A New Decarbonized Energy Station for Hospitals

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ABSTRACT: In 2020, the COVID-19 pandemic caused a significant strain on hospitals around the world. One of the key challenges for hospitals is maintaining a stable energy supply in emergency situations such as the global pandemic. This study proposes a decarbonized energy station based on a coupled reversed Carnot cycle powered by the Carnot cycle, providing a sustainable source to satisfy the various energy needs of hospitals. Carbon dioxide (CO₂) is utilized as the driving medium. Renewable energy powers the energy input, consequently replacing fossil fuels. The only power input of this proposal is work, while the proposed energy station can achieve cooling and heating simultaneously. In the reversed thermodynamic cycle, power input results in the fluid achieving a high relative pressure and temperature that is suitable for the general use of a hospital. As the CO₂ working fluid is in a dense phase, it can achieve a heating function, providing the energy to the heating systems. Next, the fluid reaches low pressure and temperature as it expands and evaporates while absorbing heat to attain a cooling process that is satisfactory for a hospital. Our results show that 4,780,800 tons of carbon emission annually can be reduced if this method is implemented in all Canadian hospitals. Because this energy station will not produce any carbon emissions while providing heating and cooling, it is promising for future hospitals.

KEYWORDS: Physics; decarbonized; natural fluid; energy station; carbon dioxide; hospitals.

■ Introduction

Due to the COVID-19 pandemic, hospitals are running at full capacity, resulting in significantly heightened levels of energy consumption. Among public and commercial institutions, hospitals are one of the highest consumers of energy. Energy intensity in American hospitals ranks second among all buildings. A Canadian health care institution typically needs 324 gigawatt hours (eGWh) in a year to keep up with the energy demands from various sectors such as ventilation, biomedical material refrigeration, and other specialized medical equipment.¹ In total, Canada needs around 388,800 gigawatt hours (eGWh) a year. Chinese studies delineate that energy consumption by hospitals are 1.6-2.0 times that of other public buildings. Hospitals have higher energy consumption levels due to the distinct features and functions of the buildings. For example, the large construction scale, the complex functions, the concentrated equipment, the diverse energy demand, and the high comfort degree and high infection control requests.

The energy demands of hospitals are diversified, involving two main sectors: heating and cooling. For example, lighting, air conditioning, heating, dehumidification, bathing, refrigeration, freezing, drying, are some of the various energy needs.² Figure 1 shows an operating room in a hospital, containing energy demands such as lighting, ventilation, purification, cooling, heating, and dehumidification.

In the energy system of traditional hospitals, electricity—usually produced by coal- and natural gas—are the main sources of energy supply. Canada's electricity generation is 60% hydro; however, Canada does still rely on coal and natural gas.³ Energy supply efficiency is tremendously low as shown in the traditional method of energy supply in Figure 2. In addition,

Figure 2A illustrates that the required energy is supplied by power plants, which are usually powered by fossil fuels, such as coal and natural gas. The generated electricity is also used for cooling in hospitals. The heating in hospitals is usually produced by boilers, which are also powered by burning natural gas, but boilers are much more efficient than power plants. This is shown in Figure 2B. Traditional energy stations rely solely on burning fossil fuels to provide energy. It can be seen from Figure 3 that numerous harmful gases especially CO₂ are emitted to the environment during the energy providing process.

Figure 1: Operating room in a hospital.⁴

Figure 2A: Traditional method of energy supply for hospitals by power plants (top).

Figure 2B: Traditional method of energy supply for hospitals by boilers (bottom).

Figure 3: Traditional Energy Station.⁵

To reduce the level of energy consumption and carbon emissions of hospitals, research has been conducted from two perspectives. One is to optimize the energy output through the adoption of a new cooling and heating energy technology with high efficiency.^{6,10} The other is that fossil fuels are replaced with renewable energy to reduce the electricity production from traditional power plants.^{11,12} Fossil energy reserves are limited on Earth and face the risk of depletion; the massive and continued use of fossil energy could destroy the environment. Therefore, for future development, it is imperative to use renewable energy as the source for energy stations. Different from the traditional form of energy stations, the proposed energy system is based on the usage of renewable energy, with the goal of converting renewable energy into clean secondary energy.

Thus, in this paper, a new decarbonized energy station system covering energy output and terminal conversion is proposed to solve the problem of high energy consumption and high carbon emissions in hospitals.

■ Methods

Theoretical study of the new energy station formulation:

Carnot cycle using CO₂ fluid for power output

Carnot cycles are chosen as they are ideal; therefore maximum efficiency can be attained. In comparison with other cycles, the Carnot cycles generate substantially more energy. The basic power output is based on the Carnot thermodynamic cycle shown in Figure 4. In this figure, the heat input from the process 1-2 will produce the power output in the expansion process 2-3 which results in the heat output during the process 3-4. After the compression of the working fluid through the process 4-1, the thermodynamic cycle circulates again. Traditionally, the heat input in the process 1-2 is powered by fossil fuel. However, consider if the heat input from the process 1-2 is supplied by renewable energy, such as solar energy, then the power output from the process 2-3 is achieved exclusively through renewable energy (shown in Figure 4). Based on the Carnot thermodynamic cycle, the existing power is made by using water as the working fluid. Here, it is proposed that not only should water be utilized, but CO₂ should be considered as a working fluid in this power cycle, as depicted in Figure 4; this method effectively uses CO₂ as a useful resource instead of wasting it.^{13,14} Furthermore, when there is an excess of renewable energy produced, the captured and transported CO₂ is compressed into the CO₂ storage tank, where it is then stored. If the power generation

insufficient and cannot meet the demands of power grid, the compressed CO₂ will drive the turbine impeller to run, push the generator rotor to complete the power generation, releasing energy if energy demands are high, and meet the power generation demand of the power grid. CO₂ involved in energy output powered by renewable energy is presented in Figure 4. The figure on the left is a Pressure Vs. Volume graph of the process, whereas the right is a diagram of the process with real equipment.

Figure 4: Schematic diagram of the renewable energy powered CO₂ energy output.

* W.c.= Work in.

Reversed Carnot cycle using CO₂ fluid for heating and cooling involved in terminal energy conversion in hospitals

Figure 5 depicts a reversed Carnot cycle. In this thermodynamic cycle, the power input - which can be provided by renewable energy - can form a compression (process 1-2), in which the working fluid is compressed to high pressure and temperature as seen in state 2. The fluid at state 2 is then condensed and releases heat to the user in processes 2-3, which achieves a heating function. Subsequently, the fluid expands to state 4 and is at a low pressure and temperature. At state 4 the fluid evaporates and absorbs heat to achieve cooling during the process 4-1. From Figure 5, it is shown that the only power needed in this cycle is the compression from the work done; however, cooling and heating can be achieved simultaneously.

Figure 5: Schematic diagram of the transcritical CO₂ refrigeration and heat pump system.

This basic cycle, meeting different cooling and heating demands, is an effective energy-saving system because the cooling and heating generated is several times larger than the work consumed in the compression process. Based on the efficiency of the reversed Carnot cycle, the generated cooling and heating quantity is more than several times of the consumed work. Furthermore, regarding environmental issues, the mainstream usage of Freon working fluids in the thermodynamic cycle (Figure 5) is a contributing factor to global warming and ozone layer depletion. CO₂ is a natural

refrigerant, ODP (Ozone Depletion Potential) =0 and GWP (Global Warming Potential) =1 and can be used in the cycle shown in Figure 5 to replace the Freon fluids. It is important to use CO₂ because the rapidly increasing CO₂ levels have become a global concern. With this proposed system, the CO₂ is regarded as a useful material, not waste. As transcritical CO₂ compression cycles have high discharge temperatures and large temperature slips during condensing, it is suitable for heating while cooling.^{15,19} The viscosity of CO₂ is lower than Freon fluids, but the thermal conductivity and heat capacity are much higher than Freon fluids. This is helpful for industrial and commercial fields that require refrigeration and heating concurrently. By using the reverse Carnot cycle theory, CO₂ achieves high temperatures at the supercritical state post compression, and supercritical fluids release heat in gas coolers to meet the heat demand of various terminals. After throttling, CO₂ enters a low-temperature and low-pressure state, which can absorb heat from lower temperature mediums to meet the cooling requirements. The transcritical CO₂ cycle system, where the pressure is higher than a critical cycle, achieves a simultaneous heating and cooling. This solves the problem of meeting the various energy needs of hospitals and drastically reduces the loss of energy in the conversion process.

Renewable energy powered CO₂ cycle for terminal energy conversion in hospital

Figure 6 shows the renewable energy powered CO₂ cycle for energy demands in a hospital. At the first stage, CO₂ uses renewable energy to generate electricity (Figure 4), and the generated power is used to power the transcritical CO₂ reversed Carnot thermodynamic cycle (Figure 5) in facing the terminal needs at the second stage, which includes heating, drying, hot water, cooling, air conditioning, freezing, cold storage etc. Accordingly, CO₂ participates in the initial energy output and the terminal conversion process of various energy grades. From the analysis above, it is delineated that this novel energy station will not produce carbon emissions and utilizes CO₂ as a useful resource and driving medium. Therefore, it is an exceedingly green energy station.

Figure 6: Transcritical CO₂ combined cooling and heating system powered by renewable energy.

Methods for Calculations

All the energy consumption for cooling and heating comes from the renewable energy powered CO₂ energy output system. The energy consumption of transcritical CO₂ combined cooling and heating system is calculated according to the following method.

$$W = M(h_{c,2} - h_{c,3}) = \frac{Q}{COP} \quad (1)$$

W-Annual energy consumption of the CO₂ combined cooling and heating system *M*-Total mass of CO₂ participating in energy output, *h_{c,2}*, *h_{c,3}* corresponds to the enthalpy of each state point in Figure 4, *Q*-Total cooling / heating load of hospital. The COP can be determined according to the operating environment of the combined heating and cooling system and the enthalpy of each point in the P-H diagram.

$$\text{Summer condition} \quad COP = \frac{h_1 - h_4}{h_2 - h_1} \quad (2)$$

$$\text{Winter condition} \quad COP = \frac{h_2 - h_1}{h_2 - h_1} \quad (3)$$

Where, *h₁*, *h₂*, *h₃*, *h₄* corresponds to the enthalpy of each state point in Figure 5

The carbon emission of all the schemes is calculated by the following formula.

$$M_{CO_2} = 0.10118 \times 2.1622 \times W \quad (4)$$

The 0.10118 is the conversion coefficient between electricity and natural gas, and 2.1622 is conversion coefficient between natural gas and CO₂ emission. The comparison of carbon emissions of different schemes is shown in Figure 7.

Results

Perspective of engineering application:

The following is an engineering case of a hospital's energy system design, which is used to predict the possible benefits of adopting this new decarbonized CO₂ energy station. The selected hospital is in Shenzhen, China.²⁰ According to the survey, the energy system not only solves the electricity supply of medical equipment, but also solves the demand of cooling and heating. The cooling and heating load of the hospital per year is shown in Table 1.

Table 1: Cooling and heating load in hospital per year.

Needs	Load	Hours	Load factor
Cooling	11930kW	5040h	0.17
Heating	2850kW	2160h	0.58

To meet the needs of cooling and heating in hospitals, three possible energy supply methods are provided, which are listed respectively in Table 2, Table 3, and Table 4. A water chiller is a device that consumes electricity to generate cold water. An air source heat pump is a device that absorbs heat from the air to generate heating. In the first scheme, the water chiller is responsible for the cooling, and the air source heat pump is responsible for the heating, both of which use freon as working fluid. In the second scheme, the heating is driven by a boiler burning natural gas. In the third scheme, the lithium bromide water chiller is a device that can produce cold water by burning natural gas. Because the device burns natural gas, it can also produce hot water at the same time to meet the heating demand. It is illustrated that these systems' design schemes are all based on the traditional form of an energy station, in

which both have immense energy consumption and carbon emissions. The equipment described is depicted in Figure 7

Figure 7: Diagram of the Equipment used.^{21,26}

Table 2: The first scheme of Freon water chiller + Air cooled heat pump unit.

Item	Energy consumption
Water chiller	1939300 (kW.h/a)
Chilled water pump	696780 (kW.h/a)
Cooling water pump	1124928 (kW.h/a)
Cooling tower	347508 (kW.h/a)
Air source heat pump	3054996 (kW.h/a)
Hot water pump	149688 (kW.h/a)

- a - represents annual average. The same below.

Table 3: The second scheme of Freon water chiller + Gas boiler.

Item	Energy consumption
Water chiller	1939300 (kW.h/a)
Chilled water pump	696780 (kW.h/a)
Cooling water pump	1124928 (kW.h/a)
Cooling tower	347508 (kW.h/a)
Gas boiler	natural gas 652670 (m ³ /a)
Hot water pump	118843 (kW.h/a)

Table 4: The third of scheme of direct-fired lithium-bromide absorption chiller.

Item	Energy consumption
Direct-fired lithium-bromide absorption chiller	65360 (kW.h/a) + natural gas 3685435 (m ³ /a)
Chilled water pump	696780 (kW.h/a)
Cooling water pump	1124928 (kW.h/a)
Cooling tower	347508 (kW.h/a)
Hot water pump	102643 (kW.h/a)

If the energy station put forward in this paper is employed, both hot and cold water can be obtained through only utilizing the transcritical CO₂ cycle system. According to the needs of the hospital for cooling and heating, the energy consumption of transcritical CO₂ system is calculated as shown in Table 5.

Table 5: The Fourth Scheme of Transcritical CO₂ System Combined Cooling and Heating.

Item	Energy consumption
Transcritical CO ₂ combined cooling and heating system	4789396 (kW.h/a)
Chilled water pump	696780 (kW.h/a)
Cooling water pump	1124928 (kW.h/a)
Cooling tower	347508 (kW.h/a)
Hot water pump	102643 (kW.h/a)
Carbon emission: 0t/a	

From Figure 7, it is delineated that the carbon emissions are 1188t/a, 2336t/a, 8469t/a respectively for schemes 1, 2, and 3. The carbon emissions in scheme 4 is 0t/a here, because all the cooling, heating, and electricity consumptions are supplied

by renewable energy. Furthermore, carbon dioxide is also employed as the working fluid in the scheme 4, but no carbon emissions exist in this new energy station proposed in this paper. The annual average value of the scheme 1, 2, and 3 is 3984t, which represents the carbon emission from a traditional energy station in one hospital. For example, if there are 1,200 hospitals in Canada, carbon emissions of 4,780,800t²⁷ can be cut per year if the proposed energy station is used. Therefore, it can be concluded through these theoretical results that this new energy station should be popularized nationally and globally as it is exceptionally clean and environmentally friendly.

Figure 8: Carbon Emissions of Different Schemes.

Conclusion

The development of renewable energy stations in hospitals is shown to be advantageous in this study. The proposed system with the natural fluid CO₂ is demonstrated to be capable of supplying all the energy demands of a hospital. In detail, a new decarbonized energy station is proposed in this paper to meet the energy demands of a hospital. Specifically, This method is theoretically examined and a comparison of the energy consumption and carbon emission levels between the proposed system and the conventional energy supply schemes. The theoretical results show that the annual CO₂ emissions of the hospital can be cut around 1188t~8469t. An average value of 3984 t CO₂ emissions can be reduced per hospital. This study concludes that this decarbonized energy station is promising in the future of renewable energy implementations in hospitals, which contributes to the carbon- neutralization process.

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■ Author

Yameng (Moe) Zhang has been captivated by the intricate elements of physics since the first time she became familiar with the field. In this paper, she proposed a decarbonized energy station after recognizing the great energy strains on hospitals during the COVID-19 pandemic. In the future, she hopes to pursue a degree in physics to help others through her research.