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Hospital-oriented quad-generation (HOQG)—A combined cooling, heating, power and gas (CCHPG) system

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HIGHLIGHTS
• Hospital-oriented quad-generation is explored for sustainable energy and gas supply.
• Combined cooling, heating, power and gas is used for normal and emergency operations.
• Superconducting devices are used for high-efficiency power delivery and management.
• Cryogenic fluids of both energy fuels and medical gases are stored for back-up use.
• Simultaneous supply of energy and medical gas is proposed against the COVID-19 pandemic.

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ABSTRACT
Along with the global spread of the COVID-19 pandemic, a number of hospitals are operating in the over-loaded state, which results in the ever-increasing requirements of cooling, heating, power, and medical gas supplies. This paper investigates a novel concept of hospital-oriented quad-generation (HOQG) to produce a combined cooling, heating, power and gas (CCHPG) system. Local renewable energy source (RES), high temperature superconducting (HTS) power cable and superconducting magnetic energy storage (SMES) device are used as the low-carbon electricity producer, carrier and regulator, respectively. Compared to the conventional copper cable and electrochemical battery, HTS terminal power units have superior advantages of high-efficiency power delivery and high-quality power compensation. To accommodate the surplus electricity from local RESs and guarantee emergency supply for the targeted hospital buildings, three cryogenic fluids of liquefied methane gas, liquefied oxygen and liquefied nitrogen are used as back-ups for both energy fuel and medical gas. By adopting a series of cascade energy utilization and thermally-activated energy conversion facilities, multiple clean energies of cooling, heating and power are produced to supply medical devices, and multiple medical gases of oxygen, nitrogen and carbon dioxide are delivered to hospitals for patient treatments. Compared to conventional diesel oil and compressed gas back-ups, these three cryogenic liquids have advantages of high-capacity, high-security storage and low-pollution utilization. Another possible benefit can be the low-temperature environment of these medical gases offers vaccines an appropriate delivering pathway against the COVID-19 pandemic. Therefore, the proposed HOQG can be expected to fulfill the demand of energy conservation and emission reduction simultaneously during the normal operation, as well as the demand of sustainable energy and medical gas supply under severe conditions such as natural and man-made disasters.

1. Introduction
Hospital buildings are normally operating 24 h a day all year round, with extremely high demands of space heating and cooling to ensure the indoor air quality [1–3]. Therefore, hospitals are among the most energy-intensive facilities, and they present the highest energy consumption per unit of floor area in the building sector. These negative effects actually contribute to serious greenhouse gas (GHG) emissions and even cause a series of environmental problems [4,5].

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For the purpose of achieving energy conservation and emission reduction in these energy-intensive hospitals, a number of promising solutions have been proposed and technically verified in recent years. In addition to improving the energy efficiency of healthcare and medical facilities, there are mainly two approaches to reduce the burden of power and fuel consumptions. One is using local renewable energy sources (RESs) such as solar and wind [6–9], and the other is adopting multi-energy integration technologies such as combined heat and power (CHP), and combined cooling, heating, and power (CCHP) [10–13]. For most renewable energy sources, they are generally fluctuating, intermittent and unpredictable [14]. In order to fix these issues, different sorts of energy storage technologies are required to maintain the stability of the electrical system [15,16]. The battery [17–19], flywheel [20,21], supercapacitor [22,23] storage technologies were widely used to overcome the energy fluctuation of renewable energy systems, but these technologies either shows a low energy storage density, or difficulties in long-term and stable power compensations [24,25]. Therefore, the power-to-gas (P2G) technology has been gradually recognized as a promising method for compensating the unbalanced electrical energy system as its great advantage of long-term energy storage [26,27]. There are three main forms of P2G: Power-to-Hydrogen (P2H), Power-to-Methane (P2M) and Power-to-Liquids (P2L). The P2H has the advantages of low production cost and high energy conversion rate, but the storage and transport are expensive and risky [28,29]. The P2M has higher production cost and moderate energy conversion rate, but the transport is much safer and cheaper than P2H [30] because the methane shows lower self-discharge risk in long-term storage. The P2L have the highest production cost and its transport is risky [28,29]. The P2M has higher production cost and moderate energy conversion rate, but the storage and transport are expensive and risky [28,29]. The P2L is the safest approach to install near the hospital buildings [31,32].

Gas-to-power (G2P) technologies can exploit the methane gas as the feedstock to generate electricity during high power demand in hospitals. Two main schemes of CHP and CCHP systems show the advances in generating electrical energy, and effectively using heating and cooling energies, with overall 80–85% of the fuel converted into useful energy [33]. Therefore, they are regarded as the proper technologies to relief the air pollution and minimize the greenhouse effect. For practical applications, the CHP and CCHP systems can be well merged into the renewable energy sources in urban and apartment buildings [34–36], large plants [37], and hospitals [38–40]. Some typical cases of theoretical investigation and engineering practice in hospitals are as follows. A hospital in Philippines replaces conventional heavy-fuel–oil boiler by integrating heat pump and solar energy, the annual energy expense has reduced by about 50% when its renewable energy fraction is up to 60% [7]. A hospital in Saudi Arabia adopts an optimal solution of hybrid micro grid consisting of biogas cofire and diesel generators, photovoltaic arrays and batteries, which can reduce carbon emission and diesel consumption by approximately 84% and 81% [8]. A hospital in the United States uses a multi-objective particle swarm optimization method to design a distributed energy network consisting of CHP system, photovoltaic array, electric and thermal energy storage devices, and a peak shaving in electricity of about 300 kW and a reduction in boiler fuel consumption of about 610 kW can be attained in a winter day [12]. A hospital in Japan carries out a case study of CCHP system, which has shown an energy saving ratio of 12.3% and an emission reduction ratio of about 20.7% [13].

In addition to multiple energy demands of cooling, heating, and power mentioned above, most of hospital buildings also have essential demands of multiple medical gases like oxygen, nitrogen, carbon dioxide [41]. Particularly, along with global spread of the COVID-19 pandemic in recent months, most of the hospitals are operating in the over-loaded state, which results in ever-increasing requirements of cooling, heating, power, and medical gas supplies [4,5,42]. How to guarantee the sustainable supply of both energy and gas is very important for assisting medical diagnoses and treatments. But in almost every case, both energy and gas supplies for hospital buildings come mainly from external power grid and medical gas factory [43,44]. Only a small amount of diesel fuel and compressed gas tanks are stored for providing back-up supply in some emergency conditions such as temporary interruptions of electricity and gas.

However, these conventional back-up schemes have already encountered serious challenges since the COVID-19 pandemic outbreak...
started in early 2020 [45–48]. A lot of people were forced to stay at home, causing widespread and unplanned shutdowns of many industrial chains. On the one hand, the ever-increasing number of respiratory-infected patients has increased the power and gas consumptions; on the other hand, the external supply chain has been likely to be inadequate in some emergency situations [49]. Currently, many hospitals are still suffering from uncertain shortage risks from external supply chains, which have not been fully recovered from the on-going battle against the virus globally. This brings an urgent need to seek alternative back-up supply approaches and solutions during and after the COVID-19 pandemic.

Therefore, this paper presents a novel concept of hospital-oriented quad-generation (HOQG) for producing combined cooling, heating, power and gas (CCHPG), with an aim to simultaneously fulfill the demand of energy conservation and emission reduction during normal operation, as well as the demand of sustainable energy and gas supply during emergency conditions. The rest of the paper is organized as follows. A conceptual framework of the HOQG concept is introduced in Section 2. Basic motivations, principles and benefit evaluations of three sub-systems are presented in Section 3, 4 and 5. System modeling and two emergency case studies of CCHP and medical oxygen supply are discussed in Section 6. Finally, the comparative performance comparison and economic evaluation of the HOQG are shown in Section 7 to verify the feasibility and practicality.

2. Conceptual framework of the HOQG

From a conceptual framework of the HOQG in Fig. 1, all the energy and gas consumptions in the hospital are derived directly or indirectly from local RESs such as solar/wind power. The low-carbon power generated from local RESs is mainly divided into three parts. The first part, which occupies the largest proportion, shows the electrical power is transmitted directly to the targeted hospital through a lossless high temperature superconducting (HTS) cable [50–53]. Considering the negative impacts from solar and wind volatility, a superconducting magnetic energy storage (SMES) [54–56] based power compensating unit is adopted to improve the real-time power quality for various critical medical devices. The second part is used to produce a certain amount of cryogenic liquefied nitrogen (LN2) for cooling the whole HTS cable line. The LN2 is then collected and stored in a cryogenic tank for some back-up uses such as providing cold energy and medical nitrogen. The third part is mainly for the case when the power generation exceeds the need from the hospital. Most of the surplus electricity is sent to an electrolyzer and its equipped methanator and cooler for implementing the conversion from electrical energy to both chemical energy and cold energy. The produced liquefied methane gas (LMG) and liquefied oxygen (LO2) are then transmitted and stored in two cryogenic tanks near the hospital. The stored LO2 ensures an adequate supply of medical oxygen during both normal and emergency operations, while the LMG can be sent to a high-efficiency CCHP unit for generating multiple energy supplements if required.

In terms of terminal energy and gas supply in the hospital, the HOQG system can be practically considered as an assembly of three sub-systems, i.e., clean power supply, multiple energy supply and multiple gas supply. To describe this new HOQG concept in detail, basic motivations, principles and benefit evaluations of the above three sub-systems will be presented as follows.

3. Principle and benefit evaluation of clean power supply sub-system

3.1. Low-carbon power generation unit

In order to guarantee a reliable supply of electricity, two-way independent power feeders from utility grid are normally used to supply most of the hospital buildings. Given the fact that the main electricity producer of utility grid is still fossil-fired power plant at present, power consumptions from the hospital buildings result in serious GHG emissions indirectly. To meet the demand of energy conservation and emission reduction, local RESs can be served as low-carbon power generation sources. By comparison, the GHG emissions of wind, solar and coal power generations are about 31.36 g/kWh, 61.00 g/kWh and 755.86 g/kWh, respectively [57,58]. For instance, if a 10-MW class solar power plant is installed instead of using utility power, the corresponding emission reduction will reach about 60,882 tonnes in each year. Moreover, even when the utility grid is cut off during the emergency, these RESs can provide a continuous power supply without external electricity.

3.2. High-efficiency power delivery unit

In general, hospital building is with a total capacity of megawatt-class power loads, but most of terminal voltage supplies are in the range of 100–400 V. Therefore, tens of kiloampere are actually reached
from terminal power substation to hospital building, and further result in high resistive loss from copper cable [59]. This type of terminal cable is also called as the “last-mile cable” that operates at very low voltage and very high current. In the case of a 0.4-kV/10-MW hospital building, if this terminal power delivery employs copper cable with a resistivity of 0.02 μΩ⋅m [60] at a current density of 2 A/mm², a unit loss of 1 kW per meter cable would be incurred, resulting in a total loss of 1 MW and an overall efficiency of 90% for a length of 1 km.

To improve the power delivery efficiency of this last-mile cable, the HTS cable with zero resistive loss can be a promising solution. For a practical cable prototype, multiple parallel-connected HTS tapes are firstly wound onto a cylindrical copper former with a certain winding directions and layers, and then the whole cable body is inserted into a long cryogenic pipeline and cooled by the LN₂ with a temperature range of 65–77 K [61–63]. For the HTS cable itself, there is no loss during the last-mile power delivery. But two main kinds of heat loads should be practically considered for equivalent loss estimation. One is the heat leakage from the last-mile cryogenic pipeline to room-temperature environment, and the other is the heat leakage from the cable terminal leads to ambient copper joints. In general, these two heat loads can be considered to be proportional to the overall length and operating current of the cable. Specifically, the former and latter heat loads are usually estimated as 1 W per meter length and 0.1 W per ampere current [64].

For the same 0.4-kV/10-MW/1-km cable design, the total quantity of heat leakage into cryogenic pipeline is about 3.5 kW. Providing the cooling for this heat leakage using refrigerators requires approximately 10 times the amount of actual power of that needed for the heat leakage at liquid nitrogen temperature, meaning an equivalent loss of 35 kW [65,66]. Therefore, replacing the last-mile copper cable by this new type of HTS cable can bring an overall efficiency improvement from 90% to 99.65%.

### 3.3. High-quality power compensation unit

As mentioned above, the low-carbon electricity from local RESs can be efficiently delivered to the targeted hospital buildings using HTS cables. Then the next step is to distribute the power to supply various electrical devices located in different hospital areas. But due to the combined effects of intermittency of the RESs and uncertainty of the hospital loads, transient supply–demand imbalances across the power lines are inevitable in practice [67]. To protect critical medical devices against these power sag/swell problems, electrochemical batteries are normally used to form various types of uninterruptible power supplies (UPSs) that can be connected to the critical loads after a certain response time delay [68], e.g., tens of milliseconds. In essence, this response time delay is mainly due to the chemical-electrical energy conversion process inside the batteries.

However, along with the developments of advanced diagnosis and treatment techniques, increasingly high power quality is required to supply medical devices [69]. Specifically, some critical components and units inside the operating room and intensive care unit (ICU) have very urgent needs to be compensated within several milliseconds. To achieve an extremely fast compensating operation, replacing conventional battery-based UPS by a new SMES device could be an effective solution [70–72]. As a magnetic energy storage unit, HTS inductor inside one SMES device is allowed to be charged/discharged immediately. This advantage makes it available to compensate initial voltage sag/swell within one millisecond. In theory, if a HTS inductor is always connected to on-line UPS, its transient charge/dischARGE response depends only on the speed of power electronic switches.

In addition, it has been reported that the power density of a SMES device is about 100 times higher than that of a redox flow battery, and about 10 times higher than those of a lead acid battery and a NaS battery [73], thus the SMES can provide much larger charge/discharge power compared to a battery unit for the same mass and volume. However, practical applications of the SMES are usually suffered from relatively low energy density and high capital cost compared to commercial battery systems. To ensure both the performance and cost [74–79], a hybrid energy storage (HES) scheme composed of one small-scale SMES device and one large-scale battery device can be well expected to combine the merits of fast response and high power density from the SMES with high energy density and high economic efficiency from the battery simultaneously.

### 4. Principle and benefit evaluation of multiple energy supply sub-system

In addition to supply high-efficiency and high-quality power for various medical devices, the low-carbon electricity from local RESs is also used to meet the high demands of space heating and cooling by using a number of air conditioners. For those commercial heating ventilation air conditioning (HVAC) systems, the coefficient of performance (COP) in cooling mode and energy efficiency ratio (EER) in heating mode are about 3.5 and 2.5, respectively.

In one case when the power generation exceeds the need from the hospital, it is necessary to adopt an energy storage unit for absorbing surplus energy from local RESs. Electrochemically converting water to low-carbon fuels using surplus electricity could be a sustainable scheme [80]. In this water electrolysis concept, electricity is used for splitting the hydrogen and oxygen into their gaseous phase. Given the fact that hydrogen is difficult to store on a large scale owing to its small unit energy density and fast thermal motion, hydrogen can be further converted into methane in a methane catalytic device by capturing carbon dioxide [81]. Finally, the produced methane is liquefied into LMG for back-up fuel storage.

In another case when the delivered electricity cannot fully meet the load demands, alternative multiple energy productions from local CCHP system can be utilized as supplements [10–13]. In the LMG based CCHP scheme in Fig. 2, cryogenic fuel is firstly vaporized into gaseous methane by using a heat exchanger. Considering a normal heat transfer efficiency of 90%, this vaporizing process generates a cold energy of 1.68 MJ per kilogram LMG. The vaporized gas is then sent to combustion chamber for the operation of cogeneration. For a typical natural gas turbine, the electric and heat conversion efficiencies are about 38% and 50%, respectively. As a by-product, high-temperature waste flue from the combustion chamber can be collected to produce cooling via a thermally-activated chiller or produce heating via a heater [82]. If the gas turbine cannot provide enough by-product heat, additional electricity or fuel is then needed to compensate for the cooling/heating gap. In the case of using gas-fired chiller/heater unit, the COP and EER are about 1.5 and 1.0. In the case of using HVAC unit, the COP and EER are about 3.5 and 2.5, respectively.

### 5. Principle and benefit evaluation of multiple gas supply sub-system

As a most common medical gas, oxygen is widely used in every healthcare section, with applications from resuscitation to inhalation therapy. In the normal period before the COVID-19, most of oxygen supplies rely on external logistics chain from medical gas factory, with a very small amount of back-up gas tanks stored in hospitals. However, this conventional gas back-up scheme cannot meet the high demand due to the ever-increasing number of respiratory-infected patients as the outbreak of the COVID-19. To enhance the gas storage capacity for extending the emergency back-up time, LO₂ could be served as a high-density and safe storage form [83]. By comparison, compressed oxygen gas takes up about 1/150 of the volume of non-pressurized gas, while LO₂ takes up about 1/600 of the volume. Meanwhile, from the perspective of safe storage, LO₂ can be easily stored in the one-atmosphere pressure, but a normal tank pressure of compressed oxygen gas is up to 15 MPa in practice.
Fig. 3 shows a conceptual scenario of oxygen production, storage and consumption from low-carbon energy to medical oxygen supply. For the use of the produced oxygen from water electrolysis, it is preferred to supply various oxygen-based breathing terminals through a series of gas regulating and distributing devices. In general, the medical oxygen supply can be divided into four areas according to terminal flow rate. Four typical areas of low-flow, medium-flow, high-flow and the ICU oxygen delivery are usually designed to have average rate ranges of 0–5 L/min, 5–15 L/min, 15–20 L/min, 20–30 L/min, respectively. If the produced oxygen cannot meet the real-time demand of the whole hospital, LO$_2$ back-up is then vaporized to provide gaseous oxygen supplements. In another case when the produced oxygen is excessive, the surplus part can be liquefied into LO$_2$ for back-up storage.

In addition to provide adequate medical oxygen gas, the proposed HOQG is also designed to store and supply other medical gas series like nitrogen and carbon dioxide. Nitrogen can be used as a gas component in many medical mixtures such as lung function test gases. In its liquid form nitrogen is used as a cryogen for the storage of cell, tissue and blood. In order to ensure the safe and effective transportation of vaccines from producers to users, cold chain transportation is usually used to ensure the transportation temperature [84–85]. Given the fact that most of COVID-19 vaccines require either cold (i.e., 2–8 °C) or even freezing temperatures as low as –70 °C for storage and distribution [86–87], cryogenic LN$_2$ could provide a sustainable pathway to store and transport COVID-19 vaccines whenever and wherever needed. Carbon dioxide produced by methane combustion might be used as an insufflation gas for minimal invasive surgery. Meanwhile, a large quantity of cold energy from the stored LN$_2$, LO$_2$ and LMG has the potential to prepare the ice water and dry ice.

6. Case study on back-up energy and oxygen supply in emergency

6.1. LMG consumption modeling in emergency

In the case of emergency energy supply, the required capacities of the power, cooling and heating loads in the hospital buildings are set as $P_{\text{power}}$, $P_{\text{cool}}$ and $P_{\text{heat}}$, respectively. Firstly, the methane-based gas

![Operational process of multiple energy supply sub-system.](image1)

![Overall layout of medical oxygen production, storage and utilization.](image2)
In the scheme of using a gas-fired heater, a certain quantity of gaseous methane at 0°C is sent to combustion chamber and then drive the lithium-bromide absorption chiller/heater for providing the cooling/heating power supplements. In this case the volumetric flow equation in (8) should be modified into

\[ q_t = \frac{1}{\rho_{LMG} \cdot LHV} \left( \frac{P_{power}}{\eta_{el}} + \frac{P_{heat,extra}}{COP_3} + \frac{P_{heat,extra}}{EER_3} \right) \]  

where \( COP_2 \) and \( EER_2 \) are the COP and EER of gas-fired lithium-bromide absorption chiller/heater, 1.5 and 1.0.

For the proposed HOQG system, surplus renewable energy accommodation is normally used to produce the LMG during normal operation, while it can also prepare the methane gas (MG) directly during emergency operation. Based on the modeling of LMG consumption in emergency, the total HOQG supply can be divided into four operating sub-modes. Mode 1 defines that the gas turbine supplies the insufficient heating power when the sum of \( P_{cool} \) and \( P_{cool,2} \) is larger than the \( P_{cool} \) and similarly Mode 2 defines the air-conditioner supplies the insufficient heating power with the same condition. As shown in Fig. 4 (a) and (b), the LMG vaporizes to gaseous methane, and then the methane is sent to the gas turbine to generate the electric power, in order to fulfill the demand of \( P_{power} \). By using Eqs. (1) and (2), the \( P_{cool} \) and \( P_{cool,2} \) can be obtained to fulfill the demand of \( P_{cool} \), and meanwhile a certain heating power \( P_{heat,extra} \) is subsequently generated by the surplus high-temperature flue from gas turbine. Based on Eq. (4), the insufficient heating power is supplied by the gas-fired heater (Fig. 4 (a) or air conditioner (Fig. 4 (b)).

Mode 3 defines that the gas turbine supplies both the insufficient heating and cooling power when the sum of \( P_{cool} \) and \( P_{cool,2} \) is smaller than the \( P_{cool} \) and similarly Mode 4 defines the air-conditioner supplies both the insufficient heating and cooling power with the same condition. Fig. 4 (c) and (d) show that by using the Eqs. (5) and (6), the insufficient cooling power \( P_{cool,extra} \) and the whole heating power \( P_{heat} \) are supplied by the gas-fired chiller/heater (Fig. 4 (c)) or air conditioner (Fig. 4 (d)). Finally, the total volumetric flow \( q_t \) of the LMG consumption in the above four sub-modes can be estimated by using Eqs. (8) and (9). This value can be further used to evaluate the emergency back-up time by considering both the initial storage capacity and daily renewable energy accommodation in hospitals.

6.2. Emergency back-up time modeling with renewable energy accommodation

Continuous supply of oxygen is the primary requisite of every medical unit. As an economical and convenient form of oxygen storage, eight LO2 tanks with 8*10 m³ storage capacity in total are adopted by Wuhan Huoshenshan Hospital (a large-scale specialized hospital against the COVID-19 pandemic in China), in February 2020 [88]. It has been reported that the total oxygen consumption is about 6–12 m³ depending on the emergency state of medical assistance, and thus the corresponding back-up time is about one to two weeks. In the most urgent emergency condition, every breathing machine is even estimated to have a maximum gas flow rate of 90 L/min, resulting in a total oxygen consumption of 4666 m³/h for the whole hospital [89]. To ensure a stable oxygen supply, cryogenic liquid tanker is introduced to transport the LO2 supplement from oxygen factory.

In the proposed HOQG system, surplus electricity from local RESs is mainly used to produce both LO2 and LMG for the back-up storage and emergency utilization. This P2G scheme has three main processing sections as follows. The first section of the P2G involves an electrolyzer, which is used to convert water into H2 and O2.

\[ 2H_2O \rightarrow 2H_2 + O_2 \]  

(10)

The second section involves a methanator, in which the methanation reaction occurs on a catalyst. The major reaction is the hydrogenation of
carbon dioxide (CO$_2$)

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$  \hfill (11)

The main sources of CO$_2$ come from carbon capture, biomass, industrial processes, and air [90]. The CO$_2$ capture is already well-developed and three processes are used in industrial installations: post-combustion capture, pre-combustion capture and oxy-fuel capture [91,92].

In an actual conversion from electrical energy to chemical energy, about 20 kWh electricity is generally consumed for producing 2 m$^3$ oxygen gas and 1 m$^3$ methane gas [93–95]. In the third section, all the oxygen and methane gases are sent to cryogenic liquid refrigerator for producing LO$_2$ and LMG. About 800 m$^3$ oxygen gas and 625 m$^3$ methane gas at one atmosphere can be pressured into 1 m$^3$ cryogenic liquid for the convenience of storage. During the condensation process from the pure gas to liquid, about 1 kWh electricity could be further consumed in commercial liquefaction devices [96].

These newly-added gas and energy quantities have great potential to extend the overall back-up time. Two basic formulas for estimating the LO$_2$ back-up time $D_1$ and LMG back-up time $D_2$ are as follows

$$D_1 = \frac{A_1 k_1}{(B_1 k_1 - E/C_1)}$$  \hfill (12)

$$D_2 = \frac{A_2 k_2}{(B_2 k_2 - E/C_2)}$$  \hfill (13)

where $A$ is initial liquid storage capacity, m$^3$; $B$, average liquid consumption per day, m$^3$; $C$, average electricity consumption for producing per unit volume gas, kWh/m$^3$; $E$, renewable energy accommodation per day, kWh; $k$, coefficient of cubical expansion after gasification. The subscripts 1 and 2 represent the parameters of LO$_2$ and LMG, respectively. The coefficients of cubical expansion in LO$_2$ and LMG are set as 800 and 625, respectively.

### 6.3. Case study of emergency supply in the proposed HOQG system

In a case of emergency oxygen supply, initial capacity and daily consumption of LO$_2$ are set as 30 m$^3$ and 5 m$^3$, respectively. If the produced oxygen from electrolyzer is sent to terminal breathing machines as a supplement in Fig. 3, an obvious extension of back-up time can be practically achieved. Fig. 5 shows a growth process of emergency

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**Fig. 4.** Four main operating sub-modes of multiple energy supply in emergency.
back-up time of gas supply versus renewable energy accommodation per day. For a total surplus electricity of 20 MWh accommodated in each day, daily oxygen production is about 2000 m³ in total, and the resulting back-up time can be extended to 12 days.

In a case of emergency energy supply, the power, cooling and heating loads are set as 200 kW, 300 kW and 400 kW, respectively. For a power generation efficiency of 38% in Fig. 2, about 2.31 m³ LMG will be consumed to output a continuous power supply of 200 kW. The total latent cold energy from gasification is about 1633 MJ, corresponding to 18.9 kW cooling power. Then, about 16191 MJ by-product heat from gas turbine should be sent to flue-gas chiller for producing the rest cooling power of 281.1 kW. Finally, the rest by-product heat of 6545 MJ is sent to flue-gas heater for producing a heating power of 75.8 kW. For the sake of full compensation for 400 kW heating power, two feasible solutions could be considered. One is using a gas-fired heater (EER = 1.0), and the other is using an air conditioner (EER = 2.5). Considering the secondary utilization of latent cold energy and by-product heat, the total daily LMG consumptions are about 3.7 m³ and 3.3 m³ in the above two solutions. Assuming that an initial LMG capacity is set as 22.2 m³, then the emergency energy back-up are about 6 days and 6.73 days accordingly. Similarly, the produced methane supplement from local RESs can also contribute the extension of emergency back-up time of energy supply, as shown in Fig. 6. For a total surplus electricity of 20 MWh accommodated in each day, practical back-up time in the above two solutions rises to about 13.9 days and 11.1 days, respectively.

7. Comprehensive performance comparison and economic evaluation

7.1. Performance comparison

Fig. 7 presents a typical framework of the conventional energy and gas supply for a hospital. Currently the main electric power supply for most hospital buildings is from the city main grid, and the power transmitter is generally the copper cable. If in the low-voltage distribution network with higher electric current, the power loss in the copper cable can be massively high. Some hospitals have introduced the clean energy (such as the wind/solar energy) to locally generate the electric power to shrink the carbon emission, and meanwhile reduce the dependency of external power sources [97–99]. The back-up power supply for hospitals is mainly based on the diesel generator and bulk batteries [100]. Batteries are generally used for the short-time power compensation, and the diesel generator can be used as the steady power supply if the external power supply is no longer available. Considering the high-level pollution from the diesel generator, some hospitals use the low-pollution and high-efficiency gas-turbine generator as the long-time back-up power supply [101,102].

As a major back-up fuel for the gas-turbine generator, the source of methane gas can be directly obtained by the electrolyzer and methanator powering by the electric energy from the peak-load regulation of renewable energy. The compressed methane gas (CMG) is normally stored by high-pressure containers, and will be depressurized and supplied to power the gas-turbine generator. When the methane gas is insufficient, it will be reinforced from the local natural gas supply network. In order to further improve the energy efficiency, the CHP [103–105] and CCHP technologies will be adopted by using the high-temperature flue from the gas turbine to power the lithium-bromide chillers/heaters, and meanwhile using the surplus energy to assist the cooling/heating loads of air conditioners [106–108].

For the oxygen supply system in hospitals, the gaseous oxygen is normally supplied through liquid oxygen tanks, and high-pressure oxygen cylinders are also available as back-ups [109]. In general, most of the liquid oxygen and gaseous oxygen containers are externally delivered from the gas factory to the hospital, and the scale of local storage is normally not large.

Fig. 8 shows a comparative analysis of advantages from the proposed HOQG system. Compared to conventional multiple energy and gas supply schemes in Fig. 7, the HOQG in this work has a series of technical features and advantages. In order to further clarify the feasibility and practicality, six main features are summarized and discussed as follows.

(1) Low carbon

The low-carbon feature mainly includes three aspects. The first is introducing the renewable energy instead of using fossil-fired power. Assuming that 100% solar energy is achieved in a 10-MW hospital building case, about 60,882 tonnes carbon emission can be reduced in each year. The second is adopting power-to-gas technology instead of direct electricity storage. A certain amount of carbon dioxide is firstly absorbed to react with gaseous hydrogen for producing methane fuel, and an equivalent amount of carbon dioxide is generated for achieving the goal of carbon neutrality in the following methane combustion process. The third is adopting a series of efficient energy transmission, storage and utilization devices such as HTS cable, SMES, CCHP, etc. These devices can conserve energy and then reduce carbon emission indirectly.

(2) High efficiency

The high-efficiency feature also includes three aspects. The first is adopting the HTS cable instead of the copper cable. An overall efficiency improvement from 90% to 99.65% can be achieved for the last-mile power delivery in a 10-MW hospital building case. As a result, about 8453.4 MWth electricity is saved and then about 6390.8 tonnes carbon emission is reduced every year. The second is adopting SMES instead of electrochemical battery. Assuming that a 10-kWh energy storage unit carries out ten full charge-discharge operations per hour, replacing battery-based UPS by a new SMES device can save about 219.0 MWh...
electricity per year. The third is introducing CCHP instead of diesel generator. Thanks to both the cascade utilization of different energy carriers and the adoption of thermally activated technologies, a typical CCHP system can improve the overall efficiency from 30% up to 80%, or even more.

(3) High capacity

The high-capacity feature mainly refers to the high storage capacity for energy fuel and medical gases in the proposed HOQG system. For the purpose of achieving a very high reliability of emergency back-up supply, it is advantageous to have a high-capacity back-up of both energy fuel and medical gases within limited storage space near the hospital buildings. Compared to compressed gas counterparts, practical storage capacities of LMG and LO₂ inside the same tank volume can be increased by a factor of about 2.5 and 5.3, respectively. Therefore, this cryogenic liquid storage scheme can be well expected to relieve the existing severe dependency on external power and gas supply networks under both

![Fig. 7. Typical framework of conventional energy and gas supply for a hospital.](image)

![Fig. 8. Comparative analysis of advantages from the proposed HOQG system.](image)
normal and emergency conditions. In addition, the total cross-sectional area of a 10-MW HTS cable is only about 37.5% of that of copper counterpart. This means that more than twice of the transmission power can be delivered within the same last-mile cable trench.

(4) High security

The high-security feature comes from the low storage and operating pressures of cryogenic liquids used in the proposed HOQG system. Two cryogenic liquids of LMG and LO₂ can be easily stored in one atmosphere pressure, but a normal tank pressure of conventional compressed gas is up to 10–30 MPa in practice. In addition, the cryogenic operating environment inside HTS cable pipe avoids the potential risk of overheated breakdown which often occurs in practical use of last-mile copper cables.

(5) High quality

The high-quality feature comes from two remarkable merits of fast response and high power density in SMES-based compensating units. In theory, a SMES inductor can be charged/discharged immediately without any time delay. To protect critical medical devices against those millisecond-level power sag/swell problems, replacing conventional battery-based UPS by a new SMES device could be an effective solution. Moreover, the SMES can provide much larger charge/discharge power compared to a battery unit for the same mass and volume. This is very favorable for improving power supply stability and reliability during transient sag/swell periods.

(6) Low pollution

The low-pollution feature comes mainly from the use of both SMES and CCHP units. The introduction of SMES lowers transient power demands for the equipped battery unit in a HES device. In terms of the battery technology, its overall battery lifetime can be efficiently improved because of performance degrading mitigation. In this way, environmental pollution can be well mitigated owing to the battery recycling and disposal. In addition, replacing conventional heavy-fuel–oil based boiler and generator by a new LMG-based CCHP unit avoids using highly-polluting diesel oil.

7.2. Economic evaluation

The HOQG is an integrated system containing the renewable energy generation, transmission, conversion and storage. The capital costs are approximately 443.36 €/kW and 652 €/kW for the solar and wind power generation sub-systems, and their operation and maintenance (O&M) costs are 13.04 €/kW and 6.52 €/kW per year [110–112]. For a 10 MW renewable energy case, the annual solar power is 21.9 GWh and wind power is 36.5 GWh, which include the solar power generation 6 h per day and wind power generation 10 h per day. Considering that all the renewable energy are supplying for the hospital buildings (e.g. the demand is 10 MW), the electricity fee saved is about 65.2 €/MWh. It is estimated that the cost-recovering cycles for solar and wind power generations are about 3.4 years and 2.8 years. Further, some additional environmental co-benefits of renewable energy generate from avoiding the disposal cost of greenhouse gases and pollutants. Life cycle analysis (LCA) shows that the estimated co-benefit of the HOQG concept is about 22.95 €/MWh [113–114], which can further shorten the cost-recovering cycle of solar power to 2.5 years and wind power to 2.1 years.

By conducting the economic analysis of different devices in the above conventional and HOQP systems, important basis can be established for the real industrialization in near future. As shown in Table 1, for the conventional electric power transmission, the copper cable is used with the standard of YJV-0.6/1kV, and the cost is approximately 25.7 €/km, with the rate current 705 A. In a 0.4 kV/10 MW transmission case, the last one-mile transmission needs 72 units of copper cable, and thus the total capital cost is 1850.4 €/k. By contrast, the single HTS tape’s critical current is 200 A, and if considering the safety factor of 1.5, the rate current is 133 A and the cost is about 12.8 €/k. The cost of the cryostat is about 83.2 €/k, and for the same condition the SMES has a higher power density and thus a lower unit power cost (208 €/k. As Fig. 9(a) shows the total cost of HTS cable is approximately 4896 €. During the process of power transmission, the annual maintenance cost of HTS cable is about 19.62 €, which is much lower than the maintenance cost of copper cable 560.64 €. Therefore, the SMES shows technological and economic advantages, and also has the eco-friendly benefit.

Regarding the power storage technologies, batteries are widely used as a common method. The NaS battery and SMES have been compared with economic analysis. The unit cost of NaS battery and SMES are 332.8 €/kWh and 4576.5 €/kWh [116]. If a 10-kWh energy storage unit carries out ten full charge–discharge operations per hour, the capital cost and the annual operating cost of the NaS battery are 3328 € and 16,820 €, and for the same condition the SMES’s capital cost and the annual operating cost are 45,765 € and 2803 €. Fig. 9(b) shows the cost of SMES is cheaper than the cost of NaS battery after 3.1 years. Moreover, the SMES has a higher power density and thus a lower unit power cost (208 €/k), which is much cheaper than the NaS battery (1664.2 €/k). Therefore, the SMES shows technological and economic advantages, and also has the eco-friendly benefit.

For the power to fuel conversion, the capital cost of P2L 3500 €/kW is higher than that of P2M 2630 €/kW, as the P2L needs further liquefaction [117]. However, P2L in the low-temperature condition can realize the low-pressure storage and large-scale compact installation. With the increasing energy consumption and higher safety standard in hospitals, the P2L will supply high-density energy, but also provide a more reliable scheme of energy back-up for most hospitals in future.

Overall, compared to the conventional system, in the proposed HOQP system the HTS cable has much higher energy transmission efficiency, the SMES has both the economic and technological advantages, and the P2L has the benefits of high-density energy storage and compact installation. Therefore, the HOQP system can be more suitable for the
highly energy-intensive constructions, particularly for hospital buildings.

8. Conclusion

A novel hospital-oriented quad-generation (HOQG) system has been proposed and analyzed in many aspects to explore the simultaneous supply of multiple clean energies and medical gases during both normal and emergency operations. Compared to conventional multiple energy/gas supplies in hospital buildings, the HOQG system has been technically verified to have six main advantages, e.g., low carbon, high efficiency, high capacity, high security, high quality and low pollution. For the 10-MW hospital building case, replacing the last-mile copper cable and electrochemical battery by HTS cable and SMES can save approximately 10643.4 MWh electricity per year. During the normal operation, surplus electricity from local renewable energy sources can also be used to convert water and air into energy fuels and medical gases. By adopting the cryogenic fluids of LMG, LO$_2$ and LN$_2$, more than twice of the storage capacities can be achieved for the back-up use, compared to the conventional compressed gas tank having the same volume. This is favored to guarantee continuous energy and gas supplies even when utility grids and external gas supply chains are cut off. Moreover, the daily accommodation of local renewable energy sources can also extend the overall back-up time in emergency. For a total surplus electricity of 20 MWh accommodated in every day, the practical back-up durations of emergency gas and energy supplies rise from 6 days to more than 12 days. In conclusion, the proposed HOQG system has remarkable advantages in high-capacity delivery and storage of both energy and gas compared to the conventional hospital supply scheme. In view of the current situations of global spread and long-standing battle against the COVID-19 pandemic, the new HOQG system lays technical basis of bulk energy and gas supplies for assisting medical diagnoses and treatments. As an additional benefit, a large quantity of cold energy from the cryogenic fluids in the HOQG system can create a suitable cryogenic environment, and provide a sustainable pathway to store and transport COVID-19 vaccines.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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