Small and Domestic Ammonia Cooling Systems for Energy and Sustainability of India

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Abstract. Preserving the environment should be everyone's first and greatest concern. Technology has caused the climate to change as a result of fast industrial development. As a result of climate change, people have had to rely on increasingly complex technologies to live comfortably. The devices primarily require electrical energy, the majority of which is generated by thermal sources. The air conditioning and cooling industry is a fast-growing industry. Air conditioning systems are expected to reach 25.4 million units in 2030, using more than 7700 TWh globally. The cooling systems predominantly use HCFC and HFC-based refrigerants, both of which have Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) concerns (GWP). When compared to natural refrigerants, the Coefficient of Performance for systems using ODP and GWP refrigerants is also moderate. Using a natural refrigerant like "Ammonia," which has zero ODP and 0% GWP, will reduce energy consumption by 1925 TWh and 3080 TWh, respectively, when compared to systems using R134a and R410. In comparison to R134a and R410 systems, ammonia systems will lower power generation by 1546.9 and 2476.3 TWh, respectively, and CO2 generation through thermal plants by 25 and 40Despite the fact that ammonia gas is utilized in commercial systems, it is a toxic and flammable gas that should be employed with safety measures when used in domestic applications.

Keywords: Ammonia Refrigeration, Air conditioning, Cooling systems, CO2 emissions, Energy, Electrical power generation.

1 Introduction

Climate change has become an unavoidable phenomenon that necessitates the preservation of comfortable conditions. It also raises as Mother Nature forces the world to endure the most extreme conditions. Providentially, nowadays people have become more civilized and advanced. Life progress has brought new machines and systems into people's living environments. These machines and systems, in turn, need energy, usually electrical energy to work. As a result, from 2000 to 2018, energy generation increased by 3.6 percent year on year, generating more than 25000 TWh. Coal and gas-fired electricity generation account for 58% of overall energy generation [1]. When conventional fossil fuels are used to generate electricity,

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CO_2 emissions are produced, which contribute to global warming and have a negative impact on the atmosphere and environment. This produces a lot of hardship for the people in living [2]. Global CO_2 emissions are increasing by 3 percentage year on year, with about 1 billion tonnes of CO_2 released into the atmosphere every year. According to the International Energy Agency (IEA), fossil fuel emissions totalled more than 33000MT CO_2 in the year 2017. The amount of CO_2 emitted varies from region to region, regardless of the population[3]. North America, Oceania, Europe, and Latin America, which account for 5% of the global population, generate 18% of total emissions, Asia, which accounts for 60% of the global population, emits 49%, and African nations, which account for 16% of the global population, emits only 4% of total emissions [2]. This is because people in developing countries live more affluent lives using more gadgets. The per capita energy intake of different countries demonstrates this. The most developed countries, such as those in North America, the European Union, and the Middle East, have higher per capita energy consumption, with more than 10000 kWh per human, while the developing countries have lower per capita energy consumption [4], [5]. Sophisticated people's lifestyles lead to CO_2 emissions through their day-to-day habits. The UNFCCC, through its Kyoto Protocol, set a target for developing countries to reduce CO_2 emissions by 5% below 1990 levels, and in its subsequent Paris Agreement of 2015, adopted a goal to keep global mean surface temperature rise below 2°C above preindustrial levels[6], [7]. As a result of the aforesaid agreement, member countries enacted strict restrictions to reduce pollution by lowering fossil fuel power generation and promoting renewable energy generation. The automotive sector was mandated to produce engines with low emission norms. The industries which are contributing to the pollution were asked to control and minimize or shut down. In this context, the air conditioning and refrigeration industries, which commonly used synthetic CHFC refrigerants, are a substantial contributor to GWP and GHG emissions. It was observed that the Chlorine and Fluorine atoms when leaked or discharged into the atmosphere, they deplete ozone, causing global warming. According to the Montreal Protocol, countries must reduce their use of CHFC chemicals, which would result in a 0.5°C increase in global warming by the year 2100 [8]. Also, the systems operating with CHFC have moderate energy efficiency leads indirectly to high emissions of CO_2 This review investigates the feasibility of replacing synthetic refrigerants with natural refrigerants (NH_3), which would reduce ODP and GWP while improving energy efficiency and lowering CO_2 emissions.

2 Air conditioners and Refrigerants

The rise in the living standard of people due to economic growth, along with the increase in population and extreme heatwaves have increased the demand for air conditioners. Campbell et.al had stated that penetration of air condition systems in the US and Europe is more than 90 percentage, 85 percentage in Japan and Korea, 60 percentage in China, and about 20 percentage in India, Brazil, Mexico, and Indonesia[9]. The global air conditioning market grew by 10percent in 2018-2019[10]. The worldwide air conditioners sales are forecasted to reach over 25.4 million by 2030[11]. In the Indian context, the growth is expected to be 16 percentage annually. Air conditioner systems in many countries are mainly used to cool the confined space as the temperature in the summer varies from 33 to 47. A throttled refrigerant is circulated through copper coils to provide the required comfort condition at the confined space. Currently, R22 and R410, and R134a are the refrigerants used in these systems, R410 and R134a are considered as a substitute for ozone-depleting (OD) chlorofluorocarbons [12].

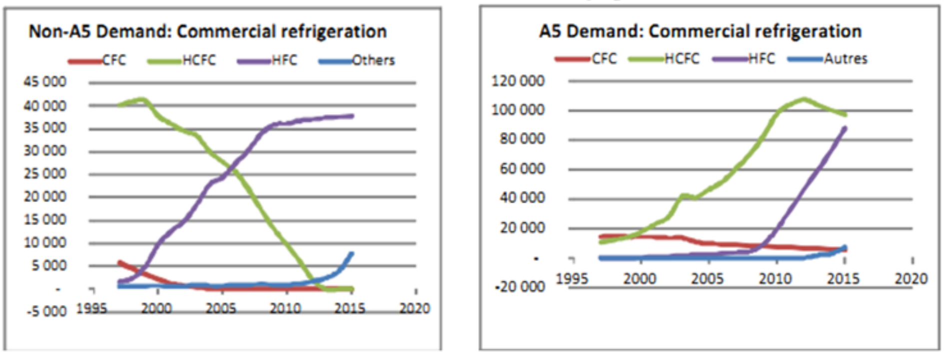

Fig. 1. Demand of Refrigerants in Non - article 5 and article 5 countries according to UNEP TEAP 2012 report

The UNEP report 2019 illustrates the state and usage of various refrigerants. The UNEP classifies the developing and underdeveloped countries globally as Article 5 countries and the developed countries as non-Article 5 countries and stipulates different timelines to phase ODPs. According to figure 1, the non-article countries will reduce and phase out the HCFC refrigerants by 2015 and will supplement systems that use HCF. On the other hand, the demand for systems operating HCFC will increase in the article 5 countries due to lack of technology and high cost. The number of units in these countries will exceed one million tons of refrigeration [12]. The demand for the HCF-based cooling system has reached 90 percent of the total demand worldwide after 2015 [13]. Overall HFC emissions from the cooling systems are growing at a rate of 8 percentage per year and the annual rise in emissions is projected to be 7-19% of global CO2 emissions by 2050. The magnitude of radiative forcing by ozone-depleting substance HCFC is 0.32W/m2 and its alternative HFC was 0.12W/m2 in 2010 and tends to grow to 0.40 W/m2 in 2050. The intergovernmental Panel on Climate Change (IPCC) had stated that due to the above refrigerants the CO2 emission had increased from 14percent as of 2010 to 27 percent by 2050 [12].

Table 1 provides information about the ozone depletion and global warming potential of various refrigerants used currently. The substitute refrigerants have a lower ODP but have a very high GWP, they also have a very long time to degradation. Whereas, the natural compound ammonia has zero ODP and zero GWP [14] [15]. In recent years, the use of HFCs as ODS replacements have increased by 10-15% a year globally [16]. The increased use of HFCs is a direct consequence of the Montreal Protocol's intention and activities, and therefore, an unintended negative impact of these actions can be seen as the contribution of the HFC to climate change the increase in long-term HFCs will result in the benefits of the Montreal Protocol being reduced or completely lost [9].

Table 1. Refrigerant Properties.

Refrigerant	Type	ODP	GWP	Atmospheric lifetime (years)
R12	CFC	0.9	8500	102

R22	HCFC	0.06	1700	13.3
R134a	HFC	0	1300	14
R407C	HFC blend	0	1610	36
R410A	HFC blend	0	1900	36

3 Energy impact

The energy efficiency of all machines absorbing power is a major concern. These machines have to consume as minimal power as possible to achieve the desired effect. The energy efficiency of the refrigeration cycle is referred to as the Coefficient of performance (COP). The COP is the ratio of the refrigeration effect to the power input to the compressor. The heat absorbed in the evaporator is the refrigeration effect. The refrigeration systems' COP ranges from 1 to 6. Many factors are associated with achieving higher COP, and an important factor is the refrigerant used and its thermal properties. Many refrigerants have been developed over the years to achieve the best performance. Each refrigerant will have its own set of advantages and disadvantages. Lower COP systems will absorb more energy for the same cooling effect. Today, all the air conditioner systems use electrical energy to compress the refrigerant. The global electrical energy consumption for space cooling by air conditioners is approximately 2300 TWh in 2016 and is expected to increase to 7700 TWh in 2050, representing a 330percent increase in consumption [16]. At the generating stations, 1.2 kWh of power is to be produced for every 1 kWh of power consumed by the air conditioners. Thermal energy accounts for nearly 58 percent of all electricity generated in India [14]. These thermal power plants emit 0.99 kg CO2/kWh of electricity generated [17], [18]. As a result, CO2 emissions from air conditioners were 2277 x 1012 tonnes kg CO2 in 2016 and are expected to rise to 7623 x 1012 tonnes kg CO2 by 2050 globally [8]. The CO2 emissions from air conditioners cannot be eliminated but can be reduced to a certain extent by improving the system's operating performance. Many countries have begun to implement various methods to increase the energy efficiency of room air conditioners. Since 2009, appliances in India have been labelled with energy stars from one to five. Appliances with one star will have a low energy efficiency ratio, while those with five stars will have the highest ratio, additionally, the efficiency values are increased regularly, as shown in table 2. This method ensures the most efficient use of electrical power for electrically powered home appliances. If an air conditioning system can operate above these maximum ratings, it will be more beneficial in terms of lowering CO2 emissions.

Table 2. Energy Efficiency ratio (Watt/Watt) as BEE [19].

Star level	Jan-2009	Jan-2012 to Dec-2013	Jan-2014	Jan-2016	Jan-2018 to Dec-2020	Jan-2020 to Dec-2023
1 Star	to Dec-2011	2.5 – 2.69	to Dec-2015	to Dec-2017	3.1 – 3.29	3.3 – 3.49
2 Star	2.3 - 2.49	2.7 – 2.89	2.7 – 2.89	2.7 – 2.89	3.3 – 3.49	3.5 – 3.79
3Star	2.5 – 2.69	2.9 – 3.09	2.9 – 3.09	2.9 – 3.09	3.5 – 3.99	3.8 – 4.39
4 Star	2.7 – 2.89	3.1 – 3.29	3.1 – 3.29	3.1 – 3.29	4.0 – 4.49	4.4 – 4.99
5 Star	2.9 – 3.09	3.3	3.3 – 3.49	3.3 – 3.49	4.5	5.0

A detailed study is carried out in this analysis for the reduction of energy consumption when an alternative natural refrigerant is used and its impact on reduction in the carbon emission and global warming for a sustainable environment

4 Air conditioning Systems

Figure 2 describes a layout of an air conditioning system, the system has an air filter, sensible cooling and heating coils, a humidification chamber, filters, and a blower apart from compressor condenser and throttle valve on the outdoor side. According to the Indian environment, the air is treated for cooling and dehumidification only.

Figure 3 illustrates the working of the refrigeration cycle used to provide the required cooling effect. The major working and power absorbing element in the cycle is the compressor. The performance of the total system is defined by EER or COP. The COP of the system is given by equation 1 and theoretically computed from the P-H chart shown in figure 4.

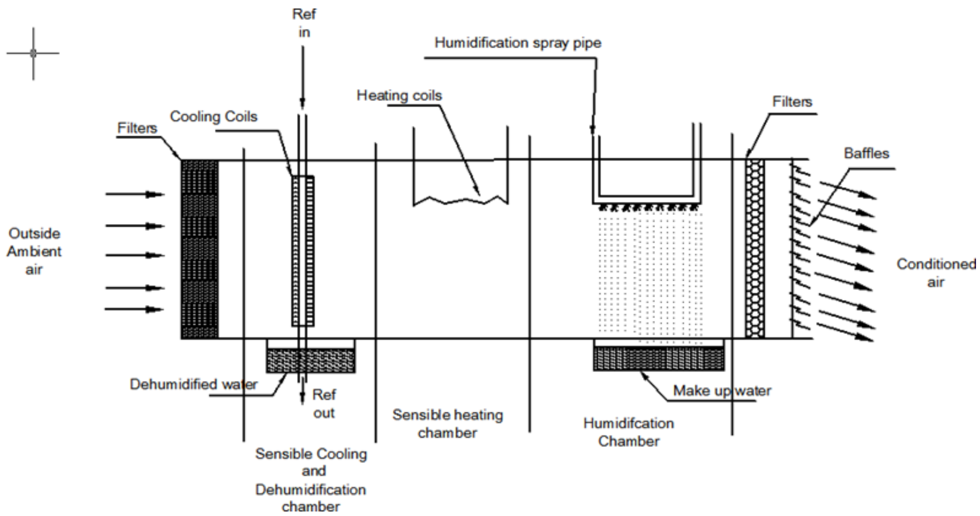

Fig. 2 Schematic layout of an air condition system.

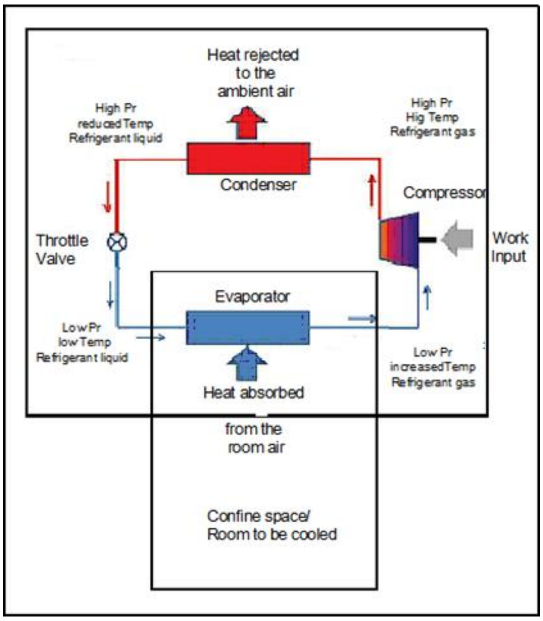

Fig. 3. Refrigeration cycle.

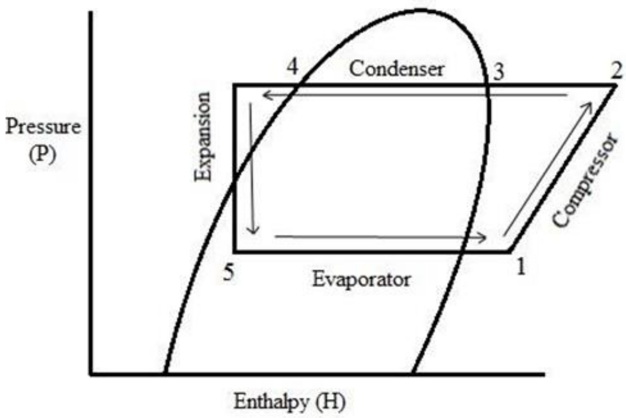

Fig. 4. P-H Plot of a refrigeration cycle.

From the P-H plot (figure 4), it is observed that for the high latent heat of the refrigerant at lower pressure and with minimum compressor work, the Cop of the systems increases. The COP of the refrigeration system varies from 1 to 6 normally. To get the best performance many refrigerants were developed over the decades. Each refrigerant has its pros and cons.

The properties of the refrigerant playing a major role in achieving higher COP are:

- High latent heat of vaporization
- High suction gas density

- Positive but not excessive pressures at evaporating and condensing conditions
- Critical temperature and triple point well outside the working range
- Chemically stable, compatible with construction materials, and miscible with lubricants
- Non-corrosive, non-toxic, and non-flammable
- High dielectric strength
- Zero ODP
- Zero GWP
- Low cost

The HCFC-based refrigerants with high ODP and GWP are banned completely, to be phased out by 2020 and it is to be replaced with HFC-based refrigerants in the new systems. However, air conditioning systems older than 10 years have R22, which is to be taken care of. The HFC even though have zero ODP has a very high GWP. Therefore a refrigerant that does not spoil the atmosphere and the environment is the need of the hour. Natural refrigerants such as ammonia and carbon-di-oxide are the best alternatives. In particular, ammonia is the best substitute for HFC

5 Ammonia as the refrigerant for air conditioning systems

Ammonia is a natural refrigerant that has been used for many years in a variety of applications due to its high thermal efficiency and low cost. Ammonia is an environmentally friendly gas and has zero GWP and ODP [20]. Ammonia refrigerant is presently used in industrial and commercial refrigeration, food preservation, indirect space conditioning, heat pumps, and other applications. Ammonia is emerging as one of the primary natural refrigerants of choice alternative to the ODS. It has a high latent heat of vaporization eight times higher than R- 12 and six times higher than R- 134(a). These characteristics result in a highly energy-efficient cycle with ammonia as the refrigerant with minimal environmental impact. New technologies leading to low and reduced ammonia charge designs are being developed. The application of these new low charge systems and packages creates an opportunity to use ammonia in a broad range of new industrial, commercial and indirect space conditioning applications that would not have been considered with traditional designs.

Already, ammonia-based refrigeration systems are used in thermal storage systems, HVAC chillers, process cooling, air conditioning, winter sports, district cooling systems, heat pump systems, supermarkets, convenience stores, large heat pump installations, and supermarkets, as well as in several high-profile projects, including the International Space Station and Biosphere II [21].

Since ammonia has multitudinous benefits, an evaluation is carried out for energy savings and other potential benefits in comparison with currently used refrigerants such as R22, R 134a, and R410a.

The evaluation criteria are maintained common for all the refrigerants and the system is to cool a confined space to 25° C from an ambient condition of 42°C typical summer conditions in India. The capacity of the system is 1TR (3.5 kW) and 100 percent of air is recirculated. The operating condenser and evaporative pressures of the refrigerants considered are given in Table 3.

Table 3. Operating pressure of different refrigerants.

Device	R22	R134a	R410a	R717
Condenser Pressure in bar	19.42	13.17	30.9	2.67
Evaporator Pressure in bar	4.36	2.52	6.96	11.67

The cycle diagram is plotted in the Pressure-Enthalpy plot (figure 5) the properties at various state points are tabulated in table 4. State point 1 is considered as the inlet to the compressor which is dry saturated condition. Point 2 is the exit from the compressor and entry to the condenser, process 1-2 is considered as isentropic compression, the refrigerant as a superheated vapour enters the condenser. The heat rejection to the ambient air in the condenser is by a constant pressure process, the maximum reduction in temperature attained is limited to 50°C as a minimum of Δ8°C is maintained between the inner and outer fluids. At point 3 the refrigerant exits from the condenser as saturated liquid and enters the throttling valve. During the throttling process, pressure is reduced and the refrigerant enters the evaporator at the wet condition at point 4. The refrigerant flows through the evaporator coils absorbing the heat from the confined space thereby cooling the space.

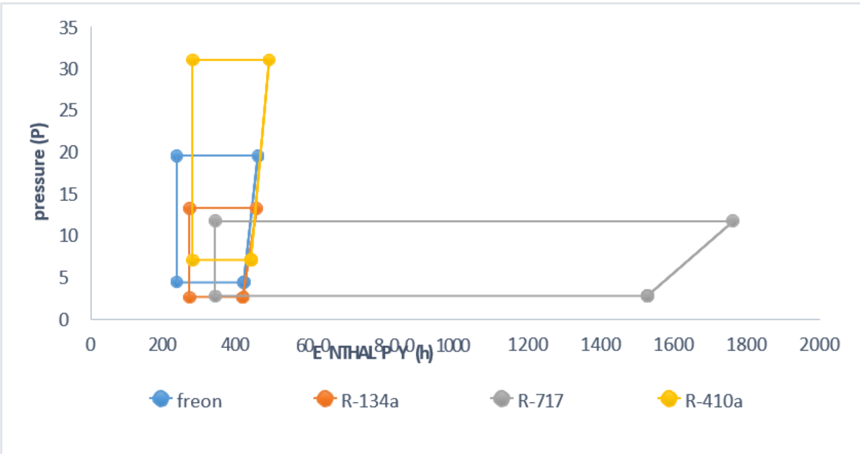

Fig. 5. Pressure- Enthalpy of various refrigerants working in vapor compression cycle.

Table 4. Operating pressure of different refrigerants.

REFRIGERANT	UNIT	R22	R134A	R410A	R717
Specific heat	kJ/kg-K	1.145	1.315	1.84	4.57
Density	kg/m³	3.66	4.25	3	0.73
Pressure					
P1	bar	4.3636	2.5257	6.96	2.6785
P2	bar	19.432	13.177	30.9	11.67
P3	bar	19.432	13.177	30.9	11.67
P4	bar	4.3636	2.5257	6.96	2.6785
Temperature					
T1	oC	20	20	20	20
T2	oC	87.5	76.205	90	115
T3	oC	50	50	50	50
T4	oC	-4	-4	-5	-12
Enthalpy					
h1	kJ/kg	420.83	417.117	440	1527.34
h2	kJ/kg	460	455.5	490	1762.35
h3	kJ/kg	263.27	271.59	280	342.08
h4	kJ/kg	263.27	271.59	280	342.08
Entropy					
s1	kJ/kg-K	1.818	1.803	1.9	6.0716
s2	kJ/kg-K	1.818	1.803	1.9	6.0716
s3	kJ/kg-K	1.2081	1.2373	0.6	1.4892
s4	kJ/kg-K			1.2	
Specific work	kJ/kg	39.17	38.383	50	235.01
mass of refrigerant	kg/s	0.022214	0.024051	0.021875	0.002953
work/TR	kW	0.870113	0.923131	1.09375	0.69397
COP	-	4.022466	3.791444	3.2	5.043445

The coefficient of performance, Mass of refrigerant required, and the power consumption for the cooling load of 1 Ton (3.5 kW) are calculated using equations 1,2, and 3 respectively, and the values are tabulated in table 4.

5 Result and discussions

The R22 (HCFC) has an evaporator and condenser pressure of 4.36 and 19.43 bar for the saturated conditions. The refrigeration effect produced is 157.56 kJ/kg and the energy required to compress the refrigerant is 39.17kJ/kg, with a COP of 4.022. The R134a is the best alternative for HCFC refrigerants and is suitable for small applications. The evaporator and condenser pressures are 2.52 and 13.17 bar, which is lower than R22. R134a has a refrigeration effect of 145.53 kJ/kg, compressor work of 37.88kJ/kg, and COP as 3.79. The R410a which is preferred for commercial applications has the highest condenser and evaporator pressure of 6.96 and 30.9 bar. R410a produces a refrigeration effect of 160kJ/kg and requires a 50 kJ/kg of compressor work to operate with a COP of 3.2. The natural refrigerant R717 (ammonia) has the lowest operating pressures as 2.67 and 11.67 bar for condenser and evaporator, has the highest refrigeration effect of 1185 kJ/kg for the compressor work of 234kJ/kg, it operates with a COP of 5.064.

The R22 is an ideal gas that has a lower pressure ratio and has low compressor work per kg of gas but has a very high ODP and GWP, which makes them not suitable for use. The R134a has less pressure ratio but has a lower latent heat of vaporization due to which its COP is lower than R22 and does not have ODP but has a high GWP. The R410a has a very high-pressure ratio, low latent heat of vaporization, and COP. The high-pressure ratio leads to increased cost of equipment and the refrigerant has high GWP, which is to be stopped from usage.

The ammonia has a comparatively high theoretical COP among the four refrigerants, its pressure ratio is also lower than the other refrigerants. But the work required to compress per kg of refrigerant is four hundred percent higher than the currently used refrigerants. Since the temperature after throttling is minus 12°C, much lower than other refrigerants, reduces the mass of refrigerant required to circulate in the refrigeration loop. The reduction of mass by 90 percent reduces the compressor work required for 1 TR to 0.69 KW, whereas the work required for R134a and R410a is 0.92 kW and 1.09 kW.

5.1 Energy savings and reduction in CO2

It is forecasted that in 2050 the cooling refrigeration systems will be consuming 7700TWh globally[11]. An analysis is carried out to estimate the power saving and reduction in CO2 if all the cooling systems which would be operating with R134a Case I and R410a case II are replaced with R717 and are given in figure 6-10.

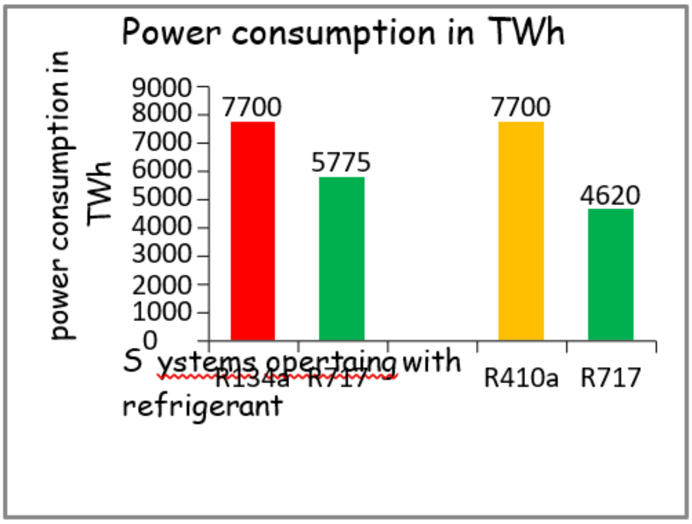

Fig. 6. Power consumption comparisons between refrigerants.

Figure 6 shows the energy requirement for cooling refrigeration systems of R134a, R410a, and if replaced with ammonia. In comparison to R134a and R410a, operating the systems with ammonia reduces energy usage by 1925 TWh and 3080 TWh, respectively. The energy thus minimized will be savings at the user end.

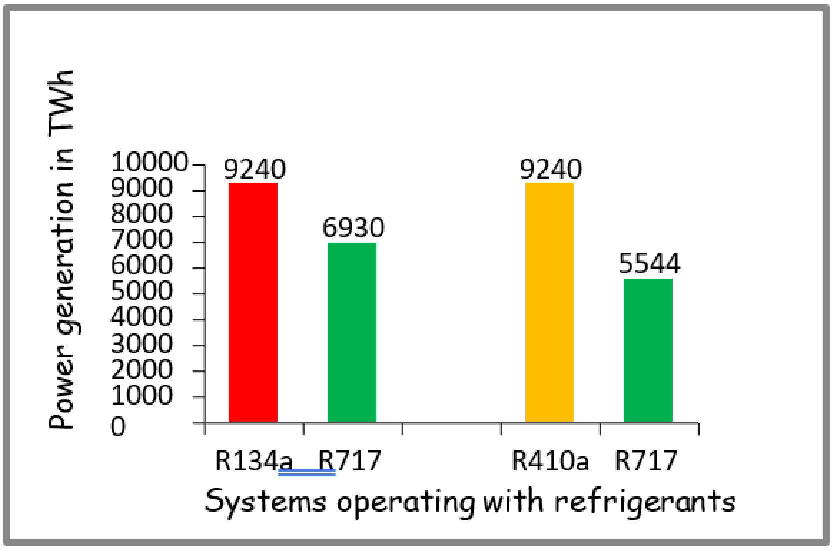

Fig. 7. Power to be generated for cooling systems.

For every 1 kWh of power to be supplied to the customer, the generation stations have to generate 1.2 kWh to account for the transmission and other losses [14]. Thus, according to the forecast, if 7700 TWh of power is required at the user end, 9240 TWh of power is to be generated at power stations. For the same tons of refrigeration cooling if ammonia is used instead of R134a, 6930 TWh of power, if produced, will be sufficient and in the case of R410 replaced by ammonia 5544 TWh of power will satisfy the need. Ammonia systems can minimize and reduce the load on power stations by 25% and 40% respectively for R134a and R410a.

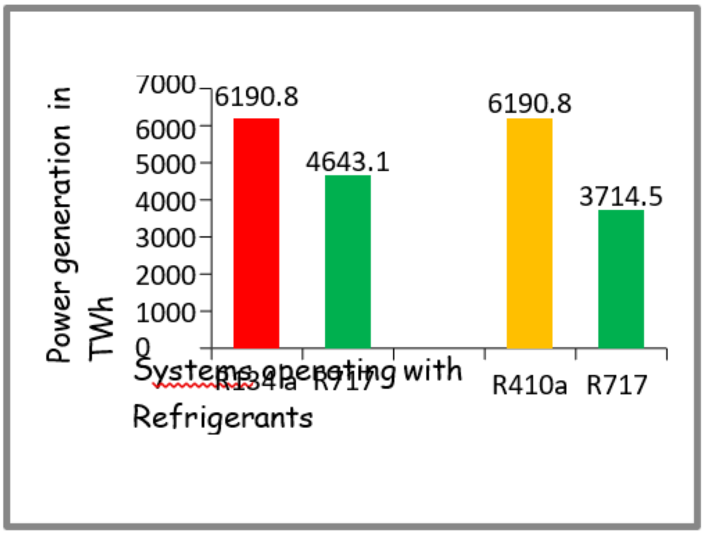

Fig. 8. Power produced from thermal sources.

According to the International Energy Agency report, the 67percent of total power produced globally is through combustible fuels. These fuels when combusted will produce CO2 emissions. Figure 8 gives the details about the share of energy consumed by refrigeration systems that are produced from thermal sources of power generation. Ammonia refrigeration cooling system may reduce the power generation to extend of 1546.9 and 2476.3TWh if replaced for R134a and R410a. The total power generation by the National Thermal Power Corporation (NTPC) plants of India for the period of 2020-2021 is about 2900 MU [22]. Many of the thermal plants can be completely shut down due to the energy saved by ammonia refrigeration systems or can be the power generated from thermal sources can be utilized for high production applications.

Chakraborty et.al had experimentally found that the average CO2 emission from various thermal power plants is about 0.998kg /kWh. Similarly, Mittal et.al had estimated the emission from thermal power plants are in the range of 0.91 to 0.95 kg /kWh in India. Indian thermal plants are modernized periodically and operate with the best standards globally[23]. Hence the global co2 emission from thermal plants can be considered regarding Indian emissions standards. By the Kigali agreement, 198 member countries had agreed to reduce 80 billion metric tons of carbon dioxide equivalent emissions by 2050 [19]. C02 emissions from thermal power plants cannot be stopped but can be reduced if the electrical power generation is reduced. Figure 8 gives the savings in power utilization based on ammonia refrigeration.

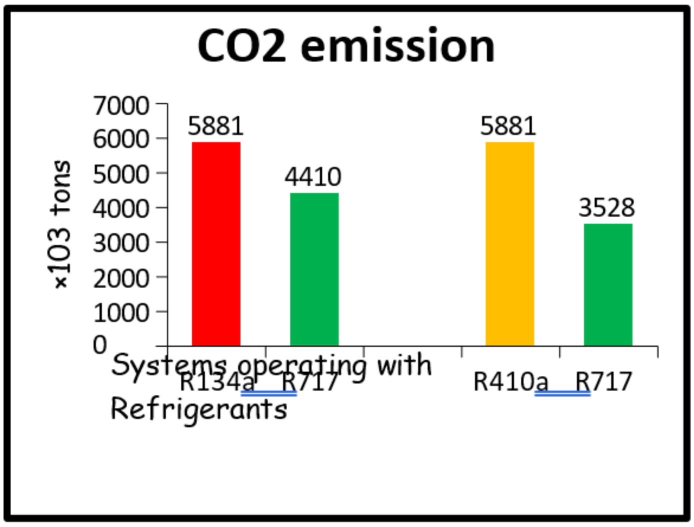

Fig. 9. CO2 production for different refrigerants based on energy consumption

Figure 9 describes the emission of CO2 due to the energy generation from thermal power plants for the power required for cooling systems operating with R134a, R410a, and ammonia refrigerants by 2050. It is evident from the above like power generation CO2 also reduces to 25 per cent and 40 percent when altered with ammonia. The CO2 emission from one application source is so substantial, which can be controlled and contained if proper action is taken.

5.2 Ammonia and its drawbacks

The main problem with ammonia is its toxicity. The U.S. Public Health Service's Agency for Toxic Substances and Disease Registry (ATSDR), as published in the IIAR Ammonia Data Book, shows the effects of various concentrations of ammonia.

Table 5. Concentration and Effects.

Concentration	Effect
5 ppm	Average odor threshold (well below harmful health effects)
100-200 ppm	Irritated eyes
300 ppm	Respiratory Protection Required above this level – IDLH
400 ppm	Immediate throat irritation
500 ppm and below	No permanent eye damage to even chronic exposure
1,700 ppm	Cough
2,400 ppm	Threat to life after 30 minutes
5,000+ ppm (vapour)	Full body chemical suit required
5,000+ ppm (pure liquid)	Second degree burns with blisters
7,338 ppm	One hour L_{50} lethal concentration (rat)

The National Institute for Occupational Safety and Health (NIOSH), in its 2007 Pocket Guide2, has set the Immediate Danger to Life or Health (IDLH) level, the level at which an individual could be exposed for 30 minutes without a respirator and not experience any lasting health effects, at 300 parts per million. The purpose of IDLH is to establish when the maximum level of respiratory protection is required by OSHA regulations. Ammonia's sharp, irritating, pungent odour helps reduce exposure to potentially dangerous concentrations. The average odour threshold is 5 ppm3, well below concentrations that may cause harmful effects to the human anatomy [19].Thus, up to a 500ppm limit, ammonia is still breathable and is detectable in case of a leakage. From the above, the maximum concentration of ammonia in a cubic meter can be up to 700mg/m3. A 1TR ammonia system will have 3-4kg of ammonia gas in the system. Any leakage inside the conditioned space will lead to serious causalities, therefore, the system should have very good active safety systems. The safety systems may include a warning alarm, a rapid emergency ventilation system, an ammonia vapour scrubber on the exhaust of the ventilation system etc. In case of any leakage, these systems can be activated and ammonia gas can be safely discharged to the atmosphere. As ammonia has a natural decomposition cycle, it easily gets absorbed by the environment and takes part in the natural nitrogen cycle. Operation of ammonia chillers requires similar skills as for HFC chillers, combined with additional ammonia safety awareness. Maintenance, in particular when opening the refrigerant circuit, needs to be done by trained specialized technicians [24].

5 Conclusion

The requirement for energy for cooling applications will increase extensively due to global warming and climate change. The refrigerants used for cooling application on one side will contribute to global warming and on the other side leads to environmental pollution by observing more power. Ammonia, the natural refrigerant plays as a better option for HCFC and CFC refrigerants in reducing the ODP and GWP. Also, ammonia has higher COP, which in turn reduces the energy generation by up to 40 percent. The reduction in energy generation will lead to reduced emissions. The reduction in CO2 will be beneficial in containing the temperature rise. Ammonia even though used in the industrial environment, has to mature to be used in the domestic environment.

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