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Kibria, Mohammad Tawheed

Kyushu University Program for Leading Graduate School, Green Asia Education Center, Kyushu University

Islam, Md. Amirul

Kyushu University Program for Leading Graduate School, Green Asia Education Center, Kyushu University

Saha, Bidyut Baran

Kyushu University Program for Leading Graduate School, Green Asia Education Center, Kyushu University

Nakagawa, Takeshi

Kyushu University Program for Leading Graduate School, Green Asia Education Center, Kyushu University

他

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Assessment of Environmental Impact for Air-Conditioning Systems in Japan Using HFC Based Refrigerants

Mohammad Tawheed Kibria^{1,2,*}, Md. Amirul Islam^{1,3}, Bidyut Baran Saha^{1,3}, Takeshi Nakagawa^{1,2}, Seigi Mizuno^{1,2}

¹Kyushu University Program for Leading Graduate School, Green Asia Education Center, Kyushu University, Kasuga-Koen 6-1, Kasuga-Shi, Fukuoka 816-8580, Japan

²Interdisciplinary Graduate School of Engineering Sciences, Department of Molecular and Material Science, Kyushu University, Kasuga-Koen 6-1, Kasuga-Shi, Fukuoka 816-8580, Japan

³International Institute for Carbon-Neutral Energy Research (WPI-I²CNER), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

*Author to whom correspondence should be addressed,

E-mail: kibria.tawheed@kyudai.jp

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Air-conditioning system notably contributes to global warming owing to the huge amount of energy consumption. Moreover, this system uses HFC based refrigerants, which have high global warming potential (GWP). This work investigates the direct and indirect impacts of GWP for commercial and residential air-conditioning systems considering the three widely used HFC based refrigerants. The warming impacts are assessed in terms of cooling load, co-efficient of performance (COP), evaporation temperature, and condensation temperature for three different locations in Japan. The indirect emission of the air-conditioning systems (commercial and residential) for different major cities of Japan is estimated in terms of energy demand and hours of operation. The results of this work indicate that the HFC based refrigerants such as R134a and R32 have lower warming impact compared to that of R410A refrigerant. Furthermore, the economic loss due to refrigerant leakage is also assessed.

Keywords: Air-conditioning system; COP; GWP; HFC; TEWI.

1. Introduction

The air-conditioning systems have a significant impact on the residential and commercial usages for space heating and cooling requirements all over the year¹⁻³. The refrigerants used in the air-conditioning systems predominantly contribute to direct and indirect global warming impact^{2,4,5}. The appropriate choice of the refrigerant is crucial for a minimum contribution to global warming. The refrigerants should have to fit with the following requirements: environmental acceptability, chemical stability, materials stability, refrigeration-cycle performance, adherence to non-flammable and nontoxic guidelines, boiling and evaporation point, critical points⁶. For hundreds of years, Carbon dioxide (CO₂) is the prime candidate to contribute to greenhouse gases.

On the other hand, refrigerants based on chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC) and currently used hydrofluorocarbons (HFC) have much higher Global Warming Potential (GWP)

than CO₂^{2,4-6}. Moreover, this CFC and HCFC based refrigerants are responsible for ozone layer depletion (ODP)^{2,5-8}. Hence, the current scenario demands a chlorine-free substance for cooling applications.

In Japan, the annual electricity consumption of each house for cooling and heating purposes is approximately 0.7 and 1.2 GWh, respectively⁹. The electricity used for operating the air-conditioning unit primarily comes from fossil-fuel based power plants¹⁰. The fossil-fuel based power plants are accountable to free global warming gases¹¹. According to the World Bank, CO₂ emission of Japan was 9.5 metric tons per capita until 2014¹². The statistics of per capita CO₂ equivalent emission is estimated to be 1.1 t/year globally, which can be reduced by harvesting sustainable energy such as fuel/ hydrogen cell¹³⁻¹⁵. For the use of the clean fuel based residential and commercial air conditioning system, assessing the environmental impacts of the current refrigeration system is inevitable. Refrigerant leakage is a serious source of emissions in the case of the household air conditioning systems. The refrigerant

leakage has a direct impact on global warming ^{16,17}.

To minimize the global warming impact and reduce energy consumption, several refrigerants have the potentiality. Among those refrigerants: R134a, R32 and R410A refrigerants have been assessed. R410A and R134a are chosen for the assessment because those are used in most of the household and office buildings cooling systems. Moreover, R32 refrigerant is recently invented and has the minimum GWP (675) among these three refrigerants ⁴. On the other hand, thermodynamic properties of R32, R134a and R410a are different. Hence, coefficient of performance (COP), leakage rate, and other important parameters are also different which have a significant impact on TEWI ^{4,17,18}. According to these reports, we calculate the total equivalent warming impact for R134a, R32 and R410A refrigerants, respectively.

2. Assessment Procedure

2.1 System Description

A schematic of a typical household cooling system is shown in Fig. 1. In the cooling system, the refrigerant evaporates and boils inside the evaporator and changes from the liquid phase to the gas phase. During the phase change, it collects latent heat from the surroundings and cools the space. This vaporized refrigerant flows through the compressor for compression at high pressure. Hot and high pressure vapor refrigerant discharges from the compressor discharge line and feeds into the condenser coil. The hot gaseous refrigerant releases the heat to the air and changes to liquid. The discharged refrigerant at the output of the condenser is high-pressure liquid. This high-pressure refrigerant flows through the expansion valve and reaches to the evaporator coil again and the refrigeration cycle repeats until it reaches to the target temperature ¹⁹.

2.2 TEWI Definition

The term “Total equivalent warming impact (TEWI)” is used to express contributions to global warming. TEWI facilitate to estimate the equivalent greenhouse gases emissions into the atmosphere from system leakage (direct emission) and energy consumption (indirect emission). The TEWI is represented by the summation of the direct and indirect discharged greenhouse gases from the system.

Total equivalent warming impact can be summarized by the following equation ²⁶.

$$TEWI = \underbrace{(GWP \times LR \times n)}_{Direct} + \underbrace{(E_a \times \beta \times n)}_{Indirect} \quad (1)$$

- GWP* : Global warming potential of the selected refrigerants (kg CO₂ eq/year)
LR : Annual leakage rate (%)
n : Number of years
E_a : Annual electricity consumption (kWh)
β : CO₂ emission factor for per kW electricity generation (kg CO₂ eq)

2.3 Assumptions

Operating conditions and relevant assumptions for household/ office cooling systems are shown in Table 1. The cooling load has been considered 5 kW for residential air-conditioning system because a typical sized-room can be cooled with that cooling capacity.

In summer, a typical outdoor temperature between 30 to 35°C. Hence, the condensation temperature is usually considered 5-10°C higher than the typical outdoor temperature so that the refrigerants can release heat. For simplifying the assessment, a constant condensation temperature of 40 °C is considered in this analysis.

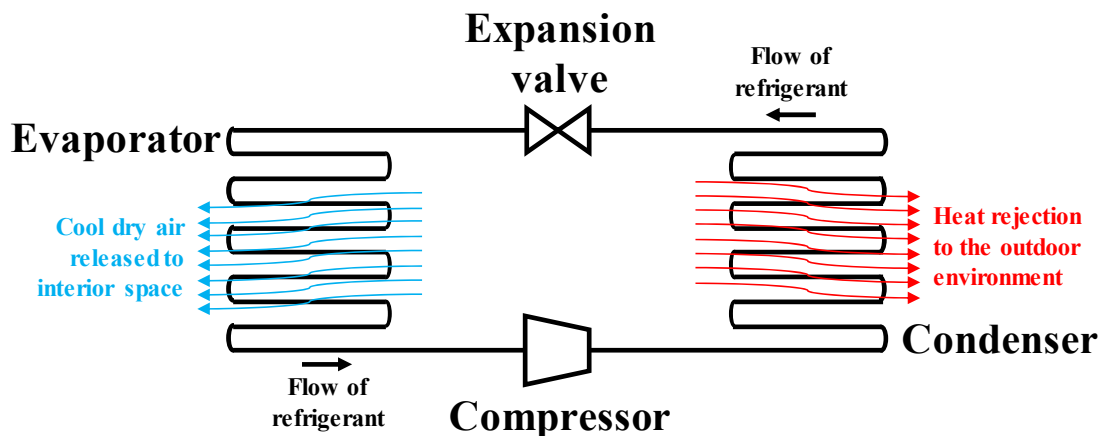


Fig. 1: Simplified schematic diagram of a household air-conditioning system.

Generally, residential air-conditioning system usage is higher in weekends than working days. Besides, commercial air-conditioning is barely used in the holidays. Hence, the usage is 56 hours per week for a residential system and 40 hours for commercial office buildings.

The refrigerants R134a and R32 are commonly used in the residential systems. Whereas, R410A is deployed as a working fluid for heavy usage such as central air-conditioning system in commercial buildings. Hence, these three refrigerants are selected for the current analysis.

Leakage of refrigerants usually depend on the operating conditions, specially the discharge pressure of the refrigerant from compressor outlet. Leakage rates of the selected refrigerants are assumed according to the thermodynamic property in the operating region.

Electricity production sources in Japan is mainly fossil fuel based which emits 0.56 kg CO₂ for per kWh electricity generation.

Required amount of refrigerant for a system is dependent on the cooling capacity, evaporation temperature, types of refrigerants and so on. However, for simplicity we considered initial charging amount is 1 kg of refrigerants for per kW cooling load.

Table 1. Conditions for TEWI assessment.

| | |
|--|--|
| Cooling load (at $T_{eva} = 15^{\circ}\text{C}$) | 5 kW |
| Condensation temperature (T_{con}) | 40°C |
| Suction gas superheat | 5 K |
| Liquid subcooling | 3 K |
| Operation Time | 56 hrs/week (residential) 40 hrs/week (commercial) |
| Refrigerants | R134a, R32 and R410A |
| GWP values of the refrigerants (kg CO ₂ eq/kg) | R134a: 1430; R32: 675; R410A: 2088 ⁶⁾²⁰⁾ |
| Annual leakage rate | R134a: 12%; R32: 15%; R410A: 20% ²¹⁾ of IC ^a |
| GWP for electricity production in Japan | 0.56 (kg CO ₂ eq/kW-hr) ^{22,23)} |
| Initial refrigerant charging amount (kg per kW cooling load) | 1 kg ²⁴⁾ |
| Refrigerant price (\$/kg) | R134a - 22 \$/kg ¹⁸⁾ , R32 - 24 \$/kg, R410A - 15 \$/kg ²⁵⁾ . |

^aIC: Initial charge

The price of the selected refrigerants is obtained from the refrigerant manufacturers to estimate the economic loss due to refrigerant leakage from the system.

2.4 Assessment of TEWI

From the definitions of TEWI, the estimation of the co-efficient of performance (COP), the indirect and direct emissions for the several refrigerants R134a, R32, R410A, are explained below:

2.4.1 Co-efficient of performance (COP)

The performance of the air-conditioning system is expressed by COP,

$$COP = \frac{\text{Cooling capacity}}{\text{Work input or electricity consumption}} \quad (2)$$

2.4.2 Direct emission

The direct release of the GHG gases to the atmosphere from the different equipment and processes are the direct emissions. Leakage of the refrigerant is the prime source of the direct emission considering household air-conditioning system ²⁶⁾. Refrigerant leakage might happen during the manufacturing process, when in operation or during the maintenance and servicing. Earlier literature reported that about 10-20% refrigerant is leaked and refilled every year ²¹⁾. Moreover, the type of refrigerant and operating conditions influences the leakage rate ^{18,21,27)}. The leakage rate for particular refrigerant and initially charged amount of refrigerant can be used for the calculation of direct emissions by using the equation (1).

2.4.3 Indirect emission

In an air-conditioning system, the compressor efficiency, system design, thermodynamic transport and heat-transfer properties of the refrigerant could affect the overall performance of the system. Indirect emission is a function of the efficiency of any parts of the entire system. Indirect emission might cause a greater effect on TEWI compared to direct emission ⁶⁾.

The indirect emissions of the R134a, R32 and R410A, are calculated from the P-h refrigeration cycles of specific air-conditioning system (Fig. 2). The refrigerant's thermodynamic properties are obtained from the REFPROP v.9.1 ²⁸⁾. In general, the air-conditioning system has the superheating and the sub-cooling phase to compress the vapour and to evade the refrigerant flashing. The COP of the refrigeration system can be determined from the refrigeration cycle of Fig. 2.

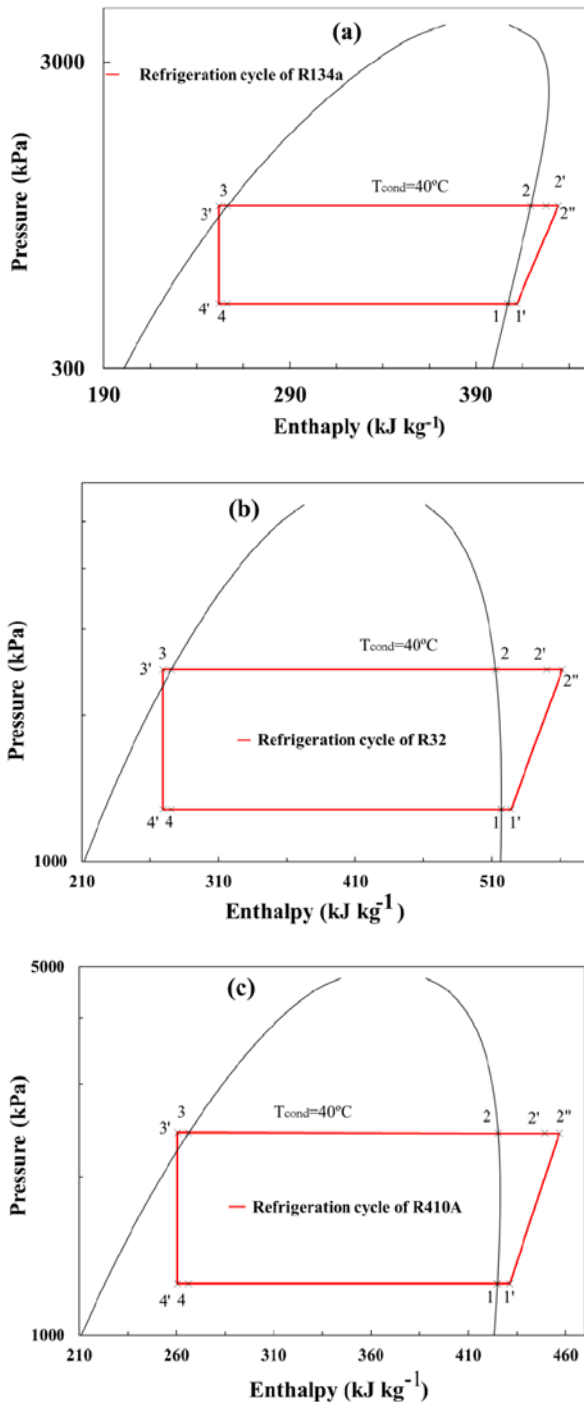


Fig. 2: P-h diagram of the refrigeration cycles for (a) R134a, (b) R32 and (c) R410A with suction superheating and liquid subcooling. 4'-1: evaporation; 1-1': suction superheating; 1'-2': compression; 2"-3 condensation; 3-3': liquid subcooling; 3'-4': expansion.

3. Results & Discussions

3.1 Direct emission

Annual direct emission is dependent on the leakage of refrigerant, which is shown in Fig. 3. The direct

emission for R134a, R32 and R410A is 0.86, 0.51 and 2.09 t eq CO₂/year, respectively. Among these refrigerants, the R410A has a significantly higher environmental impact due to its high GWP value.

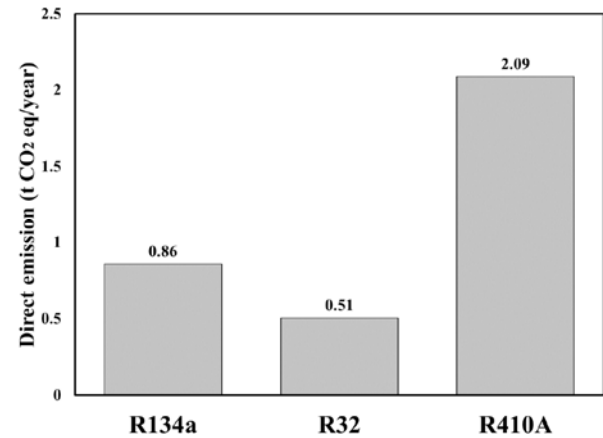


Fig. 3: Annual direct warming impact for different refrigerants.

3.2 Indirect emission

We have considered a cooling capacity of 5 kW and evaluated COP for each working fluid. COP values are compared in Fig. 4, which clearly indicate that the R134a system has the best performance. These COP values are used to assess electricity consumption and indirect emissions which are presented in Fig. 5. Annual indirect emission is evaluated for all the systems. The R134a showed the minimum indirect warming impact as compared to R410A and R32.

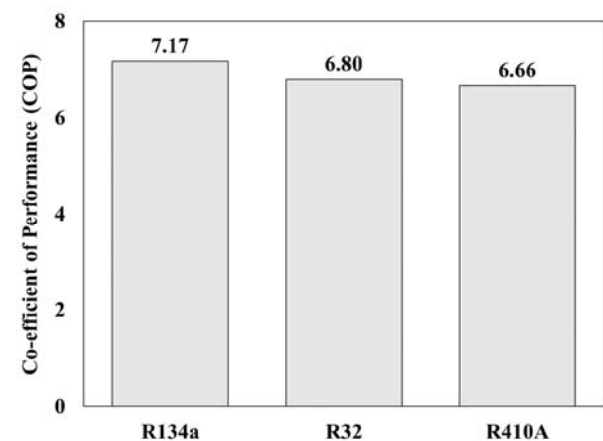


Fig. 4: COP value for HFC based refrigerants

3.3 TEWI

TEWI for the residential and commercial air-conditioning system has been assessed by aggregating direct and indirect emissions which are shown in Fig. 6. In both cases, R410A has the highest TEWI compared

to R134a and R32. The result shows TEWI of the R134a and R32 are in the range of 1 - 2 t eq CO₂/year for the commercial and residential air-conditioning system. The high GWP value of R410A accountable for higher TEWI.

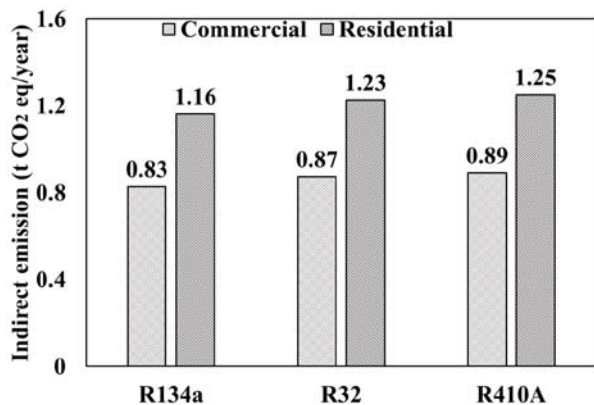


Fig. 5. Annual indirect warming impact for different refrigerants.

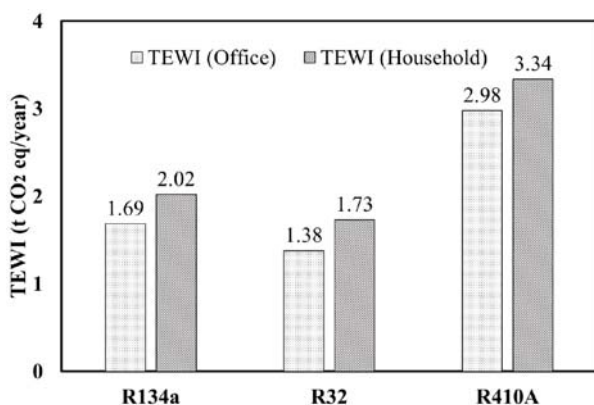


Fig. 6: Annual total equivalent warming impact for different refrigerants considering the individual air-conditioning system.

3.4 Economic loss

A certain percentage of the charged refrigerant is leaked every year and that amount needs to be refilled for uninterrupted operation of the cooling system. This refill amount is accounted for the economic loss every year. The economic loss is estimated considering the one unit with the cooling capacity of 5 kW. The refrigerant leakage is compared in Fig. 7 using R134a, R32, R410A.

According to the results, employing R134a as a refrigerant in the residential air-conditioning system might give a minimum economic loss compared to R32 and R410A refrigerants. The price and the annual leakage rate of the refrigerants affects the economic loss.

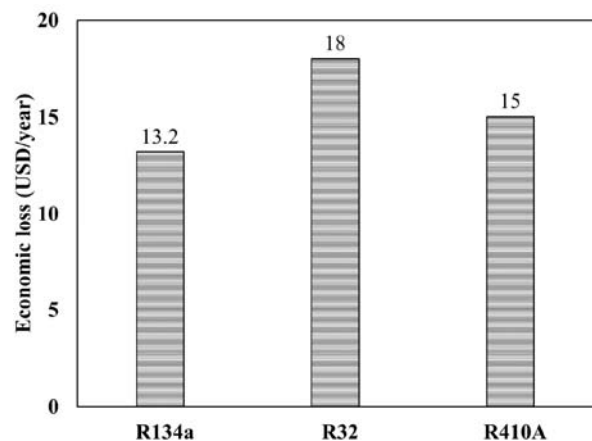


Fig. 7: Economic loss of individual air-conditioning system for R134a, R32 and R410A refrigerants.

3.5 Effects of leakage rate on direct emission, TEWI and economic loss

Direct emission is explicitly dependent on refrigerant leakage. In the analysis above, the leakage rate has been considered 12%, 15% and 20% for R134a, R32 and R410A, respectively. However, the actual leakage amount could vary. Hence, two other sets of leakage rate have been considered to observe the sensitivity of direct emission and TEWI with leakage rate. The result of the analysis is shown in Fig. 8. It can be seen that a 7% reduction of the leakage rate results in the reduction of 0.5 t CO₂ eq/ year for R134a refrigerant. On the other hand, 5% reduction of the leakage rate can reduce the total equivalent warming impact about 0.17 t CO₂ eq/ year for R32 refrigerants and 0.52 t CO₂ eq/ year for R410A refrigerants. The R32 refrigerant shows lowest TEWI change with compared to R134a and R410A. The variation in TEWI is due to the GWP values of the selected refrigerants.

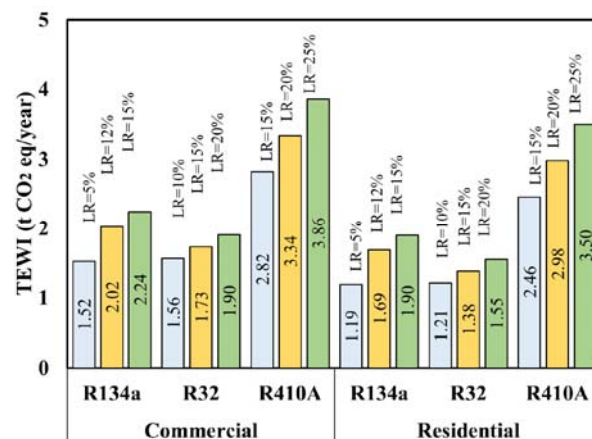


Fig. 8: Annual total equivalent warming impact for different refrigerants considering an individual air-conditioning system for different leakage rate.

4. Indirect emission of different locations in Japan

Indirect emissions at three major locations (Tokyo, Fukuoka and Hokkaido) of Japan have been estimated based on the electricity demand of those areas. These locations are selected due to their geographical locations and have a huge variation in weather and population density. Hokkaido is located in the north of Japan. Whereas, Tokyo is in the middle and Fukuoka is in the southern part of Japan. In 2014, *Koyama et al.* reported, Tokyo, Fukuoka and Hokkaido have the electricity demand of 4.67, 1.45, 1.03 GW, respectively. About 57 % of this electricity is used for domestic air-conditioning system³⁾. The indirect emissions of R134a, R32, and R410A refrigerants in Tokyo, Fukuoka and Hokkaido is presented in Fig. 9.

Evidently, the higher energy consumption for air conditioning system is responsible for higher indirect warming impact in the Tokyo region. The annual indirect emission in Fukuoka and Hokkaido is in the range of 150-350 kt CO₂ eq. every year. On the other hand, indirect emission in Tokyo is four times higher than other two regions. Annual indirect emission in Tokyo considering R134a, R32 and R410A and as refrigerants are 774, 833 and 817 kt CO₂ eq., respectively for the commercial air-conditioning system. The similar trend can be observed in the residential air conditioning system where R410A has higher indirect emission compared with other refrigerants. In Tokyo, for commercial air conditioning system, selection of R134a refrigerants can reduce the indirect emission of 58 kt CO₂ eq/year.

5. Conclusion

TEWI assessments have been conducted for the air-conditioning system (residential and commercial) by considering R134a, R32 and R410A as refrigerants. The results show that the R410A has a higher TEWI impact compared to R134a and R32 refrigerants. The LR (%) variation has a significant impact on TEWI for R134a, R32 and R410A refrigerants. Decreasing of the leakage rate of the R134a, R32 and R410A refrigerants could give smaller TEWI for the residential and commercial air-conditioning system. Moreover, the leakage rate is responsible for the economic loss because the amount needs to be refilled for the smooth operation of the system. Since, the price of R32 is higher than R134a and R410A, by using one of these refrigerants may give a higher economic profit compared to R32 refrigerant. Besides, a large indirect emission occurs in Tokyo compared to Fukuoka and Hokkaido due to higher air-conditioning demand. Indirect emission in Tokyo is three times higher than in the other two cases. This TEWI estimation addresses significant evidence to the

air-conditioning system manufacturer before choosing the refrigerant for a system.

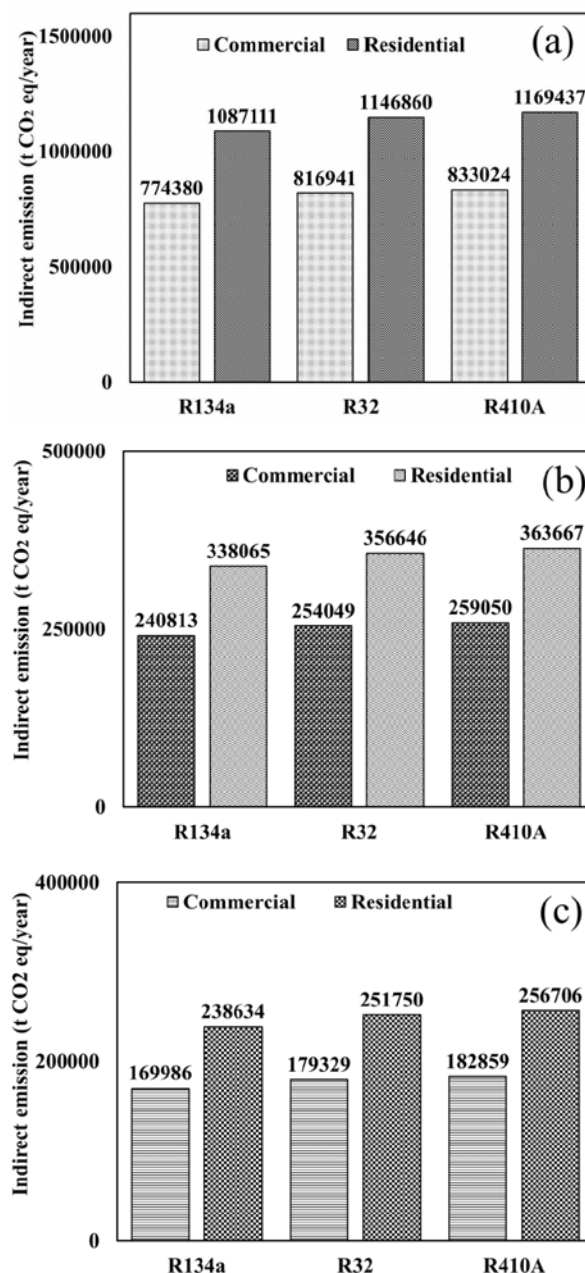


Fig. 9: Annual indirect emission of different refrigerants; (a) Tokyo; (b) Fukuoka; (c) Hokkaido.

Acknowledgements

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