Supplementary Information

Environmental Assessment of Natural and Fourth Generation Synthetic Refrigerant Blends for Sustainable Cooling in India

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Methodology:

Key performance indicators (KPI):

Evaluation of the initial replacement mixture based on volumetric cooling capacity (VCC), discharge line temperature (DLT) and condenser pressure (Pcond) must replace the refrigerant to ensure system compatibility. Other thermodynamic properties and performance criteria have been included to estimate the pressure ratio of the mixture, including NBP (PR), suction density (ρv), cooling effect (RE), capacity cooling per ton (PPTR) and coefficient of performance (COP) (1). These are promising mixtures that minimize NBP, PR and PPTR and maximize RE, ρv and COP. In addition, the energy efficiency improvement (ηII) was also evaluated with more information about the efficiency of the proposed mixture. These specifications are used to determine the compatibility of tight mixtures in the SS-VCRC cycle used with R744 and the mixtures may have KPI values equal to, lower than, or higher than those predicted by SAFT soft extreme for R744, depending on KPI.

Volumetric cooling capacity (Qv) and coefficient of performance (COP) are important parameters in the analysis and design of refrigeration systems. Volumetric cooling capacity is the amount of heat absorbed or extracted by the refrigerant per unit volume. It is expressed in units of energy per unit volume (e.g. watts per cubic meter).

$$\Delta Qv = \dot{m} \cdot \Delta H$$

In which:

• Qv is the volumetric cooling capacity.

• $\dot{m}$ is the mass flow rate of the refrigerant (kg/s).

• ΔH is the enthalpy change of the refrigerant during treatment (in J/kg).

Coefficient of performance is a measure of the efficiency of a refrigeration system. It is set differently for heating and cooling mode. The higher the COP, the more efficient is the cooling system. For refrigeration (cooling) systems, COP is calculated by:

$$COP=WQc$$

In which:

• COP is the coefficient of performance.

• Qc is the cooling capacity of the system “in watts”.

• W is the electrical power absorbed by the compressor (in watts).

The disaggregated energy consumption estimates for India’s cooling sub-sectors were developed using a bottom-up engineering approach consistent with methods reported by AEEE (2018), the India Cooling Action Plan (ICAP, 2019), and the UNEP–IEA Cooling

Emissions and Policy Synthesis Report (2020). Primary data inputs include:

- Equipment stock and sales from AEEE (2018) and BEE Star Label databases;
- Typical cooling capacities and efficiencies (EER/ISEER) from BEE, UNEP–IEA (2020), and manufacturer technical data;
- Annual operating hours derived from ICAP (2019) and climatic degree-day analyses for representative Indian cities;
- Sectoral growth rates and efficiency improvement factors from India Energy Security Scenarios (IESS, NITI Aayog) and AEEE (2018).

Calculation Approach

For each sub-sector i, annual electricity consumption (E_i) was estimated using the standard bottom-up formulation (AEEE, 2018; IEA, 2018):

$$E_i = N_i \times C_i \times \frac{1}{\mathrm{EER}_i} \times H_i$$

where

- N_i= number of installed units (stock),
- C_i= average cooling capacity (kW),
- EER_i= energy efficiency ratio (dimensionless), and
- H_i= equivalent full-load operating hours (h yr^{-1}).

Base-year (2017) stock and efficiency data were compiled from AEEE (2018) and BEE, while $H_i$values were assigned from ICAP (2019) and Khosla et al. (2021), representing typical residential and commercial duty cycles (≈ 1,000–1,500 h yr^{-1}).Projections to future years (2027 – 2087) applied sector-specific growth rates and technology-improvement factors from AEEE (2018) and IESS (NITI Aayog), maintaining internal consistency with the CAPEX and TEWI frameworks.

Validation and Sensitivity

Aggregate cooling electricity demand from the above method was cross-validated against national totals reported in ICAP (2019), CEA (2020), and UNEP–IEA (2020), showing agreement within ±10 %. Sensitivity analysis (±20 % variation in $H_i$and EER_i) indicated that while absolute values shift proportionally, the relative ranking of sub-sectors and comparative TEWI trends remain robust. This confirms that these trends are both realistic and reliable for scenario-based analysis of India's long-term cooling energy and emissions.

Environmental Impact and Economic Analysis

$$TEWI = \{GWP\cdot((L\cdot m\cdot n) + (m\cdot(1- \alpha)))\}_{Direct} + \{Ea\cdot\beta\cdot n\}_{Indirect} + AOP$$

$$CAPEX\ (\$ \cdot y^{-1})\ \Sigma C_k = (C_k \times \varphi / 3600 \times AOT)\cdot CRF$$

$$CRF= \{i(1 + i)^n / (1 + i)^n -1\}$$

$$Enviro\ (\$ \cdot y^{-1})\ C_{env}= m_{CO2eq.} \times C_{CO2} = (\beta\times Ea) \times C_{CO2}$$

where,

AOT is the Operational hours in a year

AOP is the Atmospheric Oxidation Potential

TEWI is the Total Equivalent Warming Impact (tCO_2eq)

C_{CO2} Unit cost of CO_2 avoided ($US\$\cdot kgCO_2eq^{-1}$)

C_{env} is the Penalty cost rate of CO_2 emissions ($US\$\cdot y^{-1}$)

ΣC_k Capital and maintenance cost rate ($US\$\cdot y^{-1}$)

φ Maintenance factor

i Annual interest rate

L Annual leakage rate

n System lifetime (y)

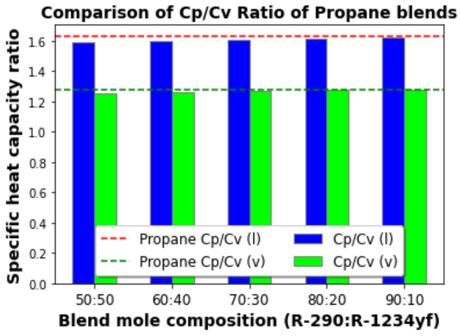
m Refrigerant charge load (kg)

β Indirect emission factor ($kgCO_2eq\cdot kWh^{-1}$)

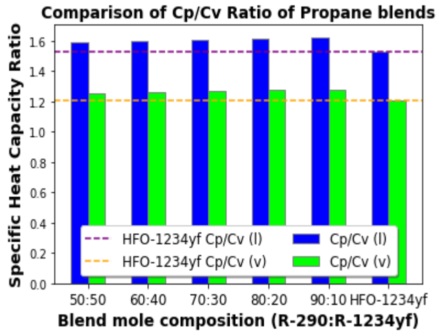
Ea Yearly energy consumption (kWh)

Table S1: Values of various parameters collected from literature

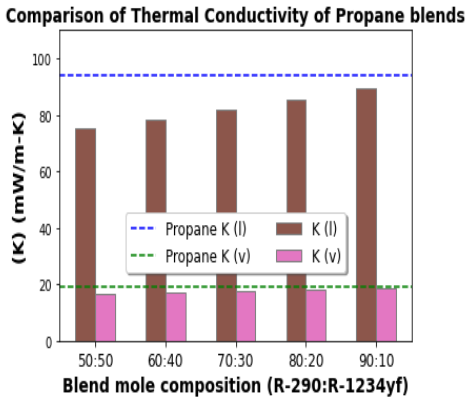
Parameter	Definition	Value	Source
AOT	Operational hours in a year	$8760 h.y^{-1}$	Alba et al., 2023
C_{CO_2}	Unit cost of CO_2 avoided	$0.087 US\$\cdot kgCO_2eq^{-1}$)	Adamson et al., 2022 Bamorovat and Kim, 2017
φ	Maintenance factor	1.06	Adamson et al., 2022; Karagoz et al., 2004; Fannou et al., 2015; Herediaet al., 2020
i	Annual interest rate	14%	Adamson et al., 2022; Karagoz et al., 2004; Fannou et al., 2015; Herediaet al., 2020
L	Annual leakage rate	12.5%	Wu et al., 2019
n	System lifetime	15Yr	Gimenez et al., 2022; Abas et al., 2018; Bolaji and Huan, 2013
m	Refrigerant charge load	1.2kg	Alba et al., 2023
β	Indirect emission factor	$0.7082 kgCO_2eq\cdot kWh^{-1}$	Alba et al., 2023
Ea	Yearly energy consumption	485.09kWh/yr	Siddegowda, 2019


Comparison of Cp/Cv Ratio of Propane blends
Specific heat capacity ratio
Propane Cp/Cv (l)
Propane Cp/Cv (v)
Cp/Cv (l)
Cp/Cv (v)
50:50
60:40
70:30
80:20
90:10
Blend mole composition (R-290:R-1234yf)

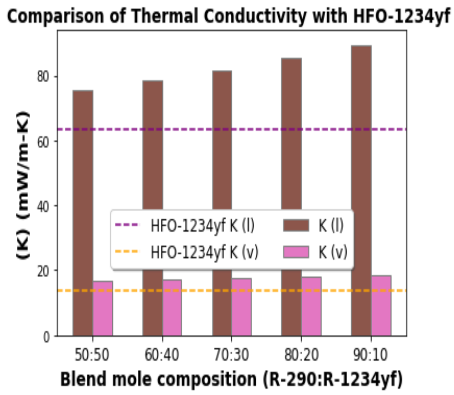
(a)


Comparison of Cp/Cv Ratio of Propane blends
Specific Heat Capacity Ratio
HFO-1234yf Cp/Cv (l)
HFO-1234yf Cp/Cv (v)
Cp/Cv (l)
Cp/Cv (v)
50:50
60:40
70:30
80:20
90:10
HFO-1234yf
Blend mole composition (R-290:R-1234yf)

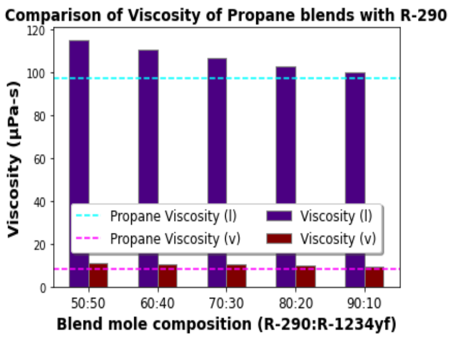
(b)


Comparison of Thermal Conductivity of Propane blends
(K) (mW/m-K)
Propane K (l)
Propane K (v)
K (l)
K (v)
50:50
60:40
70:30
80:20
90:10
Blend mole composition (R-290:R-1234yf)

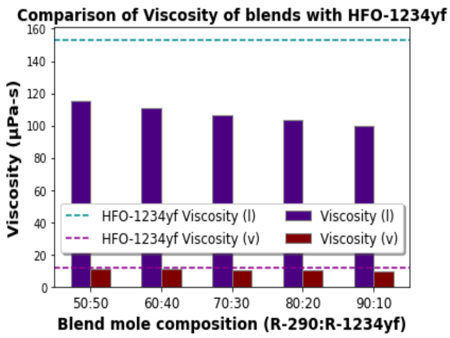
(c)


Comparison of Thermal Conductivity with HFO-1234yf
(K) (mW/m-K)
HFO-1234yf K (l)
HFO-1234yf K (v)
K (l)
K (v)
50:50
60:40
70:30
80:20
90:10
Blend mole composition (R-290:R-1234yf)

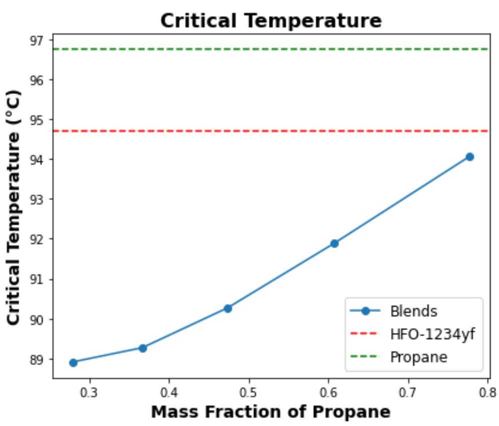
(d)


Comparison of Viscosity of Propane blends with R-290
Viscosity (μPa-s)
Propane Viscosity (l)
Propane Viscosity (v)
Viscosity (l)
Viscosity (v)
50:50
60:40
70:30
80:20
90:10
Blend mole composition (R-290:R-1234yf)

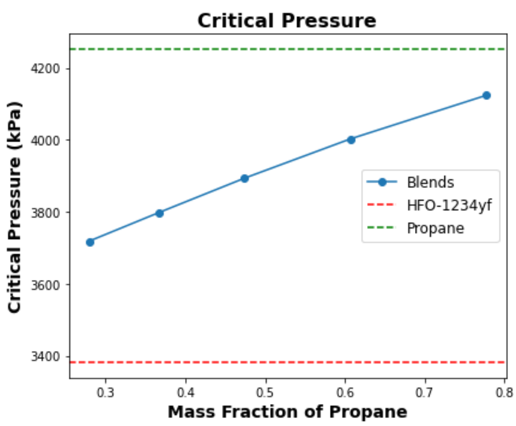
(e)


Comparison of Viscosity of blends with HFO-1234yf
Viscosity (μPa-s)
HFO-1234yf Viscosity (l)
HFO-1234yf Viscosity (v)
Viscosity (l)
Viscosity (v)
50:50
60:40
70:30
80:20
90:10
Blend mole composition (R-290:R-1234yf)

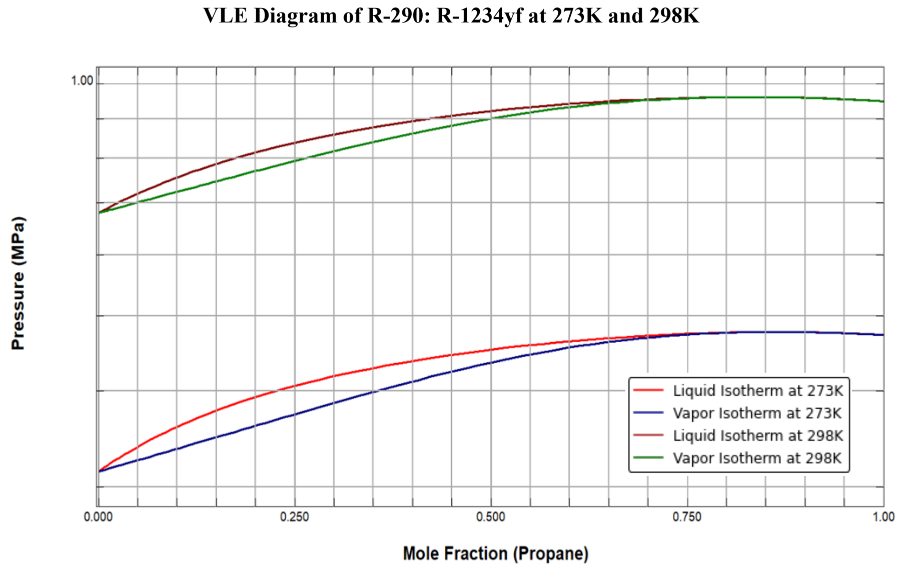
(f)


Critical Temperature
Critical Temperature (°C)
Blends
HFO-1234yf
Propane
Mass Fraction of Propane

(g)

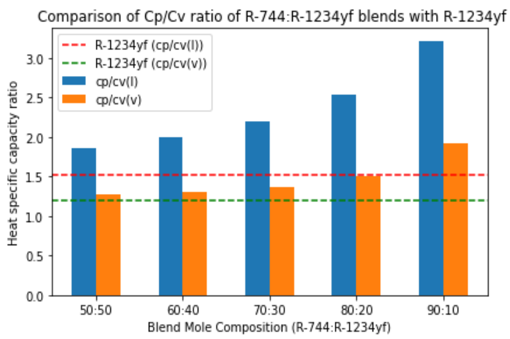

Critical Pressure
Critical Pressure (kPa)
Blends
HFO-1234yf
Propane
Mass Fraction of Propane

(h)

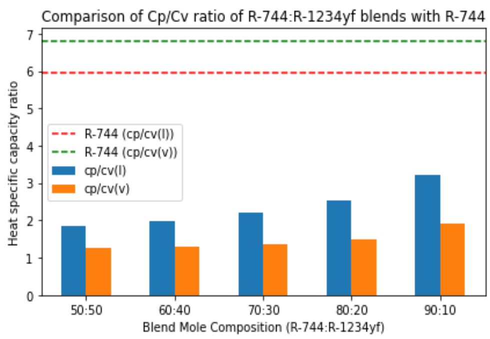


(i)

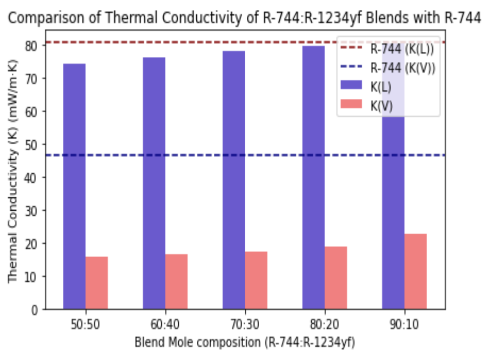
Figure S1. Thermodynamic properties of the R-290 and R-1234yf blends compared with their individual properties



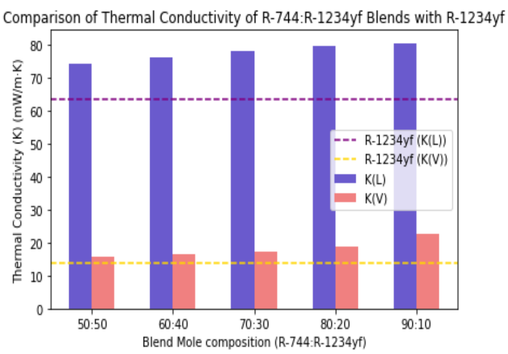
(a)



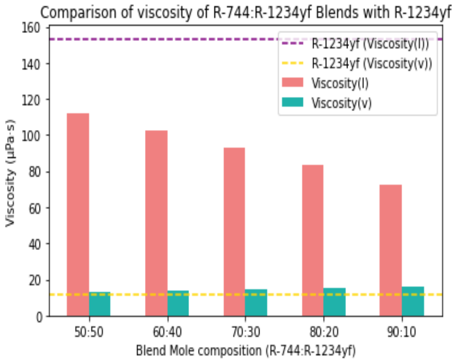
(b)



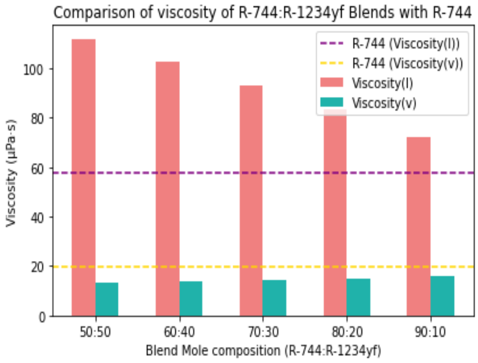
(c)



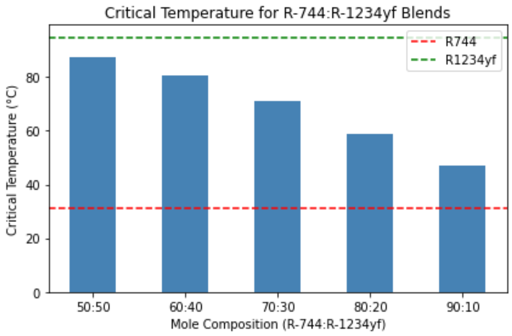
(d)



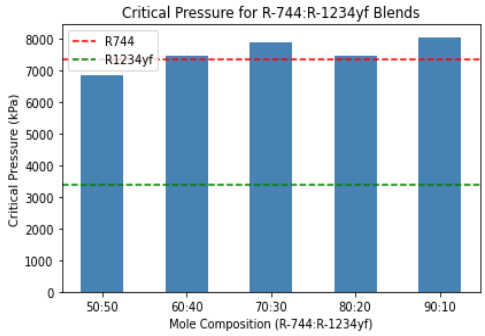
(e)



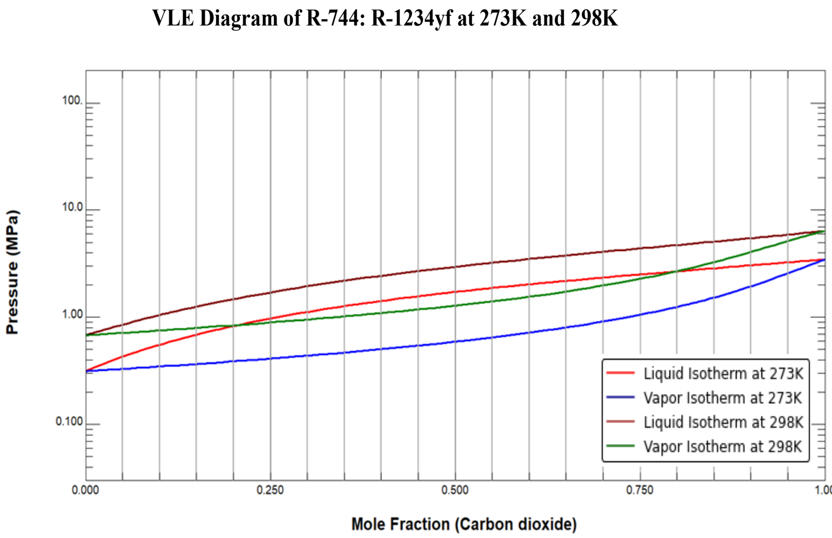
(f)



(g)



(h)



(i)

Figure S2. Thermodynamic properties of the R-744 and R-1234yf blends compared with their individual properties

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