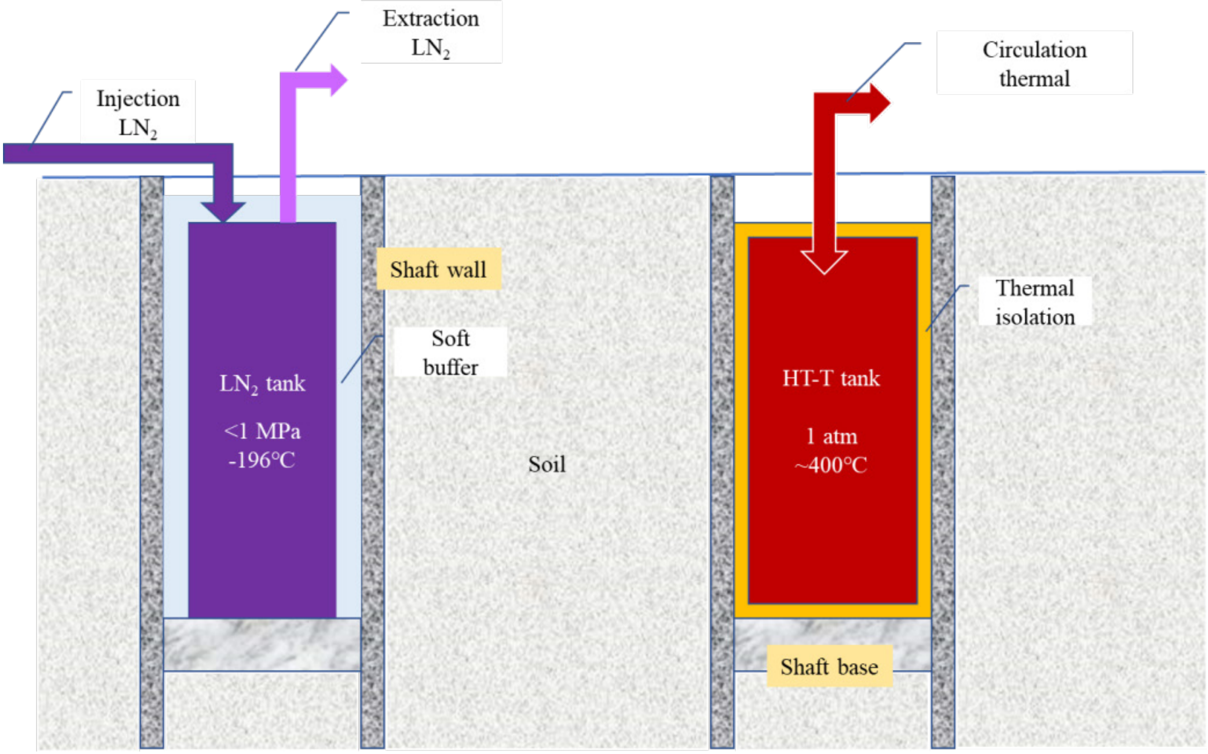


Figure 5. Concept of underground storage

Table 7. Characteristics of heat storage technology

Type	Principle	Peculiarity	Applicable scenarios
Sensible heat	Heating medium (water, rock, molten salt) raises the temperature	The technology is mature, the cost is low, but the energy density is low	District heating, solar thermal power generation
Latent heat	Utilizes phase transitions to absorb/release heat	High energy density and temperature stability, but thermal conductivity and packaging need to be addressed	Building energy storage, industrial waste heat recovery
Thermochemical	Reversible chemical reaction heat storage (e.g., calcium hydroxide)	It has the highest energy density, but the technology is complex and costly	Long-term energy storage, high-temperature industrial processes

Table 8. Examples of phase change materials

PCS	Examples	Peculiarity	Remarks
Organic	Paraffin, fatty acids	Chemically stable, none supercooling; poor thermal conductivity	-10°C ~ 100°C
Inorganic	metal Hydrate salt	High thermal conductivity and high latent heat; easy supercool, phase separation	0°C ~ 800°C
Eutectic	Organic-inorganic mixture	Customizable phase change temperature	Adjust according to the ratio

An example of sensible heat storage is the Gemasolar 19.9 MW power plant in Spain, which uses high-temperature molten salts (such as sodium nitrate and potassium nitrate, with a melting point of 220–240°C and a latent heat of approximately 160 kJ/kg). Heating the storage tank takes 15 hours. Its annual utilization rate exceeds 75%.

Latent heat storage involves encapsulating phase change materials (PCMs) in underground storage tanks or building structures and integrating them with heat pump systems to regulate district temperatures, as seen in the Marstal solar district heating project in Denmark. PCMs are functional materials that absorb or release large amounts of latent heat through phase changes (such as solid-liquid, liquid-gas, etc.) to provide thermal energy storage and temperature regulation. They maintain an almost constant temperature during phase transitions and have high energy storage density. Common types are shown in Table 8.

Thermochemical heat storage is a technology that stores heat energy through reversible chemical reactions. It offers high energy density, long-term storage without loss, and wide temperature range, making it a key research direction of the next generation for long-term thermal energy storage.

4.3.3 Storage of compressed air

Compressed air is an intermediate product in the production of LN_2. It can be used as an auxiliary supply for electricity generation. Therefore, large-scale and high-pressure storage is not the main focus of LN-ESR system

4.3.4 Storage of cyclic nitrogen

From an energy-saving perspective, nitrogen that has passed through the turbine should be stored for the next energy storage cycle to throttle and release liquid nitrogen, reducing part of the energy associated with air capture, purification and compression. Similarly, shaft storage can be utilized. Attention needs to be paid to the pressure and volume of the nitrogen storage to select an appropriate tank and match the shaft structure.

5. Release energy to balance daily usage

5.1 Supply cold energy

Liquid nitrogen can provide cold energy to HVAC systems during the summer. Liquid nitrogen could be extracted from the storage tank through a low-temperature, high-pressure (LTHP) pipeline to cool the room temperature to a normal level, such as 25 °C. Afterward, the liquid nitrogen will gasify at normal temperature, and then can be used to drive Cryogenic Air Turbine. The gas nitrogen can be circulated back to the storage tank to recharge the liquid tank after passing through a compressor and throttle.

5.2 Heating from thermal storage tank

In winter, water circulated from a low-temperature thermal storage tank can be used to heating room via a conventional heat-pump, extracted through High temperature and normal pressure pipeline (<200°C).

5.3 Generate electricity

5.3.1 Cryogenic air turbine and power generation cycle

Although the mass energy density of liquid nitrogen (~200 kJ/kg) is lower than fossil fuels, its capacity to do work is realized through the substantial volume expansion during phase change. According to standard thermodynamic properties, the volumetric expansion ratio of nitrogen from liquid to gas at Standard Temperature and Pressure (STP) is approximately 1:694 [23].

In the proposed LN-ESR system, the power generation process uses a Cryogenic Rankine Cycle. Liquid nitrogen is first pressurized by a cryogenic pump to a supercritical pressure (typically 6–20 MPa, depending on turbine design) [24], which consumes significantly less energy than compressing gaseous nitrogen. The high-pressure liquid then passes through an evaporator (absorbing ambient or waste heat), converting into high-pressure gas to drive the multi-stage cryogenic turbine. While theoretical isochoric (constant-volume) evaporation in a confined vessel could yield pressures exceeding 70 MPa, the operational pressure in this flow system is regulated to optimize the balance between turbine efficiency and component safety.

5.3.2 Pneumatic turbine

The high-pressure air stored by Compressed Air Energy Storage (CAES) can be supplied to a conventional pneumatic turbine (Pneumatic Turbine) via a normal temperature and high pressure pipeline. It can also be used with a high temperature and normal pressure (< 400°C) pipeline to replenish the heat energy in the high-temperature storage tank, delivering it the high-pressure gas expansion turbine to form a multi-stage turbine energy conversion power generation system.

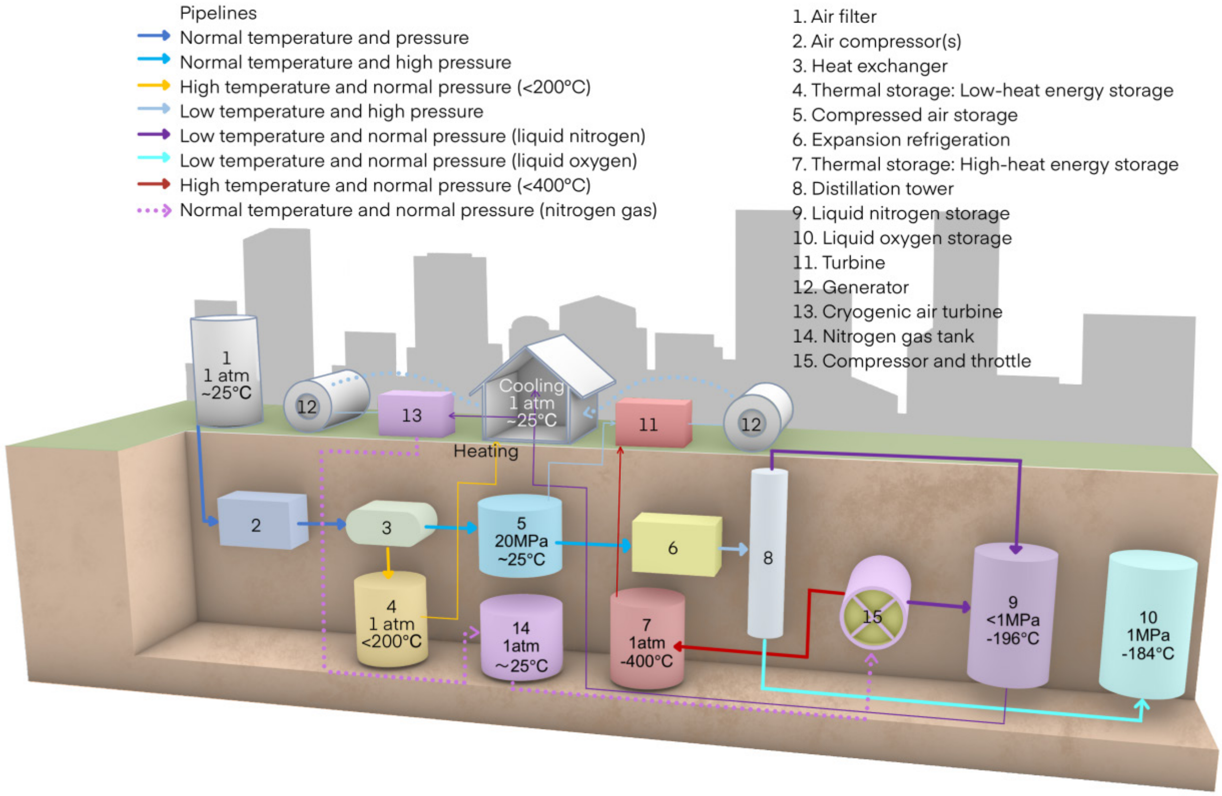


Figure 6. Layout of underground storage tanks

6. Challenge tasks

Liquid nitrogen energy storage-release-power generation is an integrated energy system that must balance energy storage capacity, energy density, primary cost, and operational safety. The following technological innovations are needed in the future to promote its development as the core solution for the new urban energy system.

6.1 Energy storage system

From Figure 3 of the LN-ESR system, it can be seen that the energy media requiring storage include liquid nitrogen, liquid oxygen, phase change heat storage medium, and gaseous nitrogen (turbine reflux). Although storage space can be constructed underground to take advantage of stable temperature and pressure condition in the soil formation, it is still necessary to further explore the structure of various storage tanks and their relationship with other process parameters like the amount of total required liquid nitrogen, to balance the target duration and the scale of a building.

Among them, one of the common problems to be addressed is the design of storage. The volume of a storage tank depends on the scale of the LN-ESR system. It is not necessary to build a shaft (diameter and depth) to host a storage tank as large as the cavern in Jintan salt rock. However, a group of shafts would be required to host different types of storage tanks. A conceptual layout of the storage tanks is displayed at Figure 6. Nevertheless, the storage tanks depend on the scale of a distributed LN-ESR system. For small scale system it might be combined with the pile foundation of a building or even the pile and shaft column of a wind turbine-generator. The construction of shaft or large-diameter pile is to identify the feasibility in soft ground, such as formation conditions, equipment capacity, and construction technology, is also a common technology.

6.2 Pipelines in process and production

The pipelines of the LN-ESR system might include the following as shown in Figure 3:

- Normal temperature and pressure: the pipeline which connects air purification equipment to air compressors, transports clean air;
- Normal temperature and high pressure: the pipeline which connects compressor to compressed air storage tanks and then to refrigerator(s) (throttle);
- High temperature and normal pressure: the pipelines collecting thermal during compressing air through heat exchanger to thermal storage tank(<200°C), or transporting stored thermal to a building as source of heating;
- Low temperature and high pressure: the pipeline which connects refrigerator to distiller;
- Low temperature and normal pressure: pipeline(s) which transport liquid nitrogen (LN_2) and liquid oxygen (LO_2) to their storage tank(s), or transport stored LN_2 to a building as cool media, or to drive cryogenic air turbine to drive generator;
- High temperature and normal pressure: pipelines which collecting released heat from refrigerator to thermal storage tank (<400°C), or transport stored thermal to heat exchange before cryogenic air turbine;
- Normal temperature and normal pressure (nitrogen gas): pipeline that transport released clean nitrogen gas from turbine to gas storage for cyclical use.

Though nitrogen has the characteristics of chemical stability safety management is still important for low-temperature or high pressure vessels or pipelines. It is suggested here that all the pipelines related to produce process should be placed in utility tunnel with separate cabin based on pressure and temperature.

6.3 Compressor, refrigerator and turbine

There are many machines in the LN-ESR system. The air compressor, refrigerator, heat exchanger, pump, gas expander, as well as turbine are the main examples equipment. Developing new technologies to improve energy conversion efficiency is a key factor in reducing energy consumption.

In addition, the operating noise of this equipment significantly affects the daily life of urban residents. Installing machines in a relatively closed, sound-absorbing underground plant can help create a more environmentally friendly ecological energy storage and release environment.

6.4 Safety and urban deployment considerations

Deploying the LN-ESR system in high-density urban environments requires a rigorous risk management framework, specifically addressing the hazards of cryogenic fluids and underground confinement. Unlike electrochemical batteries which pose thermal runaway risks, the primary risks of LN-ESR are physical and physiological, governed by mature industrial standards such as NFPA 55 (Compressed Gases and Cryogenic Fluids Code) and ISO 24490 [25, 26].

6.4.1 Oxygen enrichment and asphyxiation management

The air separation process inherently produces oxygen-rich byproducts. In an underground shaft, the accumulation of oxygen (>23.5%) significantly increases flammability, while a nitrogen leak can rapidly displace air, causing asphyxiation (<19.5% oxygen). To mitigate these risks, the underground facility must implement strict zoning strategies:

(1) Physical Separation: The Air Separation Unit (ASU) and liquid oxygen storage must be compartmentalized in fire-rated zones separate from the nitrogen storage shafts.

(2) Ventilation and Monitoring: Continuous oxygen sensors interlocked with emergency ventilation systems are mandatory. The ventilation rate should comply with ASHRAE Standard 15 for mechanical equipment rooms to prevent gas accumulation [27].

6.4.2 Cryogenic and overpressure protection

The phase change of nitrogen from liquid to gas involves a volumetric expansion ratio of approximately 1:694 at standard conditions. If cryogenic liquid is trapped in a closed piping section (e.g., between two closed valves) without pressure relief, the thermal expansion can rapidly generate pressures exceeding 70 MPa [24], leading to catastrophic vessel rupture or physical explosion.

In accordance with ASME B31.3 and NFPA 55, redundant Thermal Relief Valves (TRV) must be installed in every pipe section capable of isolating cryogenic fluid. The relief set pressure must be strictly calibrated below the Maximum Allowable Working Pressure (MAWP) of the piping system. Carbon steel becomes brittle and susceptible to fracture at cryogenic temperatures. Therefore, all piping, valves, and vessels in contact with liquid nitrogen must be constructed from austenitic stainless steel (e.g., 304/316L) or cryogenic-grade aluminum alloys to ensure ductility and structural integrity at -196°C.

6.4.3 Underground structural stability

The long-term storage of cryogenic fluid (-196°C) poses a risk of freezing the surrounding soil, which can cause frost heave and damage the shaft lining. A composite insulation structure consisting of vacuum-insulated panels and an active heating wire barrier (thermal break) is proposed between the tank wall and the shaft lining to maintain the soil temperature above 0°C.

6.4.4 Environmental integration and disaster resilience

In addition to process safety, placing the LN-ESR system underground provides significant benefits for urban resilience and environmental compatibility.

Disaster Resilience: Underground structures are inherently protected from extreme weather events (e.g., typhoons, heatwaves) and accidental surface impacts. Furthermore, the shaft structure also offers better seismic performance than tall surface tanks, ensuring energy security during natural disasters.

Noise Control: The operation of high-power compressors and turbines generates significant noise. Underground placement acts as a natural acoustic barrier, eliminating noise pollution for the surrounding commercial and residential communities.

6.5 Techno-economic analysis

6.5.1 Reference system definition

To ensure a verifiable assessment, we define a reference scenario based on the typical load requirements of a Shanghai commercial complex analyzed in Section 3. The proposed LN-ESR system is sized with a power capacity of 10 MW and an energy storage capacity of 40 MWh (4-hour discharge duration). The system utilizes underground vertical shafts for storage to minimize footprint.

6.5.2 Cost breakdown and assumptions

The economic analysis is based on 2023 market data [28, 29]. The Capital Expenditure for the LN-ESR system comprises three main components:

(1) Power island (40%): Includes Air Separation Units (ASU), compressors, and cryogenic turbines. Estimated cost: $1,200–1,400/kW [30].

(2) Storage system (30%): Involves the construction of Vertical Shaft Machines (VSM) and vacuum-insulated cryogenic tanks. Based on civil engineering data [22], a 20m-diameter, 100m-depth shaft costs approximately 30 million RMB (~$4.2 million), providing sufficient volume for the reference case.

(3) Balance of plant (30%): Piping, heat exchangers, and control systems

6.5.3 Comparative performance analysis

Table 9 presents a quantitative comparison between the proposed LN-ESR, Advanced Adiabatic CAES (AA-CAES), and Lithium-iron Phosphate (LFP) batteries.

Table 9. Techno-economic comparison of Energy Storage Systems (2023) [28-30]

Indicator	Unit	LN-ESR (Proposed)	AA-CAES	LFP
System Scale	MW / MWh	10 / 40	10 / 40	10 / 40
Volumetric Density	kWh/m³	~300 (Liquid N2)	2–6(Gas@ 70bar)	250–400 (System level)
CAPEX (Energy)	$/kWh	300 – 450	200 – 350	300 – 500
Round-Trip Efficiency (Elec.)	%	50% – 60%	65% – 70%	85% – 92%
System Lifespan	Years	30+	30+	10 – 15
Decay/Degradation	%/Year	Negligible	Negligible	2% – 3%
Output Products	-	Elec. + Cold + Heat	Electricity	Electricity
Comprehensive Efficiency	%	> 75%	~70%	~90%

6.5.4 Sensitivity and feasibility

Although the electrical round-trip efficiency (RTE) of LN-ESR (50-60%) is lower than that of Li-ion batteries (>85%) [28], the economic viability of LN-ESR is justified by two factors:

(1) Long-term Levelized Cost of Storage (LCOS) : LN-ESR relies on mechanical components (turbines/compressors) with a lifespan of 30+ years, whereas battery packs typically require replacement every 10-12 years [29]. Over a 30-year lifecycle, the LCOS of LN-ESR becomes competitive.

(2) Revenue form Cooling Services: For the commercial sector where HVAC consumes 47% of peak power [20], the direct supply of cold energy from LN2 regasification avoids the double conversion loss of "Electricity → Chiller → Cold", effectively offsetting the lower electrical efficiency.

6.5.5 System integration and smart energy management

(1) Scalability and grid interaction

Unlike centralized pumped hydro storage, the proposed LN-ESR system is inherently distributed and modular. It can be integrated into the urban grid as a "Virtual Power Plant" (VPP) node.

Building Scale: Small-scale units (e.g., 500 kW / 2 MWh) can be installed in commercial basements to manage individual building HVAC loads, reducing the demand charge for property owners.

District Scale: Larger systems (e.g., 10 MW / 40 MWh) utilizing underground shafts can serve as regional energy hubs, providing peak-shaving services for the district grid.

(2) AI-driven predictive optimization

To maximize the economic return and system efficiency, a Smart Energy Management System (SEMS) is essential. As analyzed in Section 3, urban loads are highly sensitive to weather and human activity. We propose integrating Artificial Intelligence (AI) and Machine Learning algorithms (e.g., Long Short-Term Memory networks, LSTM) to enhance operation strategies [31,32]:

Load Forecasting: The AI module predicts the HVAC cooling load 24 hours in advance by analyzing historical data, weather forecasts (temperature/humidity), and commercial calendars.

Dynamic Arbitrage: Based on Time-of-Use (TOU) electricity tariffs, the system optimizes the timing of liquid nitrogen production (charging during valley prices) and release (discharging cold/power during peak prices).

Efficiency Coupling: The control algorithm dynamically adjusts the ratio of electricity generation versus direct cooling supply to ensure the Comprehensive Efficiency exceeds 75% under varying operating conditions.

7. Conclusion

This paper proposes a novel Liquid Nitrogen Energy Storage and Release (LN-ESR) system designed for high-density urban environments. Based on a techno-economic analysis and the specific load characteristics of Shanghai (2024 data), the following conclusions are drawn:

(1) Targeted Solution for HVAC Peaks: Statistical analysis shows that HVAC cooling loads account for approximately 47% of the summer peak grid load in Shanghai. The LN-ESR system addresses this by decoupling the energy supply, storing power as high-grade cold energy to shave peaks more effectively than electrical-only storage.

(2) Superior Safety Profile: Compared to electrochemical batteries (e.g., Lithium-ion) which pose significant risks of thermal runaway and fire, the LN-ESR system utilizes non-flammable nitrogen as the working medium. As detailed in Section 6.4, safety risks are physical (pressure/temperature) rather than chemical, and can be rigorously managed through established industrial standards (NFPA/ASME), making it suitable for deployment in densely populated commercial districts.

(3) Efficient Utilization of Underground Space: The proposal to utilize Vertical Shaft Machines (VSM) for underground storage overcomes the land scarcity bottleneck in cities. A standard shaft (20m diameter, 100m depth) offers a viable alternative to geological caverns, providing large-scale storage capacity (~40 MWh) with minimal surface footprint and enhanced resistance to external disasters.

(4) Economic Viability through Poly-generation: While the standalone electrical round-trip efficiency of LN-ESR (50–60%) is lower than that of batteries, the system achieves a comprehensive efficiency exceeding 75% by cascading the utilization of cold energy for direct refrigeration and waste heat for domestic heating. This poly-generation capability significantly improves the Levelized Cost of Storage (LCOS) over a 30+ year lifespan.

Future work will focus on the development of AI-driven control algorithms to optimize the coupling ratio of electricity generation versus direct cooling supply under dynamic Time-of-Use tariffs.

Authors' contributions

The study was conducted by Yuan Yong, responsible for conceptualization, methodology, and original draft writing; Yao Xupeng, who contributed to conceptualization and investigation; Huang Meng-Hao, in charge of visualization, reviewing and editing; Chai Rui, providing supervision; and Zhang Jiao-Long, who provided supervision and reviewing and editing.

Conflicts of interest

All authors (Yuan Yong, Zhu Li, Huang Meng-Hao, Zhang Jiao-Long) declare that they have no conflict of interest or financial conflicts to disclose.

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