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Advantage of CO_2 heat pump chiller for the application in Indian hotels

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ABSTRACT

Hotels in India conventionally use diesel-fired hot water generators to meet hot water demands at 46°C. These are inefficient and also release high emissions. This study focuses on the energy saving and emission reduction potentials of a CO_2 heat pump chiller system for such an application. An ejector-based system of 50 kW heating capacity is proposed for a typical hotel having a hot water demand of 40 m^3/day with a 5 m^3 thermal storage tank (TST). The heat pump produces the hot water at 68°C which is stored in the proposed TST. As per the demand, the hot water from the TST will be supplied to two existing 5 m^3 hot water supply tanks (one for rooms and the other for the kitchen) after being mixed with cold water to reach the required temperature (46°C). The system also supplements up to 3.2% of the cooling demand of the hotel by contributing chilled water at 7°C. The proposed system reduces the operating cost and CO_2 emissions to approximately 10 and 30%, respectively of the existing set-up. Return on investment is found to be less than 2 years.

Keywords: Ejector, R744, Transcritical, DHW, Thermal storage, Energy savings

1. INTRODUCTION

Energy demand for the building sector is increasing rapidly due to surge in energy consumption rate since few decades. Building sector shares nearly 36% of global energy consumption and 39% of global emissions (United Nations Environment Programme, 2019). Hotels are one of the energy intensive building types in which domestic hot water (DHW) production is one of the significant consumers of energy. Energy consumption for DHW production accounts for nearly 13% of the total energy consumed by hotels (International energy agency, 2013). Conventionally diesel/natural gas fired hot water generators are being used to generate the DHW in a majority of the hotels in India. These thermal energy sources are not only inefficient but also release high emissions. The growing energy demand in the hotel sector necessitates the need for change from fossil fuels to environment-friendly energy sources which can also mitigate the effect of global warming and climate change.

Heat pumps, which are commonly used for space cooling or heating application, efficiently transfer heat from the surrounding medium (air or water) to the water, instead of using primary energy directly to heat the water (Willem et al., 2017). Due to their high energy conversion efficiency and emission reduction ability, heat pumps are regarded as an effective method to replace electric water heaters, gas, and fuel fired water heaters (Kelly and Cockroft, 2011). Most of the refrigerants currently being employed in heat pumps are synthetic compounds that are either to be phased out or to be phased down sooner or later due to their ozone depletion potential (ODP) and global warming potential (GWP). Therefore, the use of natural refrigerants has attracted the attention of many research institutions and related industries.

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CO_2 is a non-flammable, non-toxic natural refrigerant with excellent thermal properties and has a GWP of one, which makes it a prominent refrigerant of choice for heat pump systems (Ciconkov, 2018; Lorentzen, 1994). A CO_2 heat pump integrated with a thermal storage tank is an energy efficient and eco-friendly solution compared to conventional existing heat sources for simultaneous cooling and DHW production. The distinctive temperature glide of CO_2 in the gas cooler during transcritical mode allows for efficient heating of water (Nekså, 2002; Nekså et al., 1998), even up to temperatures of 90°C (Bamigbetan et al., 2017). Smitt et al., (2021, 2020) investigated the performance of an integrated CO_2 heat pump and chiller unit in a Norwegian hotel. The system consists of a single unit for heating, cooling, and DHW with an integrated 6 m^3 thermal storage tank (TST). Energy savings in the range of 5.8–13.2% were achieved based on the different seasonal scenarios. Results also suggest that the proposed strategy could be implemented in similar applications to enhance overall system performance.

The literature review concludes that a CO_2 heat pump integrated with a thermal storage tank is an energy efficient and clean and efficient solution compared to conventional existing heat sources for simultaneous cooling and DHW production in hotels. To examine the feasibility of CO_2 heat-pump chillers for hotel application in India, our INDEE+ project (Norway-India collaboration project) team has planned to assess the energy savings and emission reductions with the integrated CO_2 system for an Indian hotel. Thus, this work presents the capacity sizing of the proposed system for considered hotel based on the DHW consumption pattern. Subsequently, the assessment of annual savings and payback period with the proposed system is also carried out.

2. DESCRIPTION OF THE EXISTING HOT WATER SYSTEM IN THE HOTEL

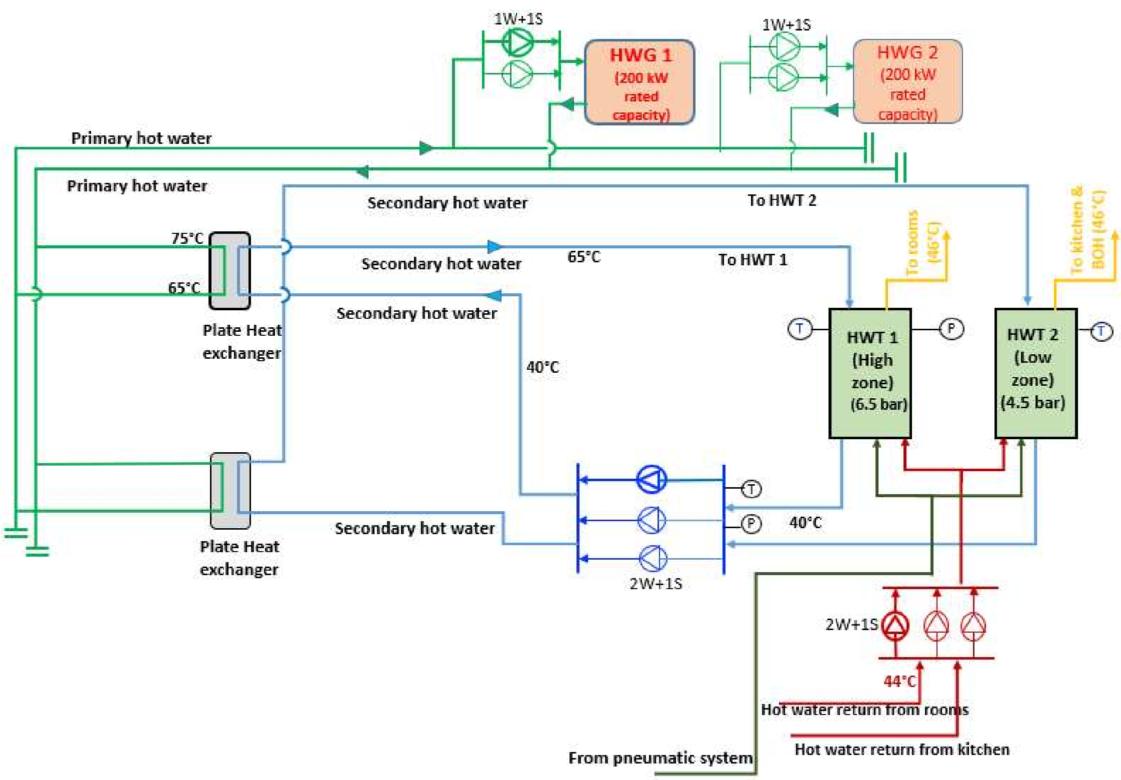

Figure 1: Schematic P&ID of hot water system for referred hotel

One of the five-star hotels in Chennai, India is considered for the analysis, and necessary data is collected. There are two chiller units each with 350 TR (Ton of Refrigeration) capacity, among which one runs at a time to serve the air conditioning purpose for rooms. Hot water tanks (HWT1 and HWT2) of 5 m^3 capacity

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pressurized at 6.5 bar and 4.5 bar serve the DHW demands for guest rooms and kitchen respectively. Schematic P&ID for the hotel hot water circuit is shown in Fig. 1. Diesel fired hot water generator (HWG) of 200 kW rated capacity provides heat to maintain the DHW supply temperature always at 46°C. Both HWT1 and HWT2 are mixing tanks in which cold water supplied from the pneumatic system (when tank pressure drops to pre-set level) gets mixed with the secondary hot water coming from the plate heat exchanger (PHE). As the hot water temperature in tanks drops to pre-set temperature, HWG actuates and heats the primary hot water to 65-70°C which passes through PHE to give the desired heat to the secondary hot water coming from HWT1 and HWT2. Hot water consumption data and operating cost per day are indicated in Table 1. The hot water consumption pattern in a day for the referred hotel is indicated in Fig. 2. Peak DHW demand for rooms is between 6-9 AM and 9-11 PM. Accordingly, DHW demand for rooms is 18 m^3 in the morning (per 3 hr) and 14 m^3 (per 2 hr) in the night on average. Similarly, the DHW demand for the kitchen is 3 m^3 in the morning (per 2 hr), 3 m^3 in the afternoon (per 2 hr), and 2 m^3 (per 2 hr) in the night on average. The amount of diesel consumed to meet DHW demands is nearly 115 l/day.

Table 1. Hot water data and operating cost per day

Hot water consumption data		
Hot water consumption for rooms per day	32	m^3
Hot water consumption for the kitchen per day	8	m^3
Total hot water consumption for the hotel per day	40	m^3
Temperature Lift (from 30 to 46°C)	16	°C
Heating requirement per day	743	kWh
Heating requirement per day with 10% circulation loss	817	kWh
HWG Operating Cost		
Fuel used	High-speed diesel	
Calorific value of fuel	45,200	kJ/kg
Density	850	kg/m^3
Fuel consumption per day	115	l
Fuel price per litre	94	Rs.
HWG operating cost per day	10,810	Rs.

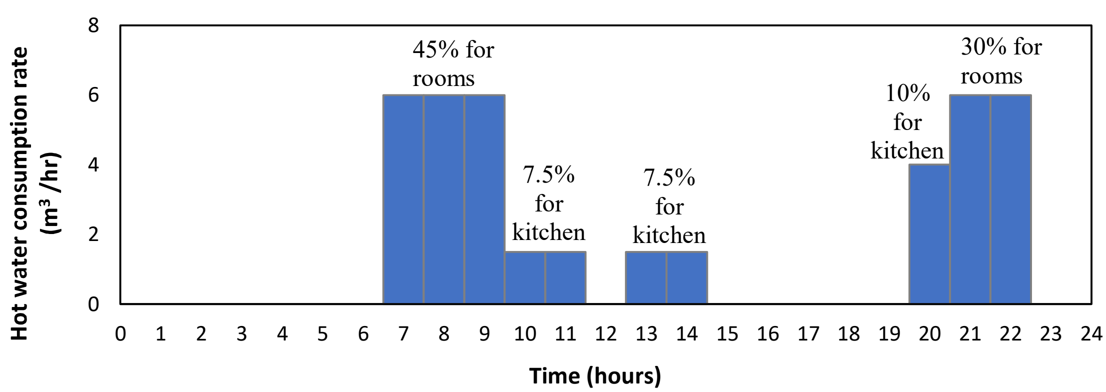

Figure 2: Hot water consumption pattern in a day for the referred hotel

3. PROPOSED INTEGRATED CO_2 HEAT PUMP SYSTEM COUPLED TO EXISTING HOT WATER SYSTEM

An integrated CO_2 heat pump system is proposed to couple to the existing system as shown in Fig. 3. CO_2 system produces chilled water as well as hot water (maximum of 95°C possible) simultaneously in evaporator and gas cooler heat exchangers respectively. TST is considered as insulated and open type. Cold water from

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the pneumatic line is tapped into gas cooler inlet to heat it to the designed temperature (68°C considered in this study). CO_2 system stops running once TST reaches the maximum level.

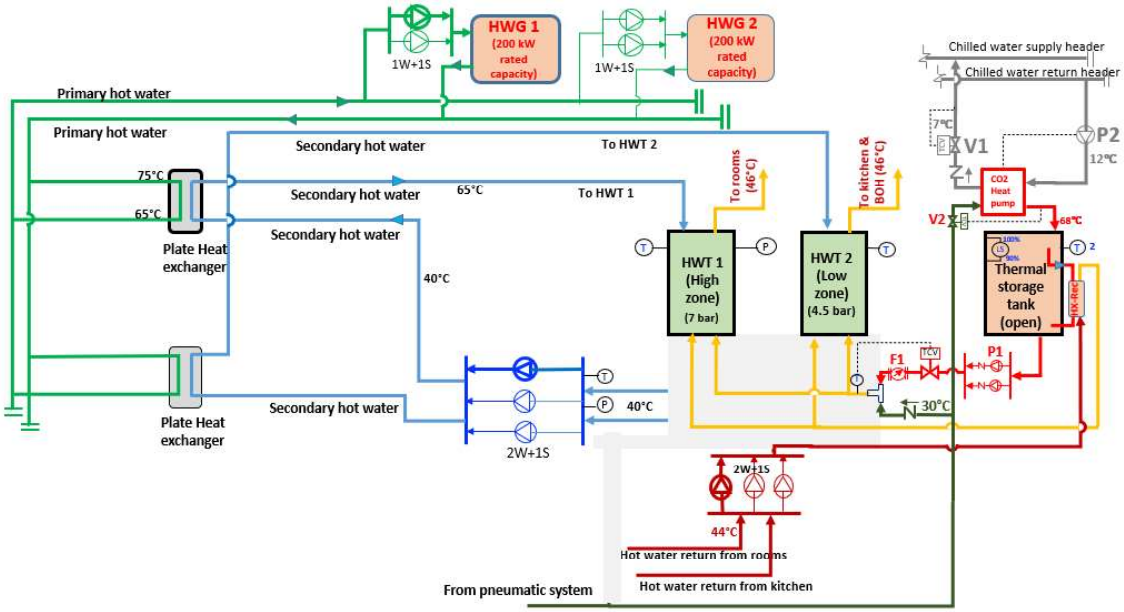

Figure 3: Proposed integrated CO_2 system coupled to the existing hot water system

When either of HWT1 or HWT2 pressures dropped to pre-set level, hot water from TST after mixing with cold water from pneumatic line will be pumped to maintain the designed pressure in tanks. The temperature of hot water pumping to HWT1 /HWT 2 will always be maintained at 46°C as required. An appropriate amount of return chilled water from the existing main return header (10°C) will be tapped to the evaporator inlet where it will be cooled to the required supply temperature (5°C). This chilled water will be connected to the main supply header so that the existing chiller operating load could be reduced. In this way, the proposed heat pump supplements the existing chilled water (CHW) system.

3.1. Capacity sizing of CO_2 heat pump and TST

DHW demand peak hours are observed to be 3 hours in the morning and 2 hours in the night per day on average. DHW demand in morning peak hours is nearly 18 m^3 at 46°C for the considered hotel. If the heating capacity of the CO_2 system is designed based on peak heat demand, the heat pump could run only whenever DHW demand arises. System heating capacity becomes nearly 120 kW in this case as indicated in Fig. 4 which has to run nearly 7 hr/day. Alternatively, by integrating a TST to store the thermal energy, CO_2 system heating capacity could be reduced (Elarga and Hafner, 2022). In this case, TST serves the desired heat through the existing tanks. As soon as the TST level drops to pre-set level, the CO_2 system actuates and supplies hot water to TST until is fully charged. By increasing TST capacity, the heat pump heating capacity could be further reduced which enforces to increase its running time. 40 kW is the limited heating capacity below which heat pump cannot meet the required DHW demands even if it runs for 24 hr. Considering investment cost, a low heat capacity heat pump and high capacity TST is an economical combination to adopt. In this study, CO_2 system of 50 kW with a 5 m^3 TST capacity is considered as optimal combination.

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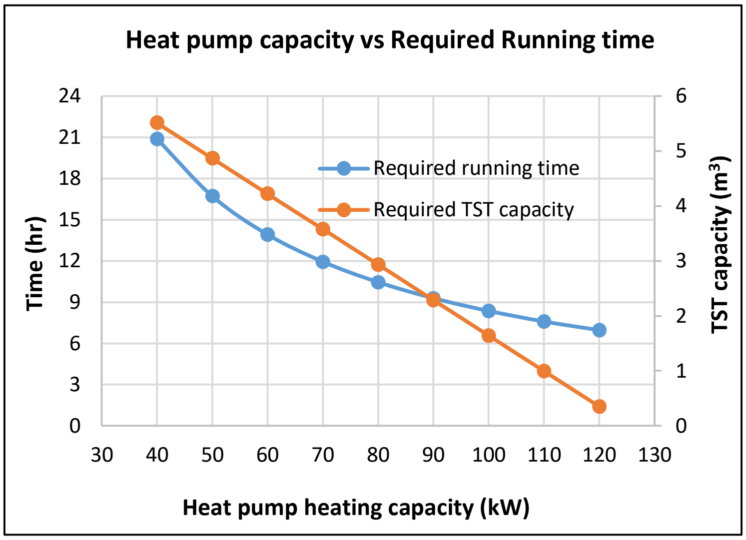

Figure 4: CO_2 heat pump and TST capacities vs required running time

It is observed from Fig. 5 that 50 kW heat pump charges 5 m^3 TST with the hot water until it reaches maximum level (up to 3:00 AM) and then stops. When peak demand arises after 6:00 AM, TST supplies required hot water to HWT1/HWT2. Then heat pump starts charging the TST to balance the level.

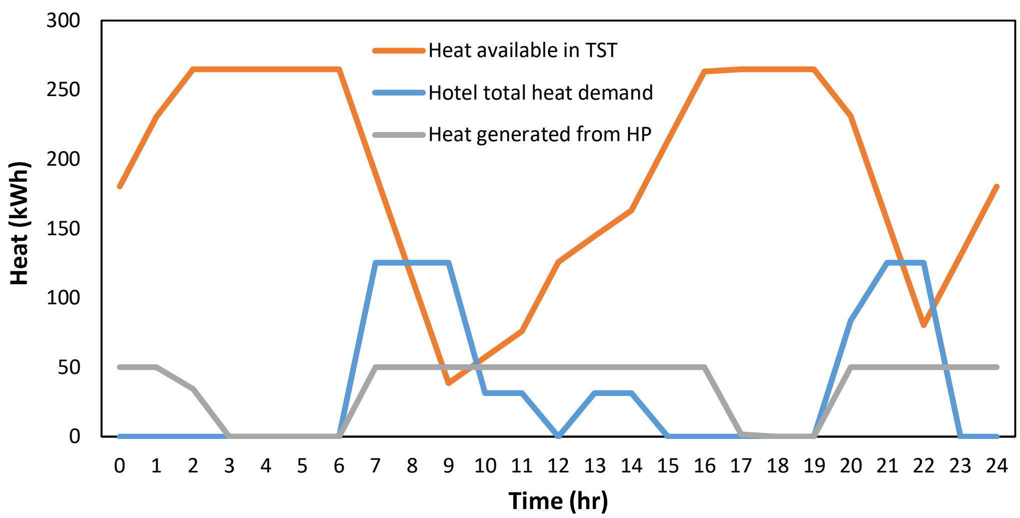

Figure 5: Heat demand and heat availability in each hour of a day

3.2. Ejector-based CO_2 heat pump of 50 kW heating capacity

An ejector-based CO_2 heat pump with an internal heat exchanger (IHX) is considered in this study to analyse its performance for the hotel application. As indicated in Fig. 6, the hot gas discharged from the compressor flows into the gas cooler where it exchanges heat to cold water. Afterward, cooled gas from the gas cooler enters the internal heat exchanger which gets further cooled by transferring its heat to the vapour coming from the receiver. Refrigerant flows from IHX into the ejector motive nozzle and draws the refrigerant vapour leaving the evaporator through the secondary nozzle. Pressure will be lifted to receiver pressure after mixing. Liquid refrigerant from the receiver passes to the evaporator through an expansion valve to exchange the heat with the chilled water. The evaporator pressure is maintained at 35 bar.

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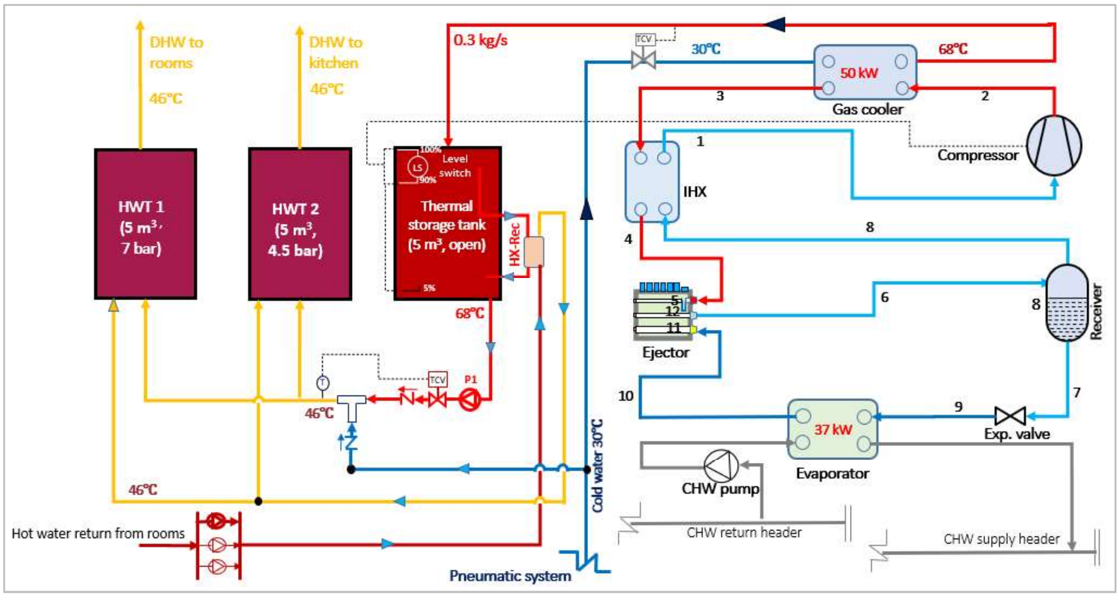


Figure 6: Simple ejector-based CO_2 heat pump system coupled to the existing hot water system

4. ENERGY SAVINGS AND REDUCTION IN CARBON FOOTPRINT WITH INTEGRATED CO_2 SYSTEM

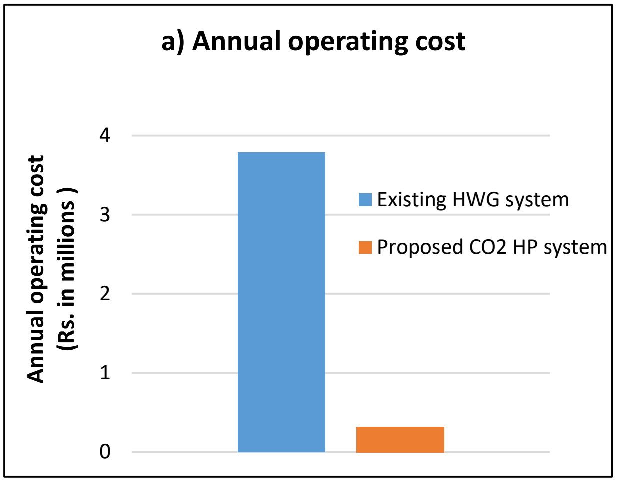
Current average diesel consumption of the referred hotel is nearly 115 l/day, costing nearly Rs. 10,810 (Rs. 94/l) for meeting the DHW demands. Annual operating cost of the existing system becomes nearly Rs. 3,783,500 as indicated in Table 2.

Table 2. Energy savings and emission reduction details

Integrated CO_2 system operating cost/day 15 kW, 16.7 h, @Rs.9/unit	Rs.2,260
Chilling benefit of 37 kW cooling, 0.85 kW/TR	Rs.1,350
Net power for heating	6.1 kW
Net cost for hot water per day	Rs. 910
Annual operating cost of CO_2 system (with chilling benefit)	Rs. 318,500
Diesel consumption for existing system/day	115 l
Diesel operating cost for existing system/day	Rs. 10810
Annual operating cost of existing system	Rs. 3,783,500
Total operating cost savings per day	Rs. 9,900
Annual operating cost savings with CO_2 system	Rs. 3,465,000
Emissions reduction in %	70 %
Return on Investment (ROI)	< 2 years

On the other hand, with energy consumption for the compressor and other pumps of 13 kW and 2 kW respectively, the total energy consumption is 15 kW. At an electricity fare of Rs. 9/kWh for the hotel, the operating cost of the CO_2 system becomes Rs.2,260 with 16.7 hr running time per day. As the chilling load of 37 kW from the CO_2 system is proposed to couple to the existing CHW system, the equivalent operating cost of existing the CHW system could be reduced. At the operating energy of 0.85 kW/TR for the existing CHW system, nearly Rs. 1,350 could be saved with the chilled water from the proposed system which otherwise has to be spent for additional load on existing CHW system. Accordingly, net cost for the proposed system per day becomes Rs. 910. Annual operating cost with chilling benefit then becomes only Rs. 318,550. Thus, total annual operating cost savings becomes Rs. 3,465,000 which implies the operating cost of the CO_2 heat pump is nearly 10% of the existing system operating cost as indicated in Fig. 7(a). Return on investment is found to be less than 2 years at the present fabrication cost in India.

Annual CO_2 emissions from the existing system are 105,044 $kgCO_2$/year at the diesel emission factor of 2.6 $kgCO_2$/lt. On the other hand, CO_2 emissions from the proposed system are only 31,670 $kgCO_2$/year at CO_2 emission factor of 0.85 $kgCO_2$/kWh for power generation in India. This can be observed from Fig. 7(b) that nearly 70% carbon footprint is reduced with the proposed system.



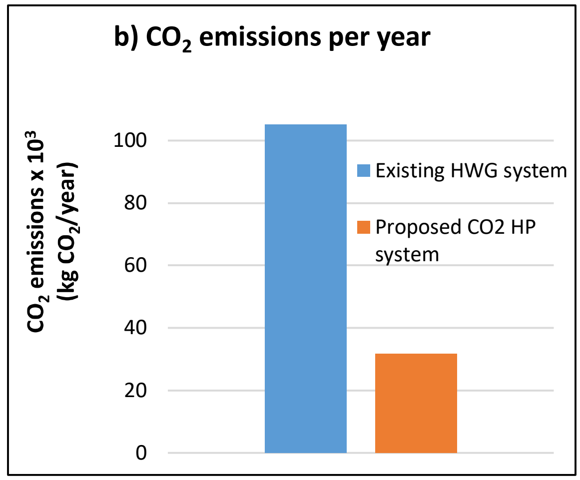


Figure 7. a) Annual operating cost and b) CO_2 emissions per year for the proposed and existing systems

5. CONCLUSIONS

Hotels are energy intensive buildings in which DHW is a significant energy consumer. Majority of the hotels in India currently use diesel fuel fired hot water generators for DHW production which are not only inefficient but also release high emissions. An ejector-based CO_2 system integrated with a thermal storage tank (TST) is proposed to be coupled to the existing system. Capacity sizing of the proposed system is presented to meet DHW demands.

The proposed system contributes up to 3.2% of the total cooling demand of the hotel by providing chilled water at 7°C. Study revealed that the proposed system offers substantial reduction in the operating cost and CO_2 emissions to approximately 10% and 30% respectively. Return on investment is found to be less than 2 years at the present fabrication cost in India. Thus, an integrated CO_2 system with TST can be adopted as an energy efficient and clean technology solution for hot water demands in hotels.

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NOMENCLATURE

PHE	Plate heat exchanger	COP	Coefficient of performance
TST	Thermal storage tank	DHW	Domestic hot water
HWG	Hot water generator	CHW	Chilled water
HWT	Hot water tank	IHX	Internal heat exchanger

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