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Report

KLD HFC free Chiller India

Environmental benefits of implementing a CO2 heat pump for combined heating and cooling at Bengaluru centralised school kitchen

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ABSTRACT

Akshaya Patra Foundation is the world's largest (not-for-profit) Mid-Day Meal Programme operating around 50 centralised kitchens supplying wholesome food to over 1.8 million children at more than 16,000 schools in 12 different states across India. In the project presented in this report, a heat pump using the natural refrigerant CO_2 is proposed as an energy-efficient and climate-friendly concept for the centralised kitchen at Bengaluru. The CO_2 heat pump does not only replace the HCFC units for space cooling, but also supplies hot water to the cooking process, reducing the steam boiler's fuel consumption. A cold and hot water storage is included to balance the mismatch in cooling and heating demand on a daily basis.

The proposed concept offers substantial reductions in greenhouse gas (GHG) emissions from the cooling system (almost 60%). For the total system (cooking process and space cooling) the reduction in energy demand, energy cost and GHG emissions are all above 30%. This clearly shows the possibility for India to efficiently bypass the use of HFCs as temporary replacements for HCFCs, and by that avoiding significant GHG emissions and costly replacement processes. Suggestions for potential future improvements include a roof-top solar power system and a steam producing heat pump using natural refrigerants.

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1 Introduction

Klima- og miljødepartementet (KLD) has awarded a grant for implementation of the project "KLD HFC free Chiller India". This report presents the proposed solution and its environmental benefits. The proposed concept – a heat pump using the natural refrigerant CO_2 - will replace not only the existing HCFC units for air conditioning but also part of the heat production in steam boilers at the centralised kitchen of Akshaya Patra Foundation, Bengaluru.

1.1 Akshaya Patra – Mid-Day Meal Programme

The Akshaya Patra Foundation is a not-for-profit organization headquartered in Bengaluru, India. The organization strives to eliminate classroom hunger by implementing the Mid-Day Meal Scheme in the government schools and government-aided schools. Alongside, Akshaya Patra also aims at countering malnutrition and supporting the right to education of socio-economically disadvantaged children.

Today, Akshaya Patra is the world's largest (not-for-profit run) Mid-Day Meal Programme operating around 50 centralised kitchens supplying wholesome food every school day to over 1.8 million children at more than 16,000 schools in 12 different states across India. The implementation model of these semi-automated kitchens can be efficiently scaled and replicated and has attracted curious visitors from around the world.

The Akshaya Patra Mid-day Meal Programme uses large quantities of heat for its day-to-day cooking. The organization strongly believes that energy sustainability is of great importance to overall sustainability given the pervasiveness of energy use, its importance in economic development and living standards, and its impact on the environment. The "Akshaya Patra Heat Pump Project" is one of the energy sustainability initiatives taken by the organisation.

1.2 Akshaya Patra - Heat Pump Project

Implementation of heat pump technology have been identified as having the potential to play a major role in reducing energy consumption of the kitchens. Heat pump technology allow heating efficiencies to be increased by over three to four times compared to conventional oil and gas boilers. In the course of identifying sustainable and energy efficient approaches, pilot air source heat pumps have been implemented in a few kitchens. However, a water source heat pump can deliver higher-performance heating and simultaneous cooling.

A heat pump based on CO_2 as the refrigerant can efficiently produce both hot water and chilled water (see section 1.3) at suitable temperatures for the cooking process and space cooling. Together with hot and cold water storage it can cover parts of the heating demand in the kitchen and the total cooling demand for the AC-system in the building complex. Such a concept also facilitates a future use of renewable energy sources and electricity production.

1.3 Briefly about heat pumps

Using heat pumps is in general an energy efficient way to up-grade a non-useable heat source at a low temperature level to provide heat to a heat sink (heat demand) at a higher temperature level. The basic design of a heat pump, shown schematically in Figure 1-1, is a closed refrigerant circuit consisting of two heat exchangers (evaporator and condenser), a compressor and an expansion valve. The working principle and system layout for a refrigeration unit is "identical", differing only in its purpose. A refrigeration system is installed to remove heat from the heat source at a low temperature and reject heat at a higher temperature, which is normally wasted to the environment.

The energy efficiency of a heat pump in a specific heating operation point is normally expressed as its coefficient of performance (COP), defined as

$$COP_{heat} = \frac{Q_{heat}}{P_{el}}$$

where Q_{heat} [kW] is the heat supplied to the heat sink and P_{el} [kW] is the power consumption of the compressor. For example, a COP of 3 implies that 3 kW heat can be produced with only 1 kW power.

In the same way, COP for a refrigeration unit is defined as

$$COP_{cold} = \frac{Q_{cold}}{P_{el}}$$

where Q_{cold} [kW] is the heat removed from the heat source.

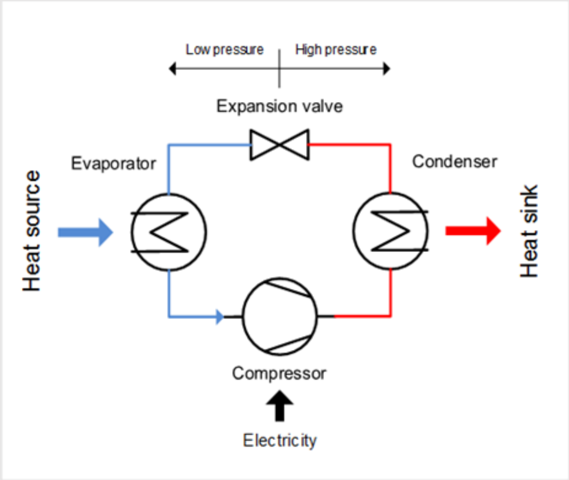

Figure 1-1: Schematic sketch of a heat pump

Ideally, to reach an even higher energy efficiency, the heat pump is used for both purposes, i.e. removing heat from a heat source that requires cooling and rejecting heat to a heat sink that requires heating. Such a combined cooling and heating heat pump is suggested for the Akshaya Patra project, producing chilled water to the space cooling units and hot water to the cooking process (schematically shown in Figure 1-2). For such a combined heat pump, a heating COP of 3 implies that for each kW power supplied the heat pump produces 3 kW heat and 2 kW cold, resulting in a total COP of 5. Accordingly, COP for a combined heat pump is defined as

$$COP_{combined} = \frac{Q_{heat} + Q_{cold}}{P_{el}}$$

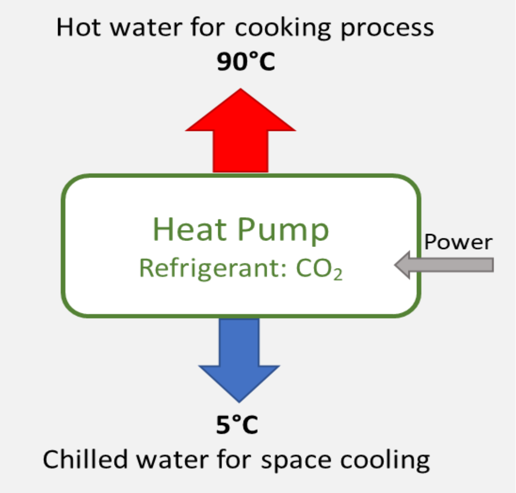

Figure 1-2: Principal sketch of a heat pump producing both hot and cold water

Generally, COP depends on the temperature lift of the heat pump (i.e. difference in heat source and heat sink temperature). However, the choice of refrigerant is also crucial for a heat pump's efficiency and environmental impact. The traditionally used synthetic refrigerants contribute to depletion of the ozone layer and/or global warming. Natural refrigerants, such as CO_2, which is proposed in this project, are environmentally benign and offers high efficiency. Research at SINTEF and NTNU has strongly contributed to today's wide use of CO_2 as refrigerant, for example in around 10,000 European supermarkets [1].

The environmental impact and corresponding regulations of refrigerants, with focus on India, is presented in section 3.5.

2 Current heating and cooling system

The heating and cooling system considered in this project supplies heat to the cooking process at the centralised kitchen in Bengaluru and cold for space cooling (AC) in the associated building complex.

2.1 Heating system

Here, a general description is given on the centralised kitchens operated by Akshaya Patra, followed by some specific information of the existing steam boilers at the Bengaluru kitchen.

2.1.1 Mid-day-meal kitchens

All kitchens of Akshaya Patra follow a standard process for preparing the mid-day meals. This process is charted out to ensure hygiene and quality of the cooked meal and to adhere to the food safety standards. The kitchens (Figure 2-1) are equipped with cauldrons, trolleys, rice chutes, dal/sambar tanks, cutting boards, knives etc. All equipment is sterilised using steam before the cooking process begins early in the morning.

Each cauldron has a capacity to cook at least 500 litres of rice and up to 3000 litres of dal. Steam, supplied from boilers, is injected into the bottom of the cauldrons, raising the water temperature to around 120 °C. Critical control points (CCPs) like cooking temperature are checked and recorded at periodic intervals to ensure the right quality of the meal.

The cooked food is packed in steam sterilised steel vessels before loaded on transport vehicles, also sterilised before the loading process. The Bengaluru kitchen supplies mid-meals to 551 schools, on 27 routes covering a radius of 50 km [2].

Figure 2-1: The centralised kitchen in Bengaluru

2.1.2 Steam boilers

In the Bengaluru kitchen, 4 steam boilers are installed (Figure 2-2), all fuelled with HSD (High Speed Diesel). The boiler generates flue gas at 150 °C at a pressure of 5 bar. The steam available at the individual cooking cauldrons is around 130 °C, considering boiler efficiency (75% - 80%) and pressure drop at individual cauldrons. Through steam injection the water in the cauldrons is heated up from around 24 °C to about 120°C.

With a heat pump implementation, the water could be heated up to 90 °C before introducing the steam into the cauldrons, thus reducing the required amount of steam.

Figure 2-2: Steam boilers and cauldrons at Bengaluru kitchen

The boilers operate 6 hours per day (4 am to 10 am), consuming in average 960 HSD fuel. In Table 2-1 some additional design data are given.

Table 2-1: Boiler data

Unit	Maximum output	Steam production 10,3 bar	Fuel consumption	
	[kW]	[kg/h]	[l/h]	[l/day]
1 boiler	530	850	40	240
Total (4 boilers)	21200	3400	160	960

2.2 Current space cooling system

The AC cooling systems in the complex area housing the kitchen consists of mostly split AC units (7-8 years old) and a few window AC units (very old). Both are using the ozone depleting refrigerant HCFC-22, which also has a relatively high global warming potential (GWP).

2.2.1 Split AC units

As shown Figure 2-3 (left) a split AC unit consists of an outdoor unit, including the condenser and the compressor, and an indoor unit with the evaporator. The evaporator removes heat from the indoor air and the condenser rejects heat to the outdoor air at a higher temperature. In Figure 2-3 (right), an example of the existing split units are shown, and Table 2-2 presents their main design data.

Table 2-2: Specifications of the existing AC split units

Unit	Cooling capacity [kW]	Power cons. [kW]	COP [-]	Refrigerant [kg HCFC-22]	No of units [-]
Split 1.5 TR	5.3	2	2.6	1.3	10
Split 2.0 TR	7.0	2.7	2.6	1.7	1
Total 17 TR	**60**	**24.7**	**2.6**	**3.0**	**11**

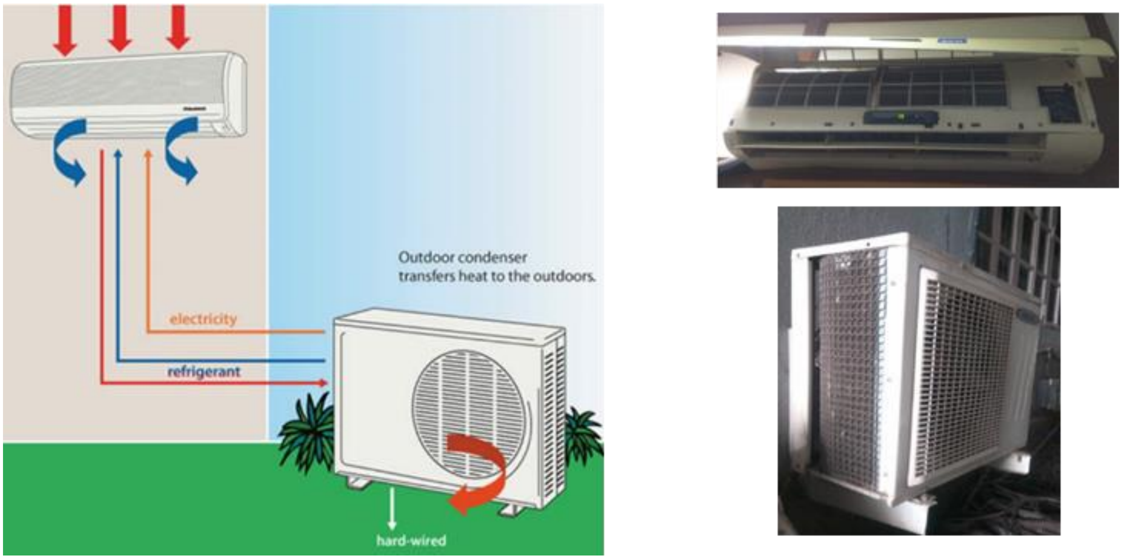

Figure 2-3: Principal sketch of a split AC unit [3] (left) and an existing split AC unit (right).

The proposed heat pump will replace the existing AC split units with a water-cooled indirect AC system. In such a system there is only indoor units, which are called air handling unit (AHU). In these heat exchangers the indoor air is cooled by the chilled water produced in the heat pump.

2.2.2 Window-AC

A window AC is mounted through the window as one single unit with the evaporator on the window inside and the condenser on the window outside (Figure 2-4, left). The existing window AC units (Figure 2-4, right) are being phased out and not considered for active cooling.

Figure 2-4: Principal sketch of a window AC unit [3] (left) and an existing window AC units (right)

3 India's energy system and refrigerant usage

To enable an evaluation of the environmental benefits of the proposed CO_2 heat pump, the current status and future scenario of India's energy/electricity generation and CO_2 emissions is presented. India's current and projected usage of refrigerants and the regulation of them are also addressed.

3.1 Energy consumption

The total energy consumption in India (2018) is over 10,0000 TWh, making it the third largest energy-consuming country after China and the United States [4]. At the same time, India’s per capita energy consumption (8 kW/h) is only one-third of the global average (23 kWh / capita) indicating a higher future energy demand as the country continues its economic development [5]

As shown in Figure 3-1, India’s largest energy source is coal followed by petroleum oil, biomass and natural gas. Renewable fuel sources (other than biomass) make up only a small portion of the total primary energy consumption, although the capacity potential is significant for several renewable resources such as solar, wind and hydro-electricity [6].

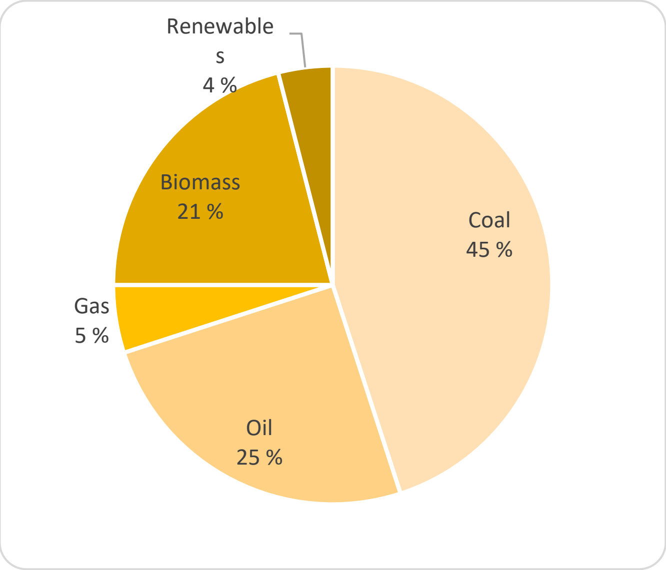

Figure 3-1: India's energy consumption mix (based on [3])

3.2 Electricity generation

3.2.1 Current situation

The total installed power generation capacity in India is 370 GW with an annual electricity generation of around 1500 TWh (2018), making India also the world's third largest electricity producer. Nevertheless, power consumption per capita remains low (1.1 kWh compared to the global average of 2.7 kWh / capita) and millions of people still do not have access to electricity [7].

As seen in Figure 3-2 (left), the installed capacity for power generation is predominantly coal-based and is therefore a major source of CO_2 emissions in India. However, there exists scope for reducing the CO_2 emissions by fuel substitution and increased use of renewable energy sources. The renewable energy production is here divided between hydro and "other renewables", including wind, small hydro plant, solar and biomass. As seen in Figure 3-2 (left), the share in installed capacity of these other renewables is over 20%. However due to its lower capacity factor the actual electricity production tends to be much lower compared to coal, nuclear and gas power plants, resulting in renewables still barely make up 10% of the total electrical energy generation, as shown in Figure 3-2 (right) [8].

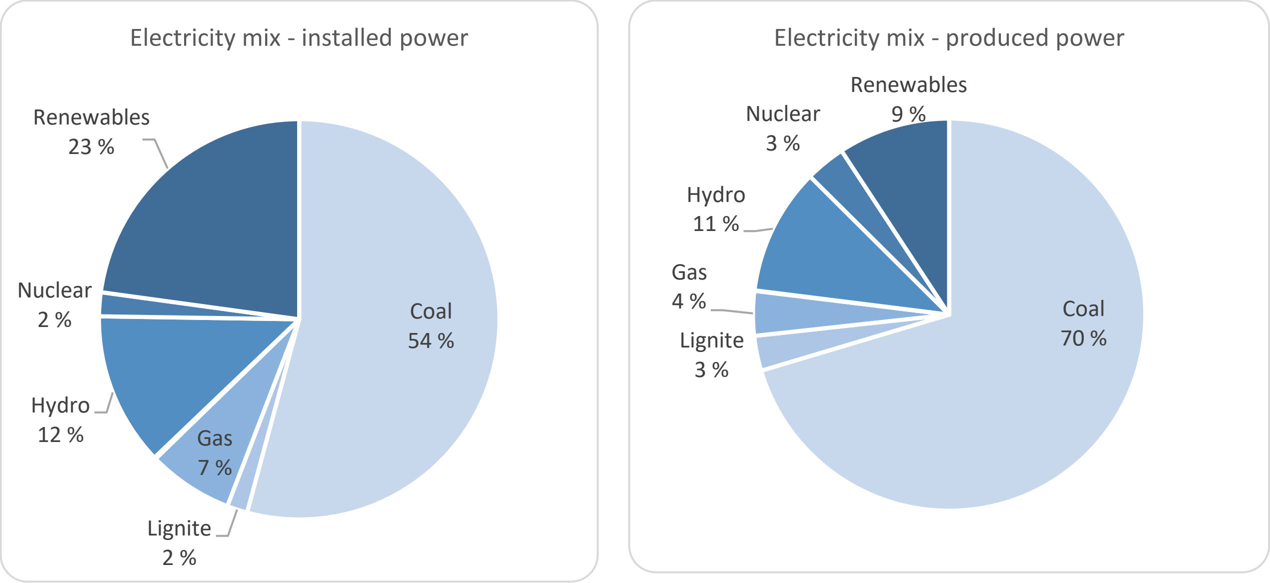

Figure 3-2: India's installed electricity generation capacity (left) and actual electrical production (right) in 2018 (based on [8]).

3.2.2 Renewable power generation

Figure 3-3 show the share of latest added capacity in India's power generation during 2016-2018. As seen even if 25% of the added capacity still is coal-based the renewable capacity additions are growing at a rapid pace, especially solar generation constituting over 50% of all new installed capacity in 2018. This transition towards renewable energy presents an incredible opportunity but also challenges. Increasing the power system flexibility is required as more intermittent renewables are added to the grid [9]. Thermal energy storage plays an important role in the integration of renewable electricity sources. Moreover, a wider up-take of variable renewable heating can be achieved by heat pumps coupled with thermal storage systems [10]. Thus, to fully benefit from the renewable added capacity hot and/or cold storages should be implemented, both on a large scale and on a more local small-scale, as proposed in this project.

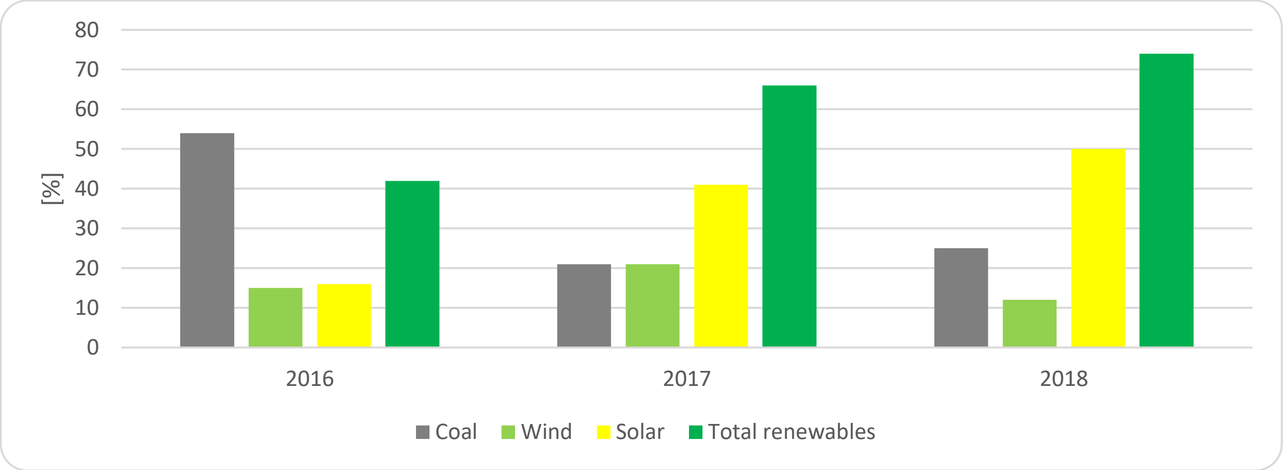

Figure 3-3: Share of various technologies in the power addition capacity during 2016 – 2018 (based on [11]).

3.2.3 Future power generation scenarios

There are many reports presenting different future scenarios for electricity generation in India, suggesting different share of renewables (hydro excluded). Figure 3-4 shows a "typical" future scenario for electricity generation in 2030, compared to 2015. Included in this figures are also "non-utilities", representing non-public independent producers of electric power for sale to utilities and end users [12].

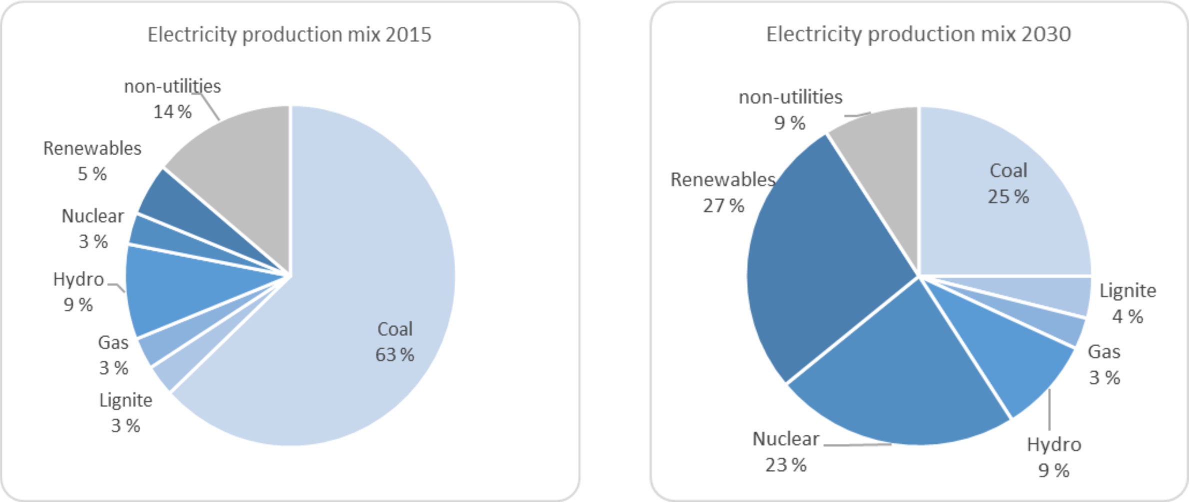

Figure 3-4 Power generation capacity in 2015 (left) and projected power generation capacity in 2030 (right), based on [12].

3.3 CO_2 emissions

The power sector is responsible for half of India's CO_2 emissions, which have doubled since 2005. This large growth of CO_2 emissions is explained by an electricity demand growing at an increasingly rapid pace, most being met by expansion of coal use. However, as seen in Figure 3-5, for the first 8 months of 2019 the emission growth has slowed down sharply, reaching its lowest annual increase (2%) in nearly 20 years [13].

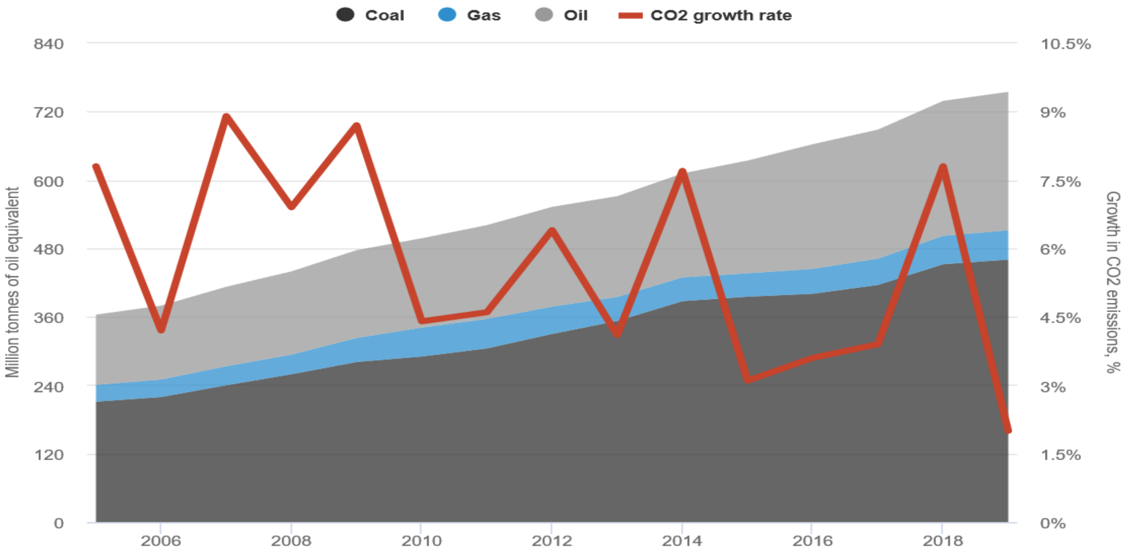

Figure 3-5: Annual use of fossil fuels and growth in CO_2 emissions (red line) during 2006-2019. [13]

Even if the emissions per capita in India is only 1,8 tons CO_2 compared to the global average of 4.9 tons CO_2 per capita, India's total emission is the third largest, after China and United States. Therefore, this trend in India's CO_2 emissions is of high global importance [13].

When implementing new technologies that implies a change in energy consumption and/or a fuel switch, an evaluation of the change in CO_2 emission can be calculated by using a CO_2 emission factor for different types of energy production technologies. For electricity consumption the weighted average emission factor describes the average amount of CO_2 emitted per unit of electricity generated in the grid. In 2018, it was estimated to 0.83 tonnes CO_2 / MWh in India. The emission factor for the HSD fuel used in the steam boilers are estimated to 0.26 tonnes CO_2 / kWh [14].

3.4 Other emissions (NOx, SOx, PM)

There are also other emissions from electrical and thermal energy production, such as sulphur oxides (SOx), nitrogen oxides (NOx) and particle matter (PM). These have not been specifically addressed in this project, but it is important to note that any energy-savings measures for reducing fossil-fuel consumption, especially coal-based, will significantly reduce these emissions and thereby benefit India's air quality efforts [13]

3.5 Refrigerants

Heat pumps and refrigeration/AC units contains a circulating refrigerant which might, occasionally or continuously, leak into the atmosphere during handling, operation and destruction.

3.5.1 Ozon depleting refrigerants

The traditionally used refigerants are chlorinated halocarbons, so called CFCs and HCFCs. These synthetic refrigerants are ozone-depleting substances (ODS) and are therefore regulated in the Montreal Protocol, which is the global agreement to protect the stratospheric ozone layer by phasing out production and consumption of ODS. India, being a signatory of the Montreal Protocol, has successfully phased out most of the CFCs and is now gradually phasing out the HCFCs [15].

HCFC-22, which is used in the AC units to be replaced in the Akshaya Patra Heat Pump Project, is the most commonly used HCFC. The UN has set a 2030 deadline for a global ban of ozone-depleting substances. India launched in 2017 a management plan which aims to phase-out the consumption and manufacturing of the key refrigerant HCFC-22 by 2030, which is a challenging process [16].

3.5.2 Refrigerants contributing to global warming

Globally, the most common replacement for HCFCs are non-chlorinated halocarbons, so called HFCs. Though HFCs are not ozon-depleting they has a global warming potential (GWP) up to 4000 times higher than CO_2, which means that any leakage of refrigerant to the atmosphere will contribute to global warming.

Therefore, in 2016, the Kigali agreement was adopted aiming at phasing down HFCs and also stresses the importance of combining refrigerant management with energy efficiency. After having phased out the HCFCs, India will have to start phasing out the HFCs. Under the Kigali agreement, India has commetted to freeze the HFC use by 2028 and phasing it down with 85% by 2047, over the 2024-2026 level (baseline) [16].

3.5.3 Natural refrigerants

Natural refrigerants, such as hydrocarbons, ammonia and carbon dioxide are environmentally benign non-patented substances. They are not ozone-depleting and their contribution to global warming upon leakage is negligible compared to the HFCs. Many of the natural refrigerants also offer lower cost and a high energy efficiency in most applications.There are a number of studies empasizing the need, opportunity and potential for using natural refrigerants in India.

3.5.4 Current status in India

As shown in Figure 3-6, stationary AC (commercial and residential) together with commercial and domestic refrigeration make up 80 % of India's installed cooling capacity. The total installed capacity is 25 million TR (88 GW). Currently, 90 % of the installed capacity is based on HCFCs and HFCs, while 10 % are based on natural refrigerants [15].

As seen in Figure 3-7, the use of HCFCs has gone down in most sectors in the recent past. Most of the HCFC usage occurs in the residential AC sector (60%) and commercial refrigeration (25%). The reduction in HCFC usage has been accompanied by an increasd use of HFCs, especially in mobile AC sector [15].

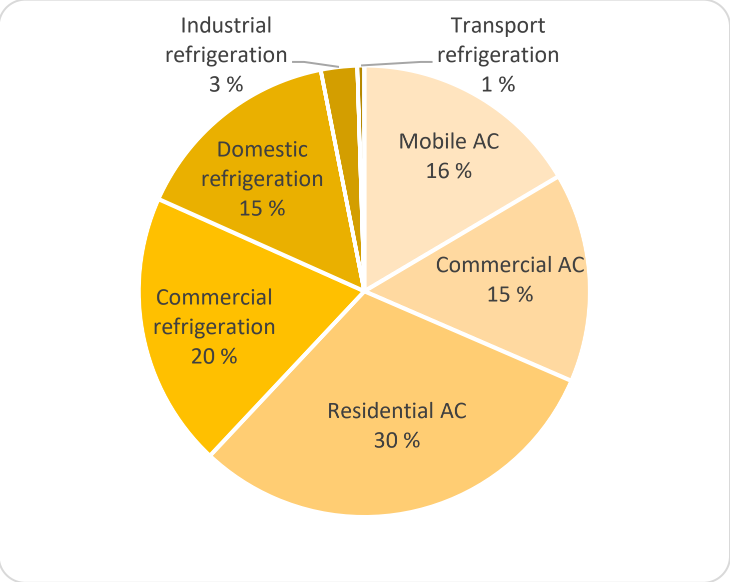

Figure 3-6: Sector-wise installed refrigeration capacity in India (based on [15])

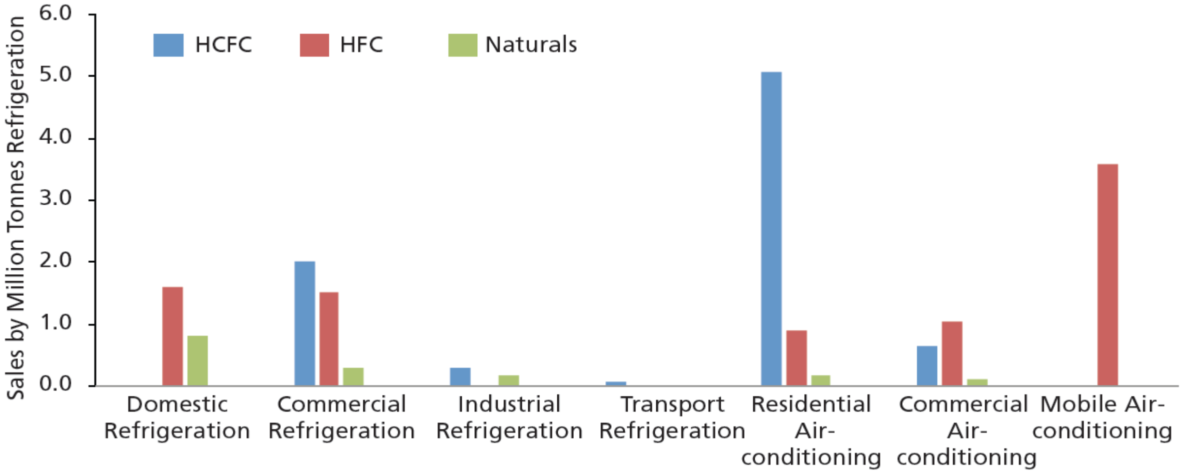

Figure 3-7: Sector-wise refrigerant mix in India (2015) [15]

The statistics presented in Figure 3-7 is confirmed by a study presenting atmospheric measurements for estimating emissions of refigerants in India, showing low emissions of CFCs (<10%) and large emissions of HCFCs and HFCs (about 45% each) [17]. Even if India has reported a complete phase-out of its production of CFCs, banks such as dated refrigeration equipment as well as fugitive emissions from industry, may persist and explains the CFC emissions.

The similar magnitude in emissions of HCFCs (HCFC-22) and HFCs (mostly HFC-134a) confirms that India is in transition between employing HCFC and HFC refrigerants. It also indicates that India is yet to adopt several common refrigerant HFC blends with high GWPs, including R-410A, R-404A and R-507A, all of which are used extensively in the developed world. However, adoption of these HFC blends is only a temporary solution, due to the future HFC phase-down according to the Kigali agreement. India's apparent lack of uptake of these refrigerant blends presents an opportunity for future climate mitigation strategies; if India can be encouraged to bypass HFCs in favour of low-GWP alternatives, such as natural refrigerants, substantial greenhouse gas emissions could be avoided. The substitution of the HCFC-22 space cooling units by a heat pump using the natural refrigerant CO_2 is an important example of such a by-pass.

3.5.5 Future scenario

India's total installed cooling capacity is estimated to increase by 5 times between 2015 and 2030. In a business as usual (BAU) scenario, 75 percent of the cooling needs will be met by HFCs in 2030, and the remaining by naturals (Figure 3-8).

India and other Articles 5 countries are offered a flexibility in the phase-down schedule which can be used to prioritize transition to natural refrigerants through funding from a multilateral fund. It is estimated that 77% of India's refrigeration and air conditioning sector can be converted to natural refrigerants with currently available technologies [15].

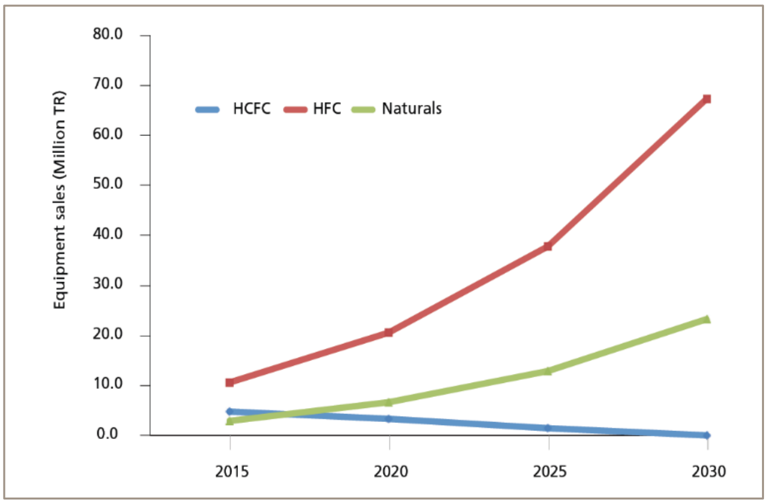

Figure 3-8: Projected refrigerant mix in India 2015-2030 [15]

Figure 3-9 shows that prioritizing natural refrigerants could result in annual savings of 50 million tonnes of CO_2 equivalents by 2030. Reaching this potential, however, will require the enabling of regulations, updated safety standards and market incentives for first movers.

Use of natural refrigerants also offers high energy efficiency in most applications. The use of natural refrigerants can therefore supplement national and international plans to improve energy efficiency and reduce GHG emissions. A doubling of the energy efficiency in the domestic AC sector alone is estimated to reduce emissions by 100 million tons of CO_2 equivalents annually in India by 2030 [15].

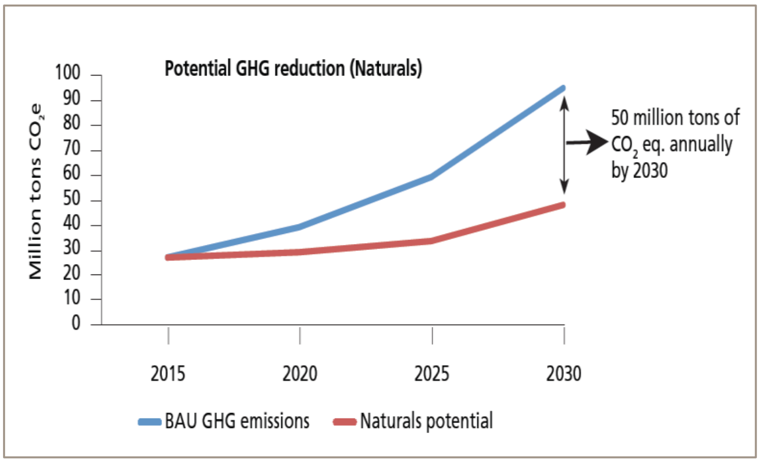

Figure 3-9: Potential GHG reduction with natural refrigerants [15]

4 The proposed system

Here the proposed system is presented in terms of general system setup, heating and cooling load profiles, heat pump specifications and volume estimates of the cold and hot water storages.

4.1 General system setup

In Figure 4-1a principal sketch of the proposed system is shown. The heat pump generates 90 °C hot water, which is supplied to a hot water storage tank, for use in the cooking cauldrons when required. The desired water temperature of 120 °C - 130 °C in the cauldrons is reached by injecting steam produced in the boilers.

The existing space cooling system, with more than ten HCFC-22 units, are replaced by a central cooling system which circulates cold water (5 °C), produced in the heat pump, through a number of air handling units (indoor units). Return water from the indoor units (12 °C) works as heat source to the heat pump. To meet any mismatch in time and load between cold and hot water need, a thermal storage system is installed.

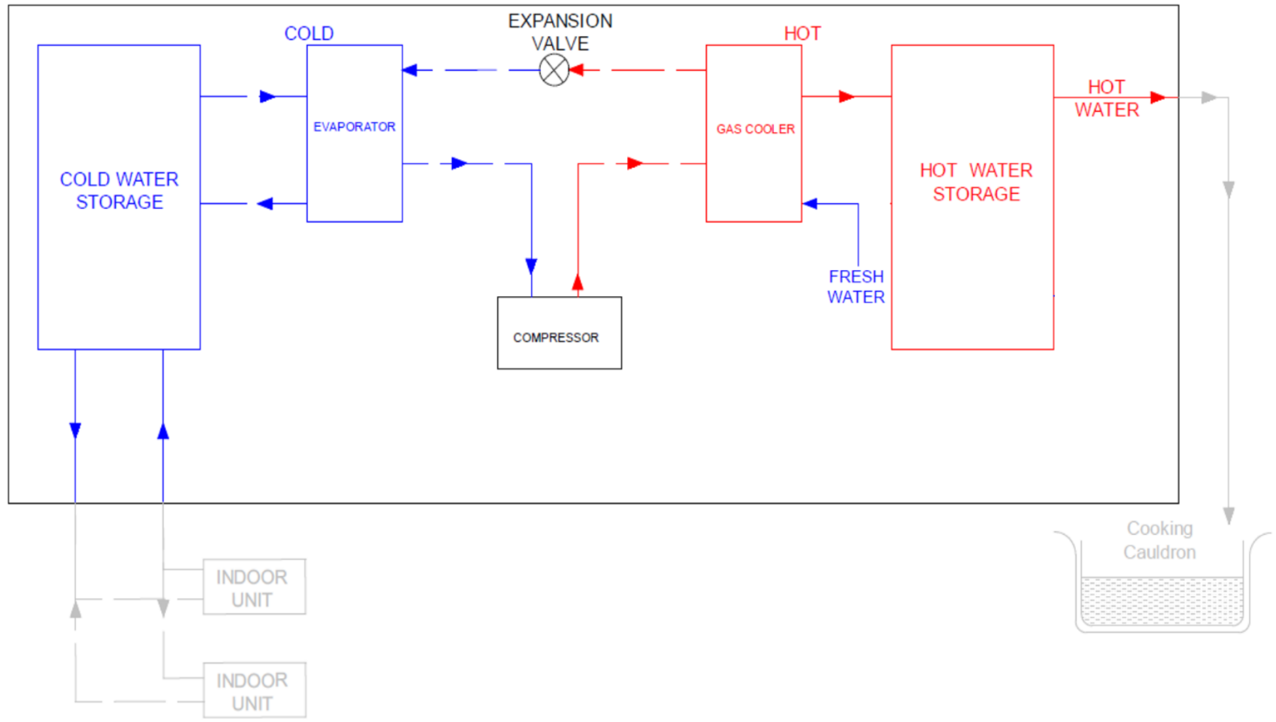

Figure 4-1: Principal sketch of the proposed system.

4.2 Heating and cooling load profile

In Figure 4-2, the heating and cooling load profile for a typical day is shown. The heating load represents only the demand for producing 90°C water, which is to be delivered by the heat pump, i.e. the remaining steam demand for the cooking process is not included. Hot water is required during 6 hours, from 4 am to 10 am, at a constant load of 305 kW, resulting in a hot water energy demand of 1830 kWh for a typical day.

The space cooling demand occurs from around 8 am to 10 pm. The maximum cooling load is 123 kW, and the total cooling demand during a typical day is 1213 kWh.

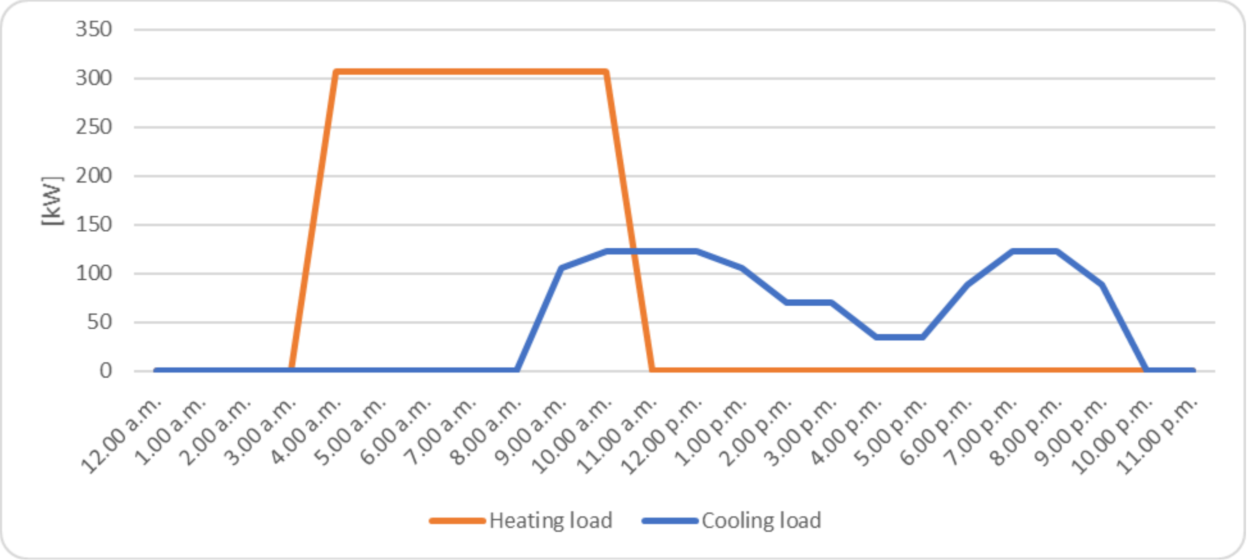

Figure 4-2: Heating load (hot water) and cooling load (cold water) profiles on a typical day[1]

4.3 The CO_2 heat pump

The heat pump was designed based on the heating and cooling load profile, shown in Figure 4-2 and summarised in the upper part of Table 4-1. The lower part (blue) presents some heat pump characteristics.

Table 4-1: Specifications of the hot water and cold water production

Hot water production **24°C to 90C**		**Cold water production** **12°C to 5°C**	
Maximum hot water demand [kW]	**306**	Maximum cold water demand [kW]	**123**
Hours of heating demand [h/day]	**6**	Hours of cooling demand [h/day]	**13**
Daily heating demand [kWh]	**1836**	Daily cooling demand [kWh]	**1213**
Average daily heating demand [kW]	**306**	Average daily cooling demand [kW]	**93**
Heat pump		**Heat pump**	
Heating capacity (kW]	**141**	**Cooling capacity (kW]**	**102**
Operating hours h/day]	**13**	**Operating hours [h/day]**	**13**
Daily heating capacity [kWh]	**1833**	**Daily cooling capacity [kWh]**	**1326**
Hot water production, [l/min]	**33**	**Cold water production, [l/min]**	**12.5**
Heating COP **Overall COP**	**3.62** **6.25**	**Cooling COP** **Overall COP**	**2.62** **6.25**
Power consumption [kWh/day]	**22.6**	**Power consumption [kWh/day]**	**16.3**

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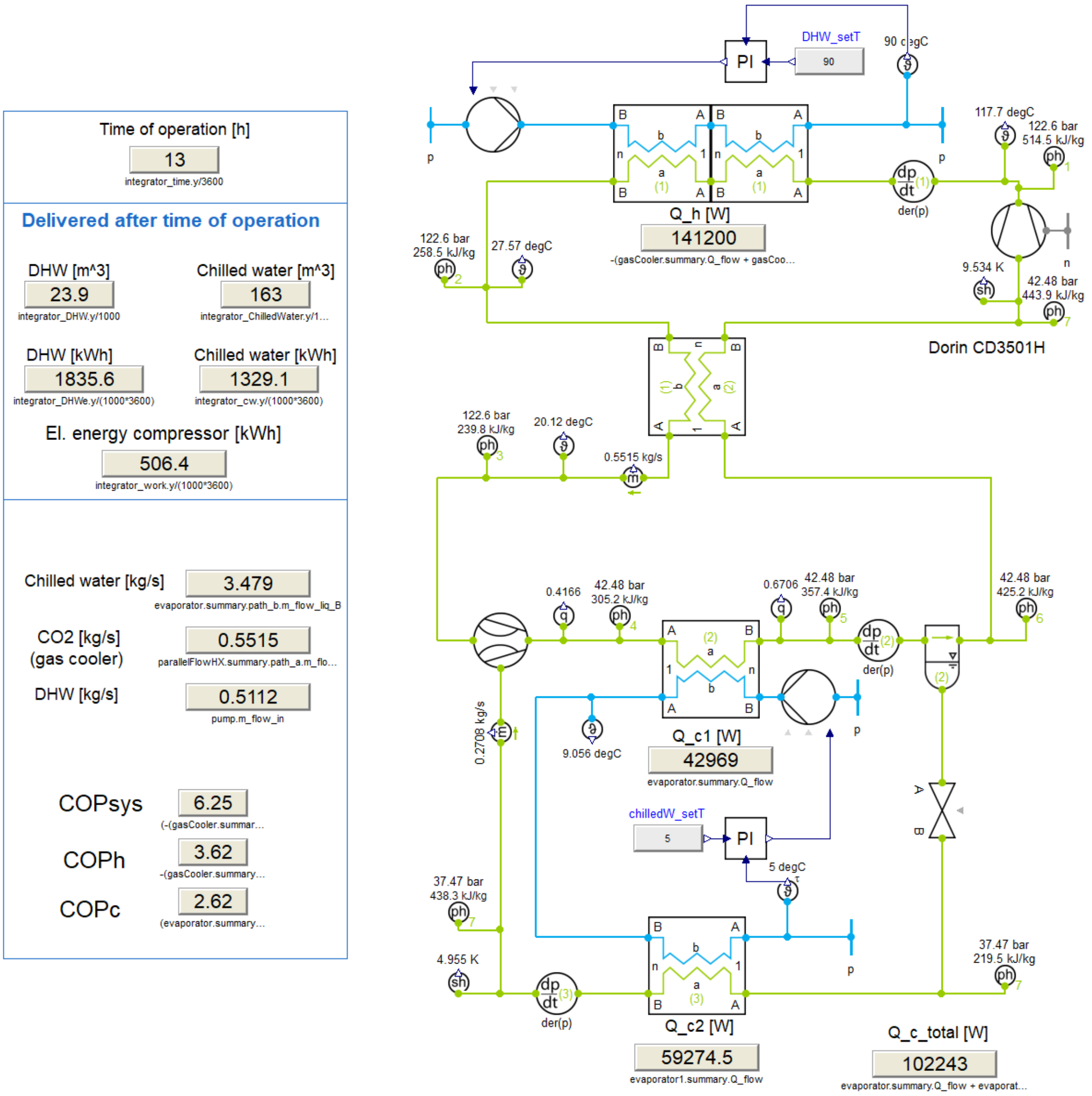
[1] Direct communication with Akshaya Patra Foundation

Considering the typical heating and cooling load profile resulted in a proposed heating capacity of 141 kW which, if the heat pump operates during 13 h, covers the daily hot water demand of 1830 kWh. According to simulations of the system (see Figure 4-3) the heating COP is 3.62 resulting in total electricity consumption of 39 kW and a cooling capacity of 102 kW. An operation time of 13 h results in a daily cold water production of 1326 kWh, which is 113 kW more than the daily average demand. If this surplus cold is not required it has to be removed in order to not fill up the cold storage (see section 4.4). This can simply be done by installing an outdoor unit, in which the surplus cold is rejected to the outside air.

As seen in Table 4-1, the cooling COP happens to be the same as for the existing HCFC chillers. The reason why the specific cooling COP is not improved in the new system is the large temperature lift for the heat pump compared to the existing AC units operating only between indoor and outdoor temperature. However, since the heat pump covers both a cooling and heating demand, it is the total (combined) COP of 6.25 that is relevant and shows the high efficiency of the proposed heat pump. This high efficiency is achieved through design features like a multi-ejector and a double-stage (i.e., two-temperature-level) evaporation process. More details about the heat pump design can be found in Appendix A1.



Time of operation [h] 13 integrator_time.y/3600

Delivered after time of operation

DHW [m^3] 23.9 integrator_DHW.y/1000

Chilled water [m^3] 163 integrator_ChilledWater.y/1...

DHW [kWh] 1835.6 integrator_DHWe.y/(1000*3600)

Chilled water [kWh] 1329.1 integrator_cw.y/(1000*3600)

El. energy compressor [kWh] 506.4 integrator_work.y/(1000*3600)

Chilled water [kg/s] 3.479 evaporator.summary.path_b.m_flow_liq_B

CO2 [kg/s] (gas cooler) 0.5515 parallelFlowHX.summary.path_a.m_flo...

DHW [kg/s] 0.5112 pump.m_flow_in

COPsys 6.25 (-(gasCooler.summar...

COPh 3.62 -(gasCooler.summary...

COPc 2.62 (evaporator.summary...

Figure 4-3: Results from simulations of the system in Dymola

4.4 Thermal storage

As seen in Figure 4-2, there is a mismatch between the hot water and cold water demand, both in time and load. Thermal energy storage (TES), such as hot and cold water buffer tanks, is an established concept for balancing the mismatch in demand and supply of heating and/or cooling. It also allows designing the production unit (heat pump in this case) for a lower maximum output.

As discussed in section 4.3, the heat pump is designed to operate 13h per day to deliver the required hot water demand. The size of tanks for storing hot and cold water depends on when these 13 h of operation occurs. Below two different scenarios are evaluated, showing the difference in required amount of stored energy. Note that any heat losses between the tank and its surrounding are neglected.

Case 1- Heat pump operation: 4 am to 5 pm.
In this case the heat pump starts operating early morning when the cooking process begins, and continuous to operate for a period of 7 hours after the cooking process is finished. Since there is no heat demand during this period the hot storage is filled up with 141 kWh each hour, which then is stored during the non-operating period of 11 h. When the coking process begin, the heat pump start again and together with the stored heat the heating demand of 305 kW ca be supplied for 6 hours. The required amount of stored heat energy is around 1000 kWh, corresponding to a storage volume of 14 m3.

The cooling demand occurs during a longer period and is more variating, being both higher and lower than the 102 kW delivered by the heat pump. This means that there is a more continuous charge and discharge of the cold water storage tank. As seen in Figure 4-4, the amount of stored cold energy is rather constant during the time of heat pump operation. For an operation period of 13 h, a surplus cold of 113 kWh is produced, which is assumed to simply be "removed" at the end of the day. The maximum amount of cold energy that has to be stored is 535 kWh, corresponding to a cold water volume of about 65 m3. Since the temperature difference of the cold water is only 7 °C, compared to 66 °C for the hot water, the storage volume for a certain amount of energy becomes much larger.

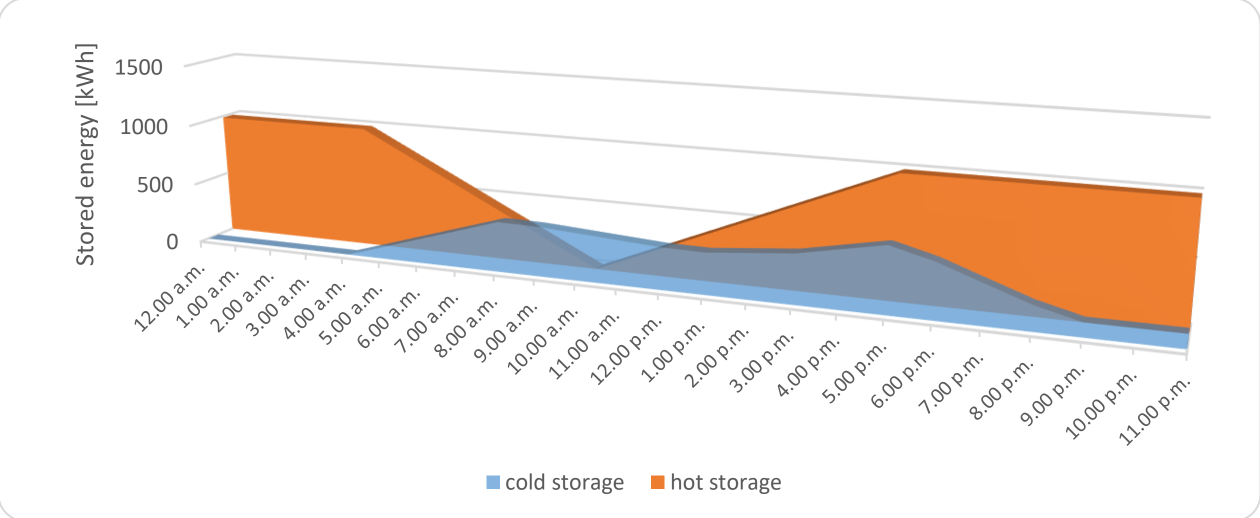


Figure 4-4: Stored energy during a typical day when operating the heat pump between 4 am to 5 pm

Case 2: Heat pump operation: 7 am to 8 pm.
This case, presented in Figure 4-5, aims at reducing the size of the cold water storage. To achieve this, the heat pump does not start to operate until just before the cooling demand starts in the morning. By that , the cold water storage is more than halved resulting in a cold energy storage of to 240 kWh or 30m^3. Again, it is assumed that any surplus cold is removed by the end of the day. If it is instead removed more continuously the cold water storage can be further reduced, down to 130 kWh (16m^3).

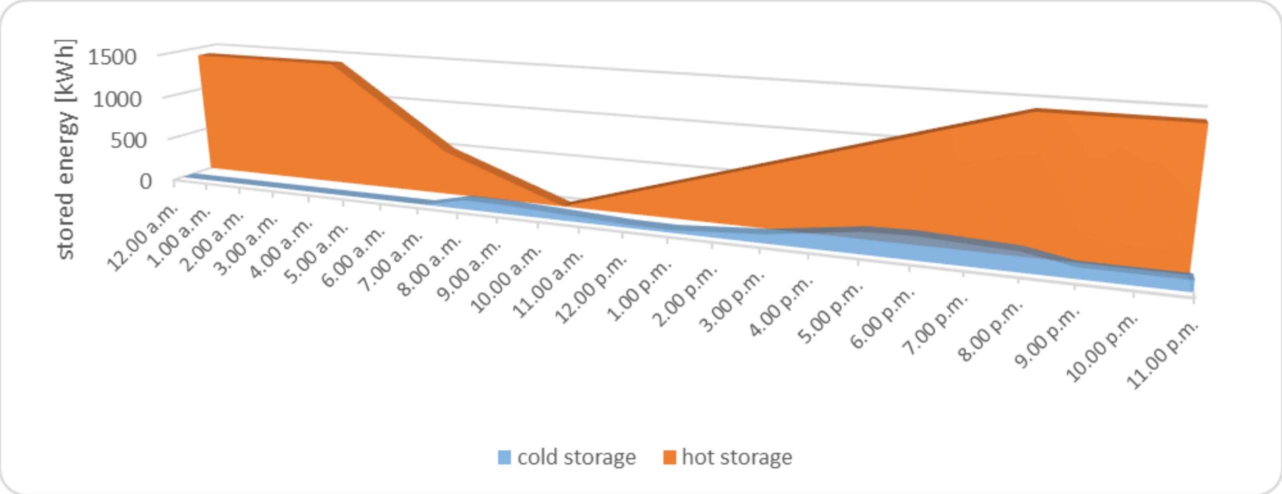


Figure 4-5: Stored energy during a typical day when operating the heat pump between 7 am to 8 pm

During the first hour of the cooking process, before the heat pump starts, the heat demand is covered by the hot water storage. The required amount of stored heat energy increases from 1 MW 1.4 MWh, which still means a reasonable size of the hot water storage tank (20 m^3).

In Figure 4-6 the volume of cold and hot water storage is shown (instead of stored energy) for Case 2. In Table 4-2 the results from Case 1 and Case 2 are summarised.

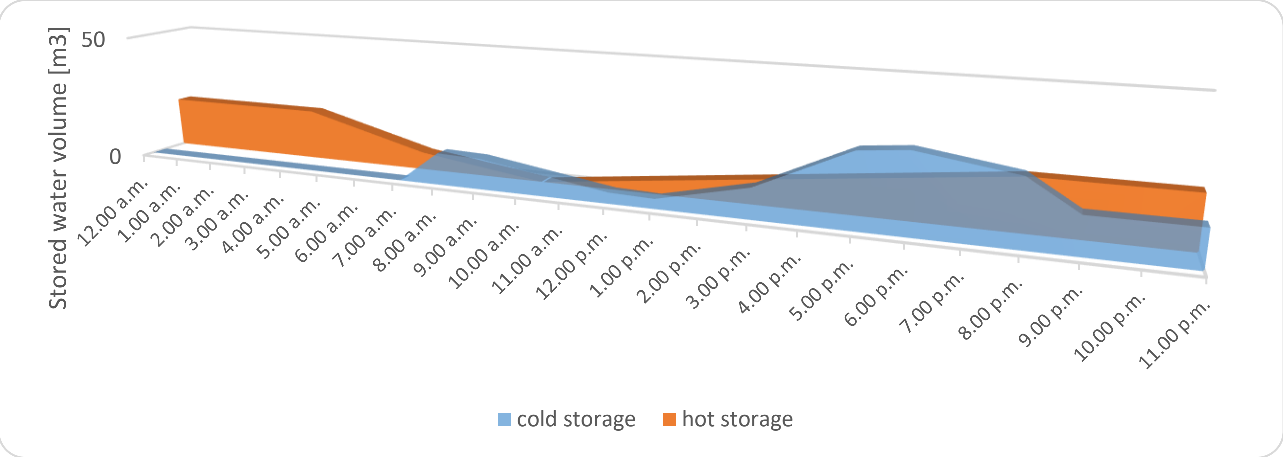


Figure 4-6: Stored volume of hot and cold water during a typical day, operating the heat pump 7 am to 8 pm

Table 4-2: Maximum required hot and cold storage

Heat pump operation	Hot water storage		Cold water storage[2]	
	[kWh]	[m^3]	[kWh]	[m^3]
4 am – 5 pm	**1000**	**14**	**535**	**65**
7 am – 8 pm	**1400**	**20**	**243**	**30**

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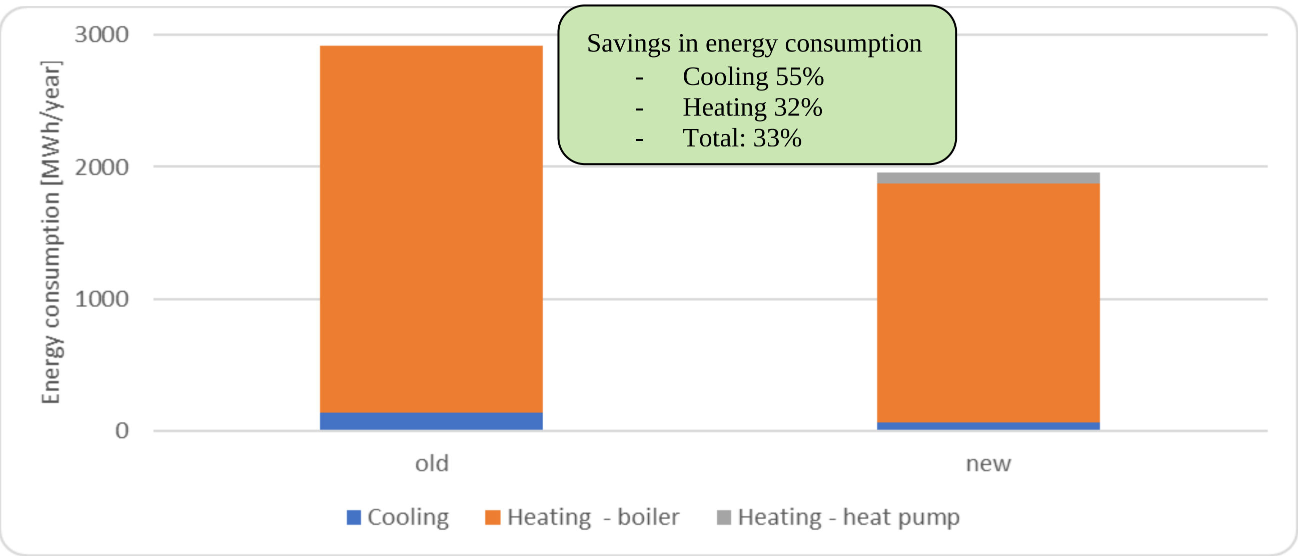
[2] If the surplus cold is waste at optimal time during the day the storage volume can be reduced to 113 kWh and 14 m^3.

5 Evaluation of environmental benefits

In this chapter the benefits of implementing the proposed system at the Bengaluru centralised kitchen is evaluated in terms of reduced energy consumption, its related cost savings and, most importantly, the reduction of greenhouse gas emissions.

5.1 Energy savings

In Figure 5-1 the energy consumption for the old heating and cooling system are compared to the new proposed solution. The reduction in energy use for the cooling system is 55% while the reduction in heating energy consumption is "only" 32%, due to the remaining steam demand for raising the water temperature to 120 °C. For the total system (cooking process and space cooling) the reduced energy consumption is 33%.

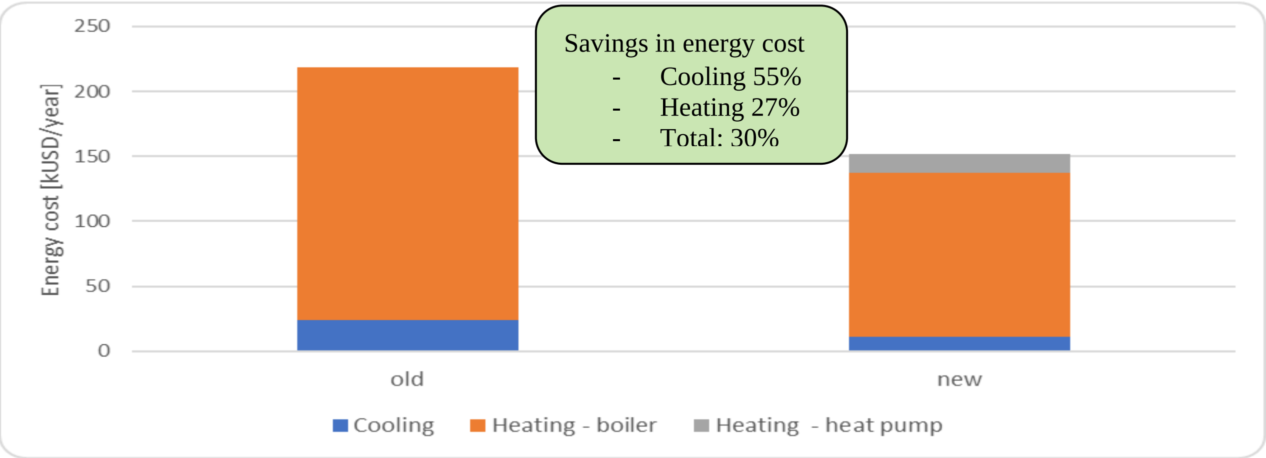


Savings in energy consumption
- Cooling 55%
- Heating 32%
- Total: 33%

Figure 5-1: Comparison of energy consumption for the old and new proposed system.

5.2 Energy cost savings

In Figure 5-2, the energy savings are converted to savings in energy cost, using an electricity cost (for industry) of 0.17 USD/kWh and a HSD fuel price of 0.98 USD/litre, corresponding to around 0.1 USD/kWh. The heat pump reduces HSD fuel consumption but since the electricity price is higher the cost savings for the heating system are slightly lower than the reduced energy consumption. Still, the total savings are 30%.



Savings in energy cost
- Cooling 55%
- Heating 27%
- Total: 30%

Figure 5-2: Comparison of energy cost for the old and new proposed system.

5.3 Reduced green-house gas emissions

Since the reduction of greenhouse gas (GHG) emissions is in focus, they are presented separately for the cooling and heating system, before showing the reduction for the total system.

5.3.1 Cooling system

A heat pump/refrigeration system's contribution to global warming is two-fold;

- Direct emissions: leakage of high-GWP refrigerants (HCFCs and HFCs).
- Indirect emissions: consumption of electricity generated with fossil fuels

Direct emissions of refrigerant leakage are converted to equivalent tons of CO_2 by using the GWP of the refrigerant (1800 for HCFC-22 and 1 for CO_2) and an assumed average annual leakage rate of 30%. In Figure 5-3 the GHG emissions are compared for the old and proposed new system, in terms tons of CO_2 equivalents.

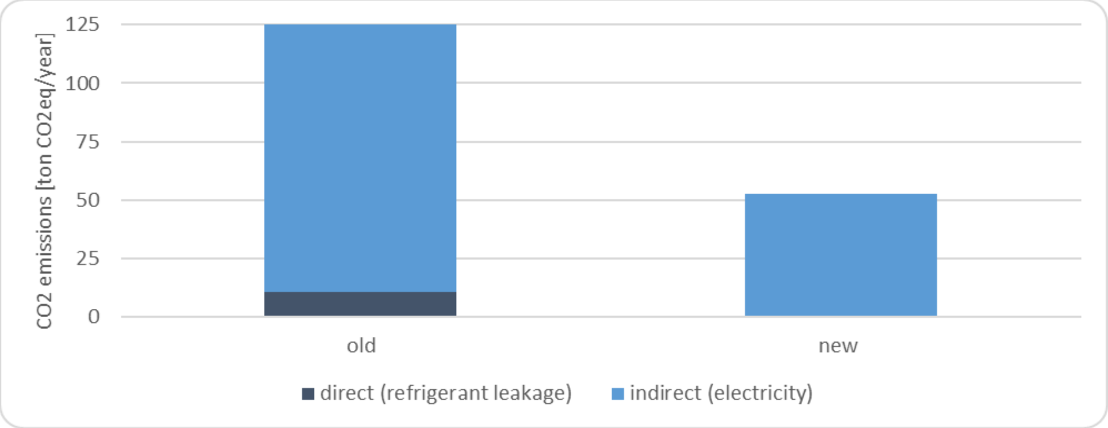


Figure 5-3: Comparison of GHG emissions (CO_2 equivalents) for the old and the proposed new system

For the CO_2 heat pump, the direct emissions are in principal zero while for the existing HCFC-22 units the direct emissions constitute 10% of the GHG emissions. This is still a relatively low share, explained by the very high carbon emission factor (830 g/kWh) of the Indian electricity mix. In a system with lower CO_2 emissions from power production, the share of direct emissions from HCFC or HFC plants would be higher.

As was shown in Figure 5-1, the new cooling system offers a 55% lower electricity demand, thus a reduction in indirect emissions of 55%. This together with the negligible direct emissions in the new system results in a total reduction in GHG emissions of almost 60%.

5.3.2 Heating system

In Figure 5-4, the GHG emissions from the old and new heating system are compared. For the old system, emissions are solely related to CO_2 emissions from burning HSD fuel in the steam boilers. For the new system the heat pump also contributes to the GHG emissions, in terms of CO_2 emissions related to the electricity consumed.

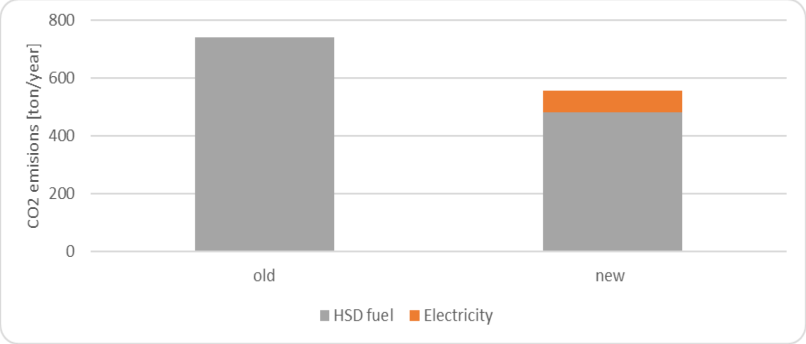


Figure 5-4: CO_2 emissions from the old and the proposed new system

The reduction in CO_2 emissions for the new heating system is 25% (Figure 5-4). This reduction is smaller than the 32% reduction in energy consumption (Figure 5-1). The reason is that the heat pump's electricity consumption replaces energy produced with HSD fuel, which has a much lower carbon emission factor compared to the Indian electricity mix. However, in a wider perspective, the energy saving achieved with the heat pump implies that HSD fuel can replace coal elsewhere in the energy/electricity generation system.

5.3.3 Total system

In Figure 5-5 the total GHG emissions from the heating and cooling system are compared for the old and new solution, showing a total reduction is 30%.

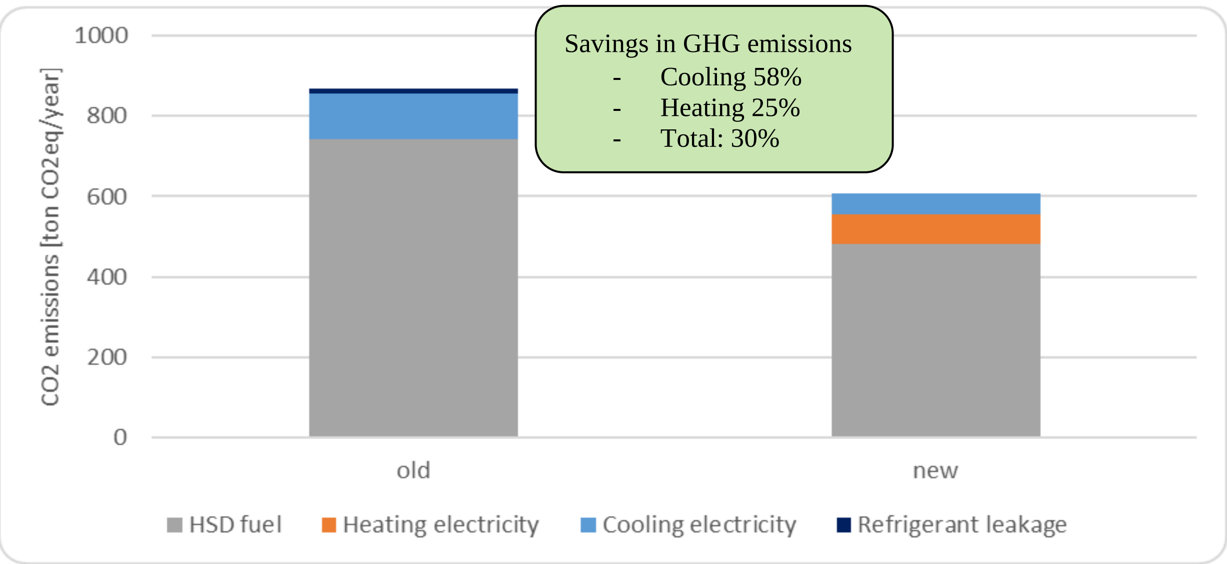


Figure 5-5: Total GHG emissions (CO_2 equivalents) from the old and proposed new system

5.4 Summary of savings

In Figure 5-5 the benefits of implementing the proposed system are summarized, showing the savings in GHG emissions, energy consumption and energy cost.

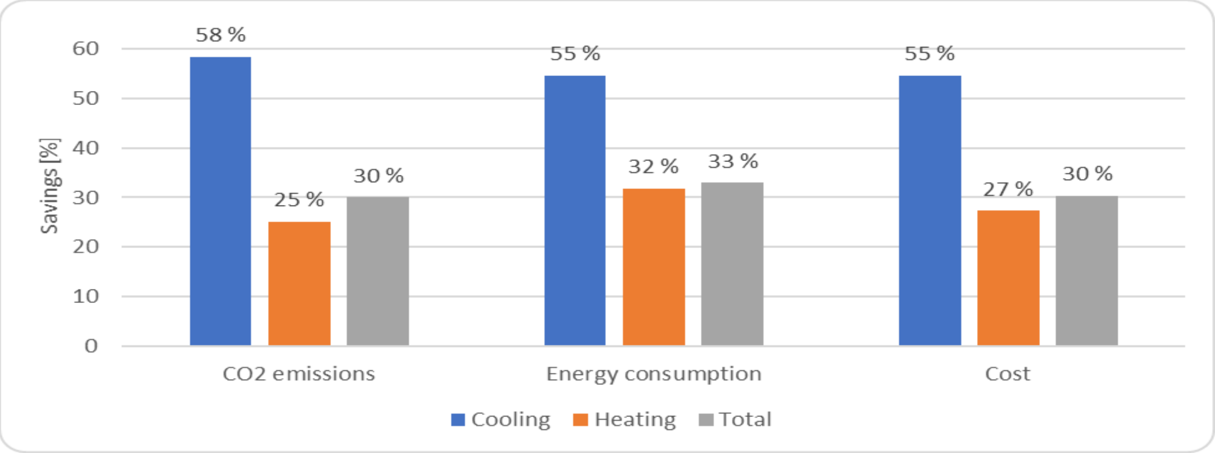


Figure 5-6: Summary of savings in CO_2 emissions, energy consumption and energy cost for the proposed system

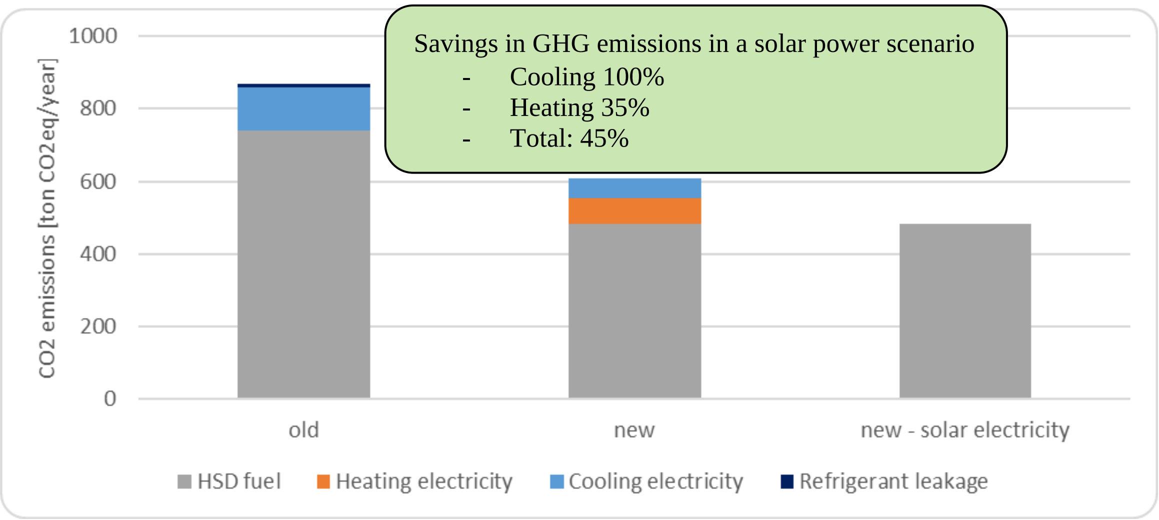
5.5 Potential for future improvements

5.5.1 Renewable (solar) electricity generation

The amount of renewable electricity generation, such as solar, is steadily increasing in India. A challenge with renewables such as wind and solar, is that they are intermittent (varying) energy sources. However, a system with thermal storages installed, facilitates the use of such intermittent electricity supply. The heat pumps power consumption of 40 kW could be, fully or partially supplied by a roof-top solar PV system [18].

Figure 5-7: Roof-top solar power

As shown in Figure 5-8, if the electricity demand for the proposed heat pump is supplied with solar power the system will in principal only generate GHG emissions from the boilers. The total reduction in CO_2 emission will be 45%, including a zero-emission cooling system.



Savings in GHG emissions in a solar power scenario
- Cooling 100%
- Heating 35%
- Total: 45%

Figure 5-8: GHG emissions for the old system, the new proposed system with today's electricity mix and the new system with solar power generation.

5.5.2 Steam producing heat pumps

As seen in Chapter 5, to implement the proposed heat pump is a very efficient way of providing hot and cold water. Since about two-thirds of the heating demand is still supplied with HSD steam boilers, for raising the water temperature from 90°C to 130°C, the implementation of a "high-temperature heat pump" (HTHP) could further reduce the kitchen's energy consumption. HTHPs are normally defined as heat pumps delivering heat above 90-100°C, covering industrial heating demands of pressurised hot water or steam [19].

The number of industrial HTHPs available on the market has grown steadily in recent years, with heating capacities of 20 kW up to 20 MW. Today mostly synthetic refrigerants are applied, [20], but there are concepts, both commercially available and as prototypes, applying natural refrigerants. For example, a prototype heat pump using propane and butane has been developed and experimentally validated in the SINTEF/NTNU lab. The concept is currently being scaled-up to cover heating and cooling demands in a food industry (Figure 5-9). Another example is the Japanese company Mayekawa, developing a steam producing heat pump using pentane as refrigerant [21].

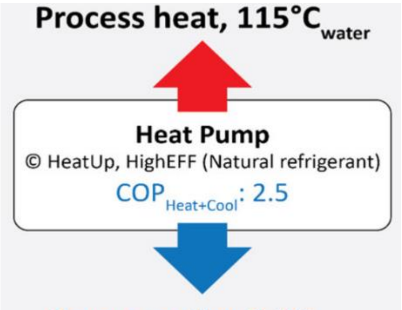


Figure 5-9: Propane-butane HTHP

6 Conclusions

A CO_2 heat pump, combined with a hot and cold storage, is proposed as an energy-efficient and climate-friendly concept for the centralised kitchen at Bengaluru. The heat pump supplies both hot water to the cooking process and cold water to a space cooling system, replacing the existing HCFC-units.

From the evaluation of the environmental benefits of implementing the proposed solution, the following indicative conclusions were drawn;

- ➢ Replacing the HCFC air-conditioning units with the CO_2 heat pump offers more than 50% reduction in power consumption for the space cooling system and almost 60% reduction in GHG emissions.

- ➢ Since CO_2 is a natural refrigerant the proposed heat pump solution offers compliance with all current and future legislations related to refrigerants.

- ➢ The proposed solution shows the possibility for India to bypass the use of high GWP rerigerants as temporary replacements for HCFCs, and by that avoiding significant GHG emissions and costly replacement processes.

- ➢ By implementing the heat pump for producing hot water to the cooking process reduces the kitchens total energy consumption (HSD fuel) of more than 30% and the CO_2 emissions with 25%. Steam boilers must still be applied for raising the hot water temperature from 90°C to 130°C.

- ➢ The CO_2 emission factor for electricity generation in India is high, due to the large share of coal-based power plants. However, the renewable share of the latest added power generation capacity is over 70%, implying that future benefits of heat pump implementation will be successively increased.

- ➢ For the total system (cooking process and space cooling) the reduction in energy demand, energy cost and GHG emissions are all above 30%

- ➢ A CO_2 heat pump producing simultaneously hot and cold water is an extremely efficient way of supplying both heating and cooling needs, especially if they occur at the same time. However, by installing hot and cold water storage tanks, the mismatch in both load and time can be balanced.

- ➢ The proposed system requires storage of around 20 000 litres of hot water and 30 000 litres of cold water. Implementing a heat pump combined with thermal storages facilitates any future uptake of renewable energy and/or electricity generation.

- ➢ Potential further improvements include installation of a roof-top solar power systems to supply the electricity to the heat pump, which would result in an emission-free cooling system and further reduce the GHG emissions from the cooking process.

- ➢ To investigate the potential to complement the system with a steam producing heat pump using natural refrigerants could be of interest for further reduction in HSD fuel consumption and CO_2 emissions.

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