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Supplementary Information for

The key role of propane in a sustainable cooling sector

Pallav Purohit[1*], Lena Höglund-Isaksson[1], Nathan Borgford-Parnell[2], Zbigniew Klimont[1], Christopher J. Smith[1, 3]

[1] Energy, Climate, and Environment (ECE) Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

[2] Climate and Clean Air Coalition (CCAC), United Nations Environment Programme (UNEP), Paris, France.

[3] Priestley International Centre for Climate, University of Leeds, Leeds, UK

* Pallav Purohit

Email: purohit@iiasa.ac.at

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Introduction

In this appendix, we include additional information about the methodology used for estimating the hydrofluorocarbon (HFC) emissions in the baseline and alternative scenarios and climate impacts in terms of the avoided warming. This section also provides more detail on the data that is used in scenario analysis and impact assessment. It is technically possible to avoid fluorinated gases (i.e., HFC-410A, HCFC-22, HFC-32) today in new single split-AC with a cooling capacity below 7 kW by using the refrigerant propane (R-290), unless national legislation or codes prohibit its use (1). Split-AC units using propane provide good energy efficiency (1-2) and are available at a very modest price increase that would likely disappear if mass produced and marketed at large scale. In this study, we present the case that the current use of HFC-410A can be replaced with propane in split-AC systems instead of HFC-32 which still have a significant warming effect as compared to propane. We model HFC emissions in split-AC units globally using the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model framework (3) and assess the warming impact while transitioning to propane-based split-AC units.

Life Cycle Climate Performance (LCCP)

To assess the environmental impact of refrigerants three commonly used environmental metrics are the Global Warming Potential (GWP), Total Equivalent Warming Impact (TEWI) and Life-cycle Climate Performance (LCCP). The GWP of a gas refers to the total contribution to global warming resulting from the emission of one unit of that gas relative to one unit of the reference gas, carbon dioxide, which is assigned a value of 1. TEWI is the sum of direct emissions (refrigerant) and indirect emissions (GHG emissions from power plants), while the more comprehensive LCCP measures the climate impact of cooling systems as the sum of direct, indirect and embodied GHG emissions generated over the lifetime of the system (4-5). While the direct emissions include the release of refrigerants into the atmosphere, including annual leakage and losses during service and disposal of the unit the indirect emissions are associated with the electricity powering the equipment, while embodied emissions stem from the refrigerant’s manufacturing process.

Few successful applications of the LCCP approach include the Society of Automotive Engineers (SAE)l approved standard J2766-200902 (GREEN-MAC-LCCP) (6), which was the basis for the industrial decision to shift from HFC-134a to HFO-1234yf rather than to other refrigerant candidates available at that time (7). Other studies focused on evaluating LCCP of different cooling technologies at different locations. For example, Li (8) evaluated various packaged air conditioners involving microchannel heat exchangers for typical US cities. Lee et al. (9) conducted an LCCP evaluation for the same heat pump system in five US cities. Choi et al. (10) developed an LCCP model and evaluated it for South Korean weather conditions. Botticella et al. (11) establish a multi-objective thermo-economic and environmental optimization of 5 kW residential space heating split system using LCCP. Kim et al. (12) applied a Neural Network algorithm to predict LCCP value using three different US weather conditions.

A recent study ref. (13) found that domestic unitary air conditioners (AC) using propane refrigerant have a lower LCCP than comparable units running with HFC-410A, HFC-32, HFC-466B and HFC-452B in 11 cities around the world. In countries where the carbon intensity of electricity generation – or the grid emission factor (GEF) – is low, the annual refrigerant leakage rate from appliances has the biggest impact on the LCCP. On the other hand, where the GEF is high, meaning more carbon-intensive power sources are deployed to generate electricity, the equipment’s energy performance had the greatest influence on the LCCP value.

Modeling HFC emissions

Figure 1 (a) presents the stock of split air-conditioners by country/region (14). In this study, we have used the stock of split air-conditioners to assess the total refrigerant consumption using an average capacity of 5.7 kW of the split-AC and refrigerant charge of 0.25 kg/kW (15). As a next step, the fraction of HCFC in the total refrigerant use is identified from reported baselines of parties to the Montreal Protocol and modeled in consistency with the phase-out schedule of HCFCs in the latest revision of the Montreal Protocol (16) and including later baseline updates reported by the parties to the UNEP Ozone Secretariat and in the HCFC Phase-out Management Plans. Finally, HFC/HCFC emissions are estimated separately for "banked" emissions, i.e., leakage from equipment in use, and for "scrapping" emissions, i.e., emissions released at the end-of-life of the equipment using the GAINS methodology (17). In the baseline scenario, it is assumed that the currently used refrigerants viz. HCFC-22 and HFC-410A (a zeotropic mixture of 50% HFC-32 and 50% HFC-125) will be used in split-ACs. Following the Montreal Protocol, the use of HCFC-22 will be prohibited after 2030 in Article 5 parties (mostly developing countries) and the new equipment will use HFC-410A under the baseline scenario. The proportion of HFC-32 models in the entire global split-type room air-conditioning market including Japan and China is estimated to have reached over 40% in 2019 (18). Therefore, we have considered 40% share of HFC-32 based split ACs beyond 2020 under the baseline scenario. In addition, existing F-gas regulations at the national (i.e., USA, Japan) and regional levels (i.e., Regulation (EC) No 842/2006; Regulation (EC) No 517/2014) are also considered. In the alternative scenarios, we have assumed the substitution of HFC-410A by transitioning towards a) HFC-32 and b) propane in split-ACs.

Modeling climate impact

Figure 2 shows global mean temperature projections relative to the baseline HFC-410A scenario for the HFC-32 and propane substitution scenarios. Projections are derived from the FaIR climate emulator (19-20) v1.6.4, run using a probabilistic sample of 2,237 ensemble members that reproduce observed historical temperature change, ocean heat content change, and present-day CO_2 concentrations along with IPCC Sixth Assessment Report-assessed ranges of equilibrium climate sensitivity, transient climate response, carbon cycle metrics and aerosol radiative forcing (21). FaIR is an emissions-driven reduced-complexity climate model with a simplified representation of the carbon cycle, greenhouse gases, aerosols and atmospheric chemistry. These outcomes determine radiative forcing which is coupled to a two-layer energy balance climate response model. The model and configuration are identical to that used in the IPCC Sixth Assessment Report Working Group 3 (22) for assessing climate responses to integrated assessment model derived emissions pathways. An underlying emissions scenario of SSP2-4.5 is used, reflective of current global climate policy (23-14). We substitute the underlying emissions of HCFC-22, HFC-125 and HFC-32 from SSP2-4.5 with emissions from our pathways. We modify the emissions of total VOCs in SSP2-4.5 to include additional emissions of propane in the propane substitution scenario. Propane has a small GWP reflective of its small direct radiative effect, but a larger indirect climate effect due to its role as an ozone precursor. The direct radiative effect of propane (or other VOCs) is not modelled in FaIR but the contribution to ozone formation is, which contributes a small positive radiative forcing and warming. However, this warming from additional ozone is more than offset by the avoided warming by HFC phase-out, including in the short term.

Uncertainties in the projected warming pathways arise from uncertainties in effective radiative forcing and climate response, shown in Figure 2 as 5-95% ranges. No uncertainty is assumed for the emissions pathways. Avoided warming from the propane substitution scenario is 0.09 °C (0.06 – 0.12 °C 5-95% range) in 2100 relative to the HFC-410A baseline, and 0.03 °C (0.02 – 0.05 °C) for the HFC-32 substitution scenario relative to the HFC-410A baseline.

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