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EXECUTIVE COMMITTEE OF
THE MULTILATERAL FUND FOR THE
IMPLEMENTATION OF THE MONTREAL PROTOCOL
Eighty-third Meeting
Montreal, 27– 31 May 2019

SUMMARY OF THE REPORT BY THE TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL ON MATTERS RELATED TO ENERGY EFFICIENCY WITH REGARD TO THE ISSUES IDENTIFIED IN DECISION 82/83(e) (DECISION 82/83(f))

Background

1. At its 82nd meeting, the Executive Committee considered a document prepared by the Secretariat presenting a summary of the Parties' deliberations at the 40th Meeting of the Open-Ended Working Group (OEWG) of the Parties and the Thirtieth Meeting of the Parties to the Montreal Protocol in relation to the report by the Technology and Economic Assessment Panel (TEAP) on issues related to energy efficiency (EE).[1]

2. Subsequent to a discussion, the Executive Committee decided *inter alia*:

(e) To discuss, at its 83rd meeting, ways to operationalize paragraph 22 of decision XXVIII/2, and paragraph 5 and 6 of decision XXX/5, including:

(i) Initiatives associated with maintaining and/or enhancing the EE of replacement technologies with low- or zero-global-warming potential (GWP) in the refrigeration, air-conditioning and heat-pump sector (RACHP), such as:

a. Methodologies to quantify changes in EE; and

b. Technical interventions associated with maintaining and/or enhancing EE;

(ii) Cost-related issues such as associated incremental costs, payback opportunities and costs of monitoring and verification;

(iii) Possible environmental benefits, particularly those associated with climate; and

(f) To request the Secretariat to prepare, for consideration by the Executive Committee at its 83rd meeting, a summary of the report by the Technology and Economic Assessment Panel

[1] UNEP/OzL.Pro/ExCom/82/65 and Add.1

(TEAP) on matters related to EE with regard to the issues identified in sub-paragraph (e) above (decision 82/83).

An analysis of decision 82/83(e) and (f)

3. Decision 82/83(e) and (f) includes specific paragraphs of two decisions of the Meetings of the Parties:

(a) Paragraph 22 of decision XXVIII/2: To request the Executive Committee to develop cost guidance associated with maintaining and/or enhancing the EE of low- or zero-GWP replacement technologies and equipment, when phasing down HFCs, while taking note of the role of other institutions addressing energy efficiency, when appropriate;

(b) Paragraph 5 of decision XXX/5: To request the Executive Committee to build on its ongoing work of reviewing servicing projects to identify best practices, lessons learned and additional opportunities for maintaining EE in the servicing sector, and related costs; and

(c) Paragraph 6 of decision XXX/5: To request the Executive Committee to take into account the information provided by demonstration and stand-alone projects in order to develop cost guidance related to maintaining or enhancing the EE of replacement technologies and equipment when phasing-down HFCs.

4. Incorporating the text of the above-mentioned decisions, substantive coverage of the decision 82/83(e) and (f) would read as follows:

To request the Secretariat to prepare for the 83rd meeting, a summary of the TEAP Decision XXIX/10 task force report on issues related to EE while phasing down HFCs, so that the Executive Committee could discuss:

(a) The development of cost guidance associated with maintaining and/or enhancing EE of refrigeration, air-conditioning and heat-pump equipment when converting from HFCs to low- or zero-GWP technologies, which should:

(i) Include initiatives such as methodologies to quantify changes in EE and technical interventions associated with maintaining and/or enhancing EE;

(ii) Include associated incremental costs, payback opportunities and costs of monitoring and verification;

(iii) Include possible environmental benefits, particularly those associated with climate;

(iv) Take into account the information provided by the demonstration projects for the introduction of low-GWP technologies in Article 5 countries and the HFC stand-alone investment projects approved by the Executive Committee; and

(v) Take into account the role of other institutions addressing EE, when appropriate; and

(b) Maintaining or enhancing EE when phasing-down HFCs in the refrigeration servicing sector taking into account best practices, lessons learned and additional opportunities for maintaining EE identified from ongoing refrigeration servicing sector plans.

5. In light of the above, the Secretariat prepared the present document in response to decision 82/83(e) and (f).

Scope of the document

6. The present document consists of the following sections:

Section I	Summary that highlights the main aspects covered by the TEAP task force report in relation to paragraphs (e) and (f) of decision 82/83
Section II	Introduction to EE in the context of HFC phase-down and adoption of low- and zero-GWP technologies
Section III	Technical interventions associated with maintaining and/or enhancing EE
Section IV	Costs related issues, including associated incremental costs, payback opportunities and costs of monitoring and verification
Section V	Environmental benefits in terms of CO_2-equivalent
Section VI	Demonstration projects for the introduction of low-GWP technologies and HFC stand-alone investment projects
Annex I	Glossary of terms extracted from the TEAP task force report with a few additional explanations (this Annex is presented as an easy reference on terminology used in the document)

7. In line with decision 82/83(f), the information contained in the present document has been extracted from the TEAP Decision XXIX/10 task force report on issues related to EE ("TEAP task force report") while phasing down HFCs with some editorial changes.[2] A few editorial changes have been introduced, and clarifications and additional information have been provided based on inputs from an independent technical expert who reviewed this document. The sequence of the information contained in the present document does not follow that of the TEAP task force report. No information from other sources has been included as this was not requested under the decision.

8. The Executive Committee may wish to note that the following two documents fully addressed the requirements of paragraph 5 of decision XXX/5, and therefore matters related to the refrigeration servicing sector are not addressed in the present document:

(a) Preliminary document on all aspects related to the refrigeration servicing sector that support the HFC phase-down (decision 80/76(c)) (UNEP/OzL.Pro/ExCom/82/64); and

(b) Paper on ways to operationalize paragraph 16 of decision XXVIII/2 and paragraph 2 of decision XXX/5 of the Parties (decision 82/83(c)) (UNEP/OzL.Pro/ExCom/83/40).

9. The Executive Committee may also wish to note that document "Paper on information on relevant funds and financial institutions mobilizing resources for energy efficiency that may be utilized when phasing down HFCs (decision 82/83(d))" (UNEP/OzL.Pro/ExCom/83/41) addressed the role of other institutions addressing EE, and therefore, is not included in the present document.

[2] The TEAP task force report includes Annex A with information on sector specific challenges to the uptake of technologies. Most of the relevant information relating to Annex A is covered under Section III of the present document.

I. SUMMARY THAT HIGHLIGHTS THE MAIN ASPECTS COVERED BY THE TEAP TASK FORCE REPORT

10. Historically, the implementation of the Montreal Protocol has focused on the phase-out of ODS and alongside resulted in EE improvement of equipment and products[3]. During the transition to alternative refrigerants, the industry has made efforts to improve the design improvement of equipment and components affordable to the consumers and this effort over a period of time, has resulted in energy efficient products at lower inflation adjusted price of products. Air-conditioning systems are receiving increasing attention due to needs for refrigerant technology change and efforts are underway to optimise the systems and components for achieving energy-efficient cooling with new refrigerants. Factors including energy pricing and billing schemes and energy labelling play an important role in energy efficient technology adoption.

11. The largest potential for EE improvement comes from improvements in total system design and components, which can yield efficiency improvements (compared to a baseline design) that can range from 10 per cent to 70 per cent (for a "best in class" unit). Integrated approach to RACHP equipment design and selection that includes ensuring minimisation of cooling/heating loads, selection of appropriate refrigerant, use of high efficiency components and system design, ensuring optimised control and operation, under all common operating conditions and designing features that will support servicing and maintenance, can contribute to energy savings; this would result in reduced greenhouse gas (GHG) emissions over the life of equipment, reduced energy costs to the end-user and reduced peak electricity demand that would result in lower investments in power generation and distribution capacity.

12. Refrigerant selection is a trade-off between environmental benefits, safety, thermodynamic cycle efficiency, system design and reliability, and cost. The impact of refrigerant choice on the EE of the units is usually relatively small – typically ranging from +/- 5 to 10 per cent.

13. In relation to technical interventions for maintaining/enhancing energy efficiency, high ambient temperature (HAT) environment imposes an additional set of challenges on the selection of refrigerants, system design, and potential EE enhancement opportunities. At HAT, system designs which maintain energy efficiency are affected by the refrigerant choice due to thermodynamic properties, safety requirements due to the increased charge, and component availability and cost. Research at HAT conditions done so far has shown the viability of some low-GWP alternatives to deliver comparable EE results to existing technologies. Further research, as well as private sector efforts, continue to focus on the optimisation of design to achieve targeted efficiencies for those alternatives. The technical, financial, market, information, institutional/regulatory, service competency and other challenges along with the mitigation measures that can be undertaken are given in the report.

14. There are methods developed by various countries with established market transformation programs for promoting EE including minimum energy performance standard (MEPS) programmes and labelling programmes. A "snapshot" of the cost of efficiency improvement programme at any given time will tend to provide a conservative (i.e. higher) estimate of the cost of efficiency improvement. In actual practice, the prices of higher efficiency equipment have been found to decline over time in various markets as higher efficiency equipment begins to be produced at scale. This applies especially for small mass-produced equipment where manufacturers quickly absorb the initial development costs and try to get to certain "price points" that help them sell their equipment.

[3] The implementation of the Montreal Protocol has resulted in gradual improvement of EE; this has also happened before the Protocol was adopted. Further, implementation of the Montreal Protocol has in many cases accelerated EE improvement, as the change of refrigerant often also was an incentive to move to a higher technology level as a result of better product redesign.

15. Retail price of products is not an adequate indicator for the costs of maintaining or enhancing EE in new equipment due to bundling of various non-energy related features with higher efficiency equipment, variation of manufacturer's skills and know-how, variation in manufacturer's pricing, marketing and branding strategies, and the idea that efficiency can be marketed as a "premium" feature. Information on analysis of costs and payback period shows that a variety of factors influence the payback for equipment that could have higher initial costs and there is a ceiling of energy efficiency beyond which the payback from energy savings over lifetime of equipment is not attractive. Rigorous cost analysis may be needed to fully understand the impact of EE improvements. These types of analyses are relevant when setting MEPS as several EE levels need to be evaluated compared with the baseline. These studies can take more than one year to conclude for a single product category.

16. Information on capital and operating costs associated with transitioning to low-GWP options in standalone commercial refrigeration equipment, condensing units, centralised and distributed system and air-conditioning and heat-pump equipment as well as matrix of technical interventions to achieve higher EE and associated cost estimates shows that a range of factors affect overall costs of transition to alternative low-GWP refrigerants and improvement in energy efficiency. Operating practices play a significant role in energy efficient performance of equipment.

17. There are also a wide variety of co-benefits of improved EE in addition to lower energy costs to the consumer, avoided CO_2 emissions, and avoided peak load such as avoided mortality and morbidity caused by energy poverty, comfort benefits, avoided SOx, NOx and particulate matter emissions, and avoided CO_2 emissions in addition to direct economic benefits. For different operating environments and weather conditions, the CO_2 emission impacts can be different.

18. Detailed information on costs associated with monitoring and reporting of EE improvement is not available in the report, no information is presented in this document.

19. Finally, the document provides information available as of date, on demonstration projects for the introduction of low-GWP technologies while phasing-out HCFCs. Further, as the results of stand-alone investment projects for HFC phase-out approved in light of decision 78/3(g) are not available, a listing of these projects is provided.

II. INTRODUCTION TO EE IN THE CONTEXT OF HFC PHASE-DOWN AND ADOPTION OF LOW- AND ZERO-GWP TECHNOLOGIES

20. Historically, the implementation of the Montreal Protocol has focused on the phase-out of ODS and alongside resulted in energy efficiency (EE) of equipment and products[4]. The Multilateral Fund has provided financial and technical assistance to support Article 5 Parties in the achievement of their ODS phase-out targets.

21. While phasing out CFCs in the domestic refrigeration sector, CFC-12 was phased out to either hydrocarbon R-600a or HFC-134a. Initially HC blends had been used but this resulted in increased energy costs. R-600a, with better EE, then became the favoured option other than HFC-134a. HFC-134a with similar EE, but higher GWP, was limited to regions where concerns about flammability and related liability were significant market barriers.

22. The industry made great efforts to improve EE when transitioning from CFC-12, mainly through better compressor and system designs. The global best practice refrigerator in 2015 has GHG emissions that are nine times lower than a typical 1980s refrigerator sold in non-Article 5 countries. The domestic refrigerator market is highly cost-competitive and benefits from enormous economies of scale via mass

[4] The context has been explained in footnote to paragraph 10 of the document.

production. The cost of the high efficiency 2015 refrigerator is lower in real terms than the 1980s model (Figure 1[5]).

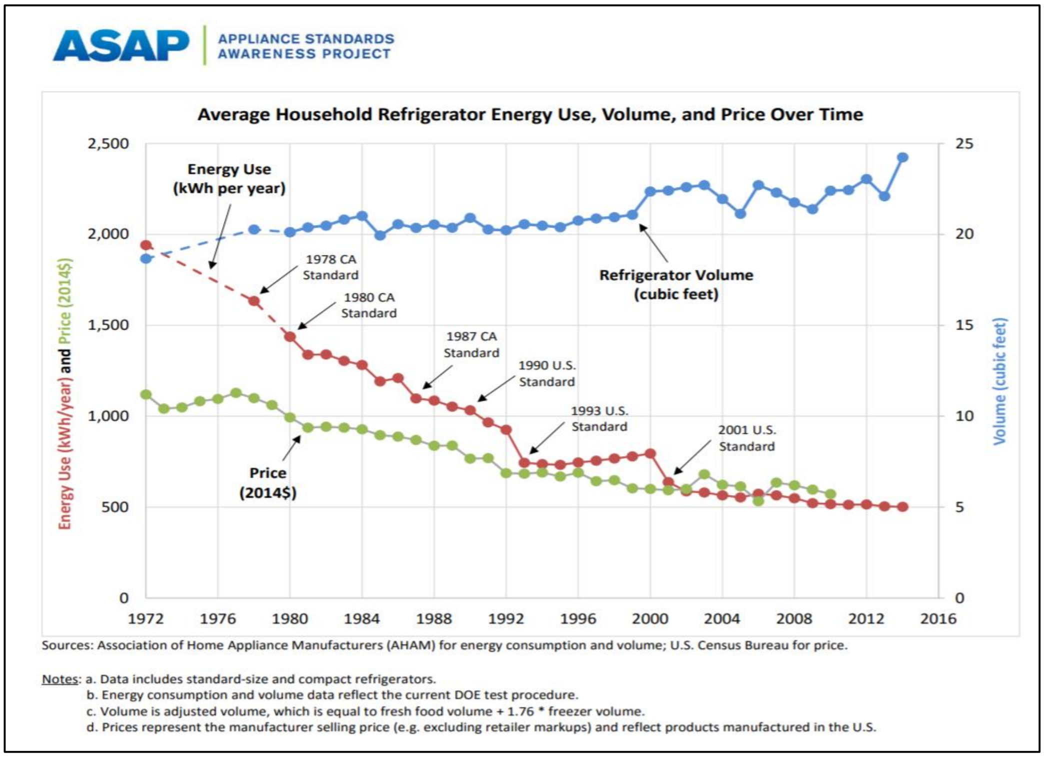

Figure 1. Average household refrigerator energy use, volume and price in the United States of America

23. The phase-out of HCFC-22 is still in progress in Article 5 Parties.[6] HFC-32 has been introduced in many countries. While R-290 has been introduced in a few countries, and offers an advantage in terms of EE, however, one major barrier for the use of R-290 in room air conditioners is the flammability rating which restricts its use.

24. The United States unitary air-conditioning equipment evolution since the 1970s has shown steady efficiency improvement while at the same time achieving cost effectiveness as shown in Figure 2. U.S. manufacturers have reduced the inflation-adjusted price of unitary air-conditioning equipment for residential central ducted air-conditioning systems (equipment costs only).[7] The trend of decreasing prices has been concurrent with the ODS phase-out, as well as periodically increased efficiency standards. The reasons for this trend are complex, including technological innovations and manufacturing efficiencies, as well as macroeconomic factors related to globalization of manufacturing and commodity price trends. The adjusted equipment price didn't increase following the introduction of the efficiency standards or the increase in the standards. Prices didn't react adversely with the ban of HCFC-22 in 2010.

[5] https://appliance-standards.org/sites/default/files/refrigerator_graph_Nov_2016.pdf
[6] HCFC-22 phase-out is largely in air-conditioning applications both manufacturing and servicing.
[7] The dotted green line depicts the Producer Price Index (PPI) while the blue line depicts the inflation adjusted PPI. The inflation adjustment is calculated by dividing the PPI series by the gross domestic product chained price index for the same years and normalize them to the year 2015.

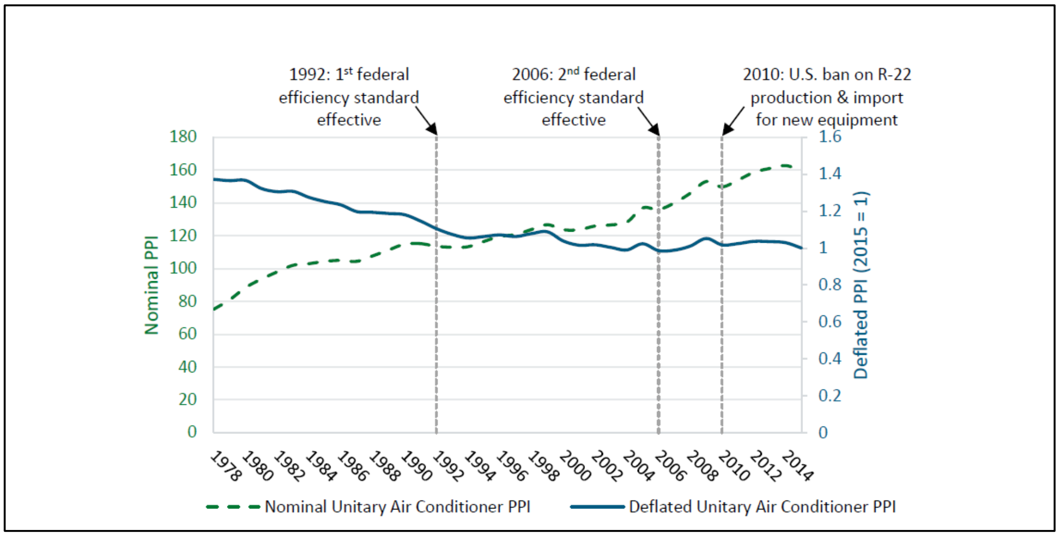

Figure 2. Residential central air conditioning equipment costs from 1978 to 2015 [Goetzler et al 2016]

25. Currently a wide range of room air-conditioners are being sold, with EEs that vary from very low to very high. The level of EE bears little relationship to capacity, or to purchase price [Shah et al., 2017, Kuijpers et al., 2018]. The optimization of performance of room air-conditioners requires attention to compressor, refrigerant charge and size of the heat exchanger. Studies with R-290, HFC-32 and HFC-161, compared to a HCFC-22 system, demonstrated that the energy efficiency ratio (EER) of the optimized room air-conditioners was within 10 per cent, irrespective of the refrigerant, whereas without full system optimization, the variations in EER exceeded 10 per cent.

26. In certain countries, air-conditioners consume up to 70 per cent of the generated electric power due to the excessive use of cooling almost all year round and for long hours. The public is aware of the burden that air-conditioning adds to their financial situation and hence could be more willing to welcome regulatory and other measures to lessen that burden through the use of more efficient systems which consume less power. This is not the case where utilities are subsidized, so that the cost of energy to the consumer is low, which removes any incentives for improving the EE of systems including those to be installed.

27. Another challenge is the billing scheme that utilities use for their residential, commercial, and industrial clients. Some countries use one billing rate across the hours of the day but increase the rate according to the consumption bracket. While this scheme can work reasonably well for residential customers, it penalizes large commercial/industrial customers operating larger, more efficient plants like district cooling if these plants are not taken in consideration.

28. Energy labelling of units and energy programmes are a step in the right direction. Most countries have energy labelling schemes for domestic air-conditioners and refrigeration units. One of the challenges of energy labelling and meeting energy standards in general is the testing and verification process to ensure that the stated levels are true and have been verified.

III. TECHNICAL INTERVENTIONS ASSOCIATED WITH MAINTAINING AND/OR ENHANCING EE

29. To provide cooling or heating, RACHP equipment and systems consume energy, which is, in most cases, electricity. The amount of energy consumed by a unit, is related to the quantity of cooling/heating load that needs to be provided (the amount of cooling or heating service) and to the energy needed to deliver

that service. A more EE unit or system will deliver the same amount of service for a lower level of energy consumed.[8]

30. Improvements to the EE of equipment are best addressed when new equipment is designed and manufactured. The designer can incorporate appropriate energy saving features that will deliver multiple benefits including:

(a) Reduced energy-related GHG emissions throughout the life of the equipment;

(b) Reduced energy costs, providing good financial benefits to the end user; and

(c) Reduced peak electricity demand, providing potential financial benefits by reducing the need for electricity generation and distribution capacity, which translates into lower investment, fuel and costs of operation for electricity generators.

31. By using a rigorous integrated approach to RACHP equipment design and selection, the opportunities to improve EE can be maximized. This approach includes:

(a) Ensuring minimisation of cooling/heating loads;[9]

(b) Selection of appropriate refrigerant;

(c) Use of high efficiency components and system design;

(d) Ensuring optimised control and operation, under all common operating conditions; and

(e) Designing features that will support servicing and maintenance.

32. Each of these five requirements is discussed in the following paragraphs.

Ensuring minimisation of cooling/heating loads

33. Eliminating or reducing loads can significantly reduce energy consumption while still delivering the desired level of heating or cooling capacity. Some examples of load reducing actions include:

(a) Building design features that reduce summer heat gains (e.g.; shading, reflective roof materials, location of windows, insulation);

(b) Putting doors on retail refrigerated display cabinets;

(c) Pre-cooling of hot products prior to refrigeration (e.g., in a food factory using cooling tower water to pre-cool a cooked product);

(d) Reducing heat created by electrical auxiliaries such as evaporator fans, chilled water pumps or lighting; and

[8] The International Energy Agency (IEA) defines EE as “a way of managing and restraining the growth in energy consumption. Something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input.

[9] This could be directly related to more energy efficient equipment design and selection, but it should be taken into account in an integrated approach because of its importance in reducing energy consumption overall.

(e) Reducing cold storage heat load with improved insulation and prevention of warm air entering through open doors.[10]

34. Reducing loads may require extra investment, e.g., added insulation, orientation of building shading or adding a door to a display cabinet case. However, the reduced cooling load may result in some capital cost savings due to, e.g., smaller-sized refrigeration systems and reduced electric interconnection rating.[11]

Selection of appropriate refrigerant

35. Refrigerant selection is a trade-off between environmental benefits, safety, thermodynamic cycle efficiency, system design and reliability, and cost. The impact of refrigerant choice on the EE of the units is usually relatively small, ranging from +/- 5 to 10 per cent. Designers should select the best refrigerant from an efficiency perspective but should also address the wide range of other design issues. It is also important to note that technologies resulting in energy efficiency improvement opportunities available for high-GWP refrigerants may be applicable to low-GWP refrigerants as well.[12]

36. Simplified thermodynamic analysis demonstrates the relative impact of different refrigerants on the EE of the unit, which can help designers create a "short-list" of options. For a given application, there will be a limited number of refrigerants that are likely to be within ±5 per cent of the baseline refrigerant(s) in terms of energy performance. A thermodynamic analysis provides a useful starting point but it is essential to consider "real-world" performance, which is based on the way the refrigerant interacts with the various system components, in particular the compressor and heat exchangers. This can be illustrated with the comparison of HCFC-22 and R-410A for use in small room air-conditioners. A thermodynamic analysis shows efficiency advantages for HCFC-22, but the most efficient equipment currently available on the market uses R-410A. This reflects the fact that equipment manufacturers stopped research and development to improve HCFC-22 equipment after the HCFC phase-out began under the Montreal Protocol. Modern R-410A equipment has a number of efficiency innovations not available with HCFC-22, making the efficiency of R-410A higher. A thermodynamic analysis of HFC-32 shows it has an advantage of about 5 per cent over R-410A for small building air-conditioners.

37. In comparison with HCFC-22, a thermodynamic cycle analysis of propane (R-290) shows coefficient of performance (COP) loss ranging from -2 per cent to zero per cent dependent on the evaporating temperature. However, the volumetric capacity for R-290 is consistently lower than HCFC-22 by approximately 14 per cent. Drop-in testing of R-290 in HCFC-22 equipment showed that COP improvement of 7 per cent and capacity reduction of 8 per cent compared with HCFC-22 at standard rating conditions. This is primarily attributed to the improved transport properties of R-290 versus HCFC-22. With engineering optimisation, HCFC-22 alternatives such as R-290, can match or exceed the performance of existing HCFC-22 units with efficiency increase of up to 10 per cent.

38. AHRI AREP[13] resulted in 67 reports on alternative refrigerant evaluation and one study on benchmarking the risks associated with the use of A2L refrigerants. The performance of the alternative refrigerants ranged widely depending on the type of the study (drop-in or soft optimized), the equipment, and the baseline refrigerant. Overall, the HCFC-22 alternatives were shown to have similar capacity performance results within ±10 per cent but efficiency ranging from -20 per cent to -5 per cent compared to the baseline HCFC-22. The R-410A alternatives showed capacity and efficiency ranging from ±15 per cent and the R-404A alternatives showed capacity ranging from -20 per cent to -5 per cent and efficiency improvement up to 10 per cent.

[10] Reduced sizing. For example, a domestic refrigerator should not be chosen larger than needed or a cold store should not be chosen larger than required.
[11] The cost reduction due to reduced cooling load is often experienced.
[12] Technologies resulting in EE improvements are generally also applicable to low-GWP refrigerants.
[13] Alternative Refrigerants Evaluation Program.

39. The Unites States Department of Energy (US DOE) studies focused on split air-conditioners and package air-conditioners and extended the evaluation to 55°C ambient conditions. The study showed that the HCFC-22 fluorinated alternatives resulted in 3 per cent to 14 per cent capacity loss and 11 per cent to 16 per cent efficiency loss at 35°C rating condition and 3 per cent to 14 per cent capacity loss and 7 per cent to 15 per cent efficiency loss at 55°C. However, R-290 resulted in 7 per cent capacity loss and 11 per cent efficiency improvement at 35°C rating condition and 10 per cent capacity loss and 8 per cent efficiency improvement at 55°C. R-410A alternatives showed capacity difference ranging from -14 per cent to 5 per cent at 35°C rating condition and from -3 per cent to 13 per cent at 55°C, and efficiency difference ranging within ±5 per cent at 35°C and up to 6 per cent at 55°C.

40. The research studies so far concentrated on performance of low-GWP alternative refrigerants compared to the presently used ODS and high-GWP HFC technologies. The studies used available products with “soft optimisation” of charge and expansion devices. Further, research is needed to study the impact of full optimisation into new products using low-GWP alternatives with changes to the compressors, heat exchangers, and other components.

Use of high efficiency components and system design, and ensuring optimised control and operation

41. Vapour compression RACHP equipment consists of a number of primary components (e.g., evaporator, condenser, compressor, expansion valve, refrigerant) and secondary components (e.g., fans, pumps and cooling towers). To maximize EE, it is important to: select an appropriate “system design” that defines the overall system arrangement and operating temperature levels; and select individual components that can contribute to the system efficiency. Controls can be treated as another component of a RACHP system, but it is helpful for the designer to consider the control and operation of the system as a separate issue. In terms of costs, as a general rule, it can be said that effective control technologies offer a cost-effective EE strategy.

42. Equipment is designed to achieve a nominal design point, which is the peak cooling load during the hottest expected ambient conditions.[14] This design point can be considered as the “worst case” load condition. In reality, most systems spend very few hours per year close to this design point. Most of the time, the cooling load is lower when the weather is cooler. In a well-controlled system, the EE should improve at conditions away from the design point. For example, in cool weather, the condensing temperature should fall, giving a potentially significant increase in efficiency; in a poorly controlled system, these improvements do not occur, and the efficiency might degrade more as compressors operate at part-load capacity.

43. The following are examples that can illustrate EE improvements related to systems design, components, and optimized controls:

(a) <u>Cooling at appropriate temperature level</u>: To maximize efficiency, RACHP systems should provide cooling at the maximum possible temperature level. Raising the evaporating temperature by just 1°C can improve efficiency by between 2 per cent and 4 per cent. A common design is to group several cooling loads onto one cooling system, even though the temperature requirement is different for each load. The evaporating temperature has to suit the coldest load – which means that the warmer loads are being cooled inefficiently. A system design that separates loads at different temperatures can be significantly more efficient, but this comes at the additional cost for multiple systems. Another example is the choice of chilled water temperature within a space cooling system – using a higher temperature provides better efficiency for the same cooling load;[15]

[14] Equipment are also designed around nominal design point that includes point of operation with maximum efficiency.
[15] This may require a larger and costlier heat exchanger.

(b) Compressor: System designers consider the optimum number of compressors to suit a given load. For very small systems, there is always one compressor. However, for larger systems it may be more efficient to select several small compressors rather than one large one, with a trade-off being made between the extra capital cost and the resulting energy savings. This is especially important to support high efficiency under part-load operating conditions. The compressor needs to be optimised for the refrigerant selected and the expected range of operating conditions (in terms of evaporating and condensing temperatures). There can be as much as a 20 per cent difference in efficiency between two compressors of similar size and cost. Good selection can provide good efficiency improvement at little or no extra cost. When a cooling load falls e.g., due to change in ambient conditions, the compressor needs to operate at part-load as the load is lower than the system's nominal design point. On small systems this is done with on-off control and on large systems with compressor load adjusters such as cylinder unloading for reciprocating compressors or slide valves for screw compressors. These are very inefficient ways of providing part-load control. Recent advances in variable speed drives (VSDs[16] e.g., the inverter) allow for the use of variable speed compressors, which can often deliver over a 25 per cent efficiency improvement;

(c) Heat exchanger selection: The designer should select heat exchangers with the lowest practical temperature difference to optimise evaporating temperature (which should be as high as possible) and condensing temperature (which should be as low as possible).[17] Heat exchangers with a tube-and-fin design with smaller diameter tubes have been introduced. This is aimed at improving the heat transfer rate and the EE, although the designer must also consider the impact of higher pressure drops. This can reduce the internal volume of the heat exchanger, making it possible to reduce the required amount of refrigerant. Micro-channel heat exchangers have also been developed and provide another design option;

(d) Condenser pressure control: Many RACHP systems have "head pressure control" which stops the condenser pressure floating downwards in cold weather. The use of such controls can be eliminated or minimised through improved design. For example, by using an electronic expansion valve in place of a thermostatic expansion valve the head pressure control setting can be significantly reduced. Energy savings of approximately 20 per cent are possible;

(e) Control of auxiliary pumps and fans: Many systems use fans to circulate air being cooled or pumps to circulate chilled water. Traditionally, these were fixed speed devices that are designed to suit the nominal design load. Auxiliary loads on the cold side of a refrigeration and air-conditioning system are "paid-for-twice" because as well as running the pump or fan, they create an extra heat load that must be removed by the refrigeration system. At part-load, these auxiliary loads can become a disproportionately large part of the total power consumption. By using VSDs, the fans and pumps can be slowed down at part-load.

44. Table 1 summarizes efficiency improvements for a range of component design improvements from a "base case" represented by a European MEPS.

[16] VSDs - Variable Speed Drives.
[17] Heat exchanger selection is almost always a techno-economic selection process. The larger the heat exchanger chosen, the higher efficiency impact.

Table 1. Efficiency improvement options and corresponding energy savings based on European conditions

Option	Description	Improvement from base case (%)*	
		Min	Max
Standby load	Reduced standby loads[18]	2	2
Efficient compressors	Two-stage rotary compressors, high efficiency scroll compressors with DC** motors	6	19
Inverter/variable speed	AC***, AC/DC or DC inverter driven compressors	20	>25
Efficient heat exchanger	High efficiency microchannel heat exchangers, larger sized heat exchangers	9	29
Expansion valve	Thermostatic and electronic expansion valves	5	9
Crankcase heating	Reduced crankcase heating power and duration	9	11

(*) The cumulative efficiency improvement of multiple measures will not be the sum of all the individual components.
(**) DC: direct current
(***) AC: alternate current

Designing features that will support service and maintenance

45. When new equipment is being considered, the designer should consider the servicing and maintenance aspect and provide features that will help ensure good ongoing EE throughout the life of the system. Proper servicing and maintenance begins with proper installation and commissioning of equipment. Poor installation and start-up practices can reduce the EE of the equipment substantially and such losses cannot be recovered for the rest of the life of the equipment. Good monitoring and control systems can help the plant operator or maintenance technician check performance and correct any energy wasting faults. It is always better to include meters and sensors as part of a new system than to add them at a later date.

High ambient temperature (HAT) considerations

46. A HAT environment imposes an additional set of challenges on the selection of refrigerants, system design, and potential EE enhancement opportunities. System design consideration to maintain energy efficiency at HAT conditions are affected by the refrigerant choice due to thermodynamic properties, safety requirements due to the increased charge, and component availability and cost. Research at HAT conditions done so far has shown the viability of some low-GWP alternatives to deliver comparable EE results to existing technologies. Further publicly financed research, as well as private sector initiatives, are optimising design to achieve the maximum efficiency in these challenging conditions.

47. One of the most effective means to improve EE under HAT conditions is to increase the condenser size. However, this results in increased refrigerant charge and system cost. There is a need to examine the transition impact on flammability, toxicity, and operating pressures. Standards and codes development bodies are working on improved adoption of the new generation of alternative lower GWP refrigerants. Table 2 below summarizes the various considerations on the effect that HAT has on EE.

Table 2. Various considerations on the effect that HAT has on energy efficiency

Consideration	Description	Effect of HAT	Special measures
Refrigerant selection	Thermodynamic properties and flammability characteristics	Closeness to critical temperature reduces efficiency Limitation of large amount of refrigerant charge	Choice of refrigerant

[18] The electricity use is just used to keep the necessary control elements active, waiting to deliver the system service and its level is generally not influenced by any refrigeration load.

Consideration	Description	Effect of HAT	Special measures
System design	Cooling loads, condensing temperatures and pressures	Larger cooling loads lead to larger equipment Higher condensing temperatures and pressures	Testing the system (burst pressure, tightness, functional) to account for higher operating pressure, while maintaining efficiency
Manufacturing	Design and construction need to account for higher pressure	Need for a special design and special components to meet EE standards at HAT conditions	Local manufacturers to continuously improve design and manufacturing capabilities
Service	Service practices at higher temperatures and pressures	Risk of system failure and loss in efficiency	Technician training
Safety	Codes	Quantities of refrigerants per occupied space due to the higher heat loads Limitation due to increased charge	Risk assessment

Challenges for the uptake of energy efficient technologies

48. More energy efficient equipment and systems in RACHP sectors are already available. For example, a study on efficiency of different air-conditioner models found that best available air-conditioner models were two to three times more efficient than average models on the global market. This indicates there is major potential for significant energy savings using equipment that is already on the market in the RACHP sector. More ambitious standards, labels, and other types of market-transformation policies (e.g., incentives, procurement or awards) would reduce the energy requirements of countries where energy is already at a premium.

49. High-efficiency products typically, but not always, have a higher up-front cost compared with low-efficiency products. This is partly because high-efficiency models are often sold as premium products bundled with other non-energy features.[19] Higher-efficiency products also tend to have a wider range of market prices compared with lower-efficiency products. The introduction of overly stringent efficiency standards could inadvertently raise prices, if not done carefully, often with step changes agreed with air-conditioner manufacturers. In order to minimise the adverse impacts of market measures such as MEPS, these measures should be designed with a long-term goal in mind and at a schedule in line with the pace of technology development and investment cycles in the relevant sector.

50. The barriers to adoption of EE measures are within the following categories: technical, financial, market, information, institutional and regulatory, service competence, and other. These barriers and mitigation measures are described in Table 3.

Table 3. Challenges for the uptake of energy efficient technologies and means for removing them

Barrier	Description	Mitigation measure	Implementation (years)
Technical	Testing facilities to evaluate, measure and verify EE may not be available at all, or lack sufficient resources or capacity to meet the demand. Local manufacturers may lack the technical capacity to manufacture high efficiency equipment. Intellectual property may be a barrier to	Installation of appropriate testing facilities Training and capacity building for local manufacturers Technology transfer of intellectual property, or design of joint venture programmes/collaborative research and development	1-3

[19] An important aspect of costs of high-efficiency products relates to high cost of components.

Barrier	Description	Mitigation measure	Implementation (years)
	manufacturing high efficiency components		
Financial	Higher efficiency equipment generally costs more to produce than less efficient equipment. Efficient components are frequently bundled with other features and sold at a premium.[20] The availability cost of finance plays a significant role	Low-cost financing, utility rebate programmes, bulk procurement programmes, buyer's clubs and other types of procurement programmes	1-2
Market	Purchasers of equipment may be different than the users of the equipment, e.g. in rental housing. This can be a barrier to the purchase of the higher efficiency equipment as the incentive to do so is not available to the purchaser	Incentives to purchasers of efficient equipment	0.5-1
Information	Information regarding the availability or benefits of higher efficiency equipment may not be available to the end-user. EE metrics can be too technical or hard to understand. This type of barrier can be partially addressed through mandatory or voluntary labelling schemes, star ratings, or other types of education and awareness programmes	Mandatory or voluntary EE labelling programmes, awareness and education campaigns	0.5-1
Institutional/ regulatory	There may be a lack of legislation for EE, a non-existent or weak regulatory framework, weak or unenforceable standards or a lack of technical capacity to enforce EE related activities such as standards or labelling	Enactment of appropriate legislation and regulatory frameworks, design of appropriate evaluation measurement and verification mechanisms, capacity building for regulators and policymakers, harmonization of MEPS	2-4
Service competency	High efficiency equipment may require use of the latest technology that requires new technician skills. If there is skill gap between that required for the equipment selected and the competency of the service provider, high efficiency equipment might not be used	Training programmes for service technicians	1-3
Other	There may be misperceptions about high efficiency products, that they may suffer in terms of quality and/or maintenance or other performance criteria[21]	Awareness and education programmes on benefits of energy efficient equipment including payback periods	0.5-1

[20] Research has shown that over time, and with increasing scale of production the prices of more efficient equipment has come down in most markets. However, at any particular time, the most efficient equipment will still tend to be sold at a premium, even if the market as a whole tends toward higher efficiency.
[21] "Unproven reliability" as these products are new to the market; installers, customers, etc. may be reluctant to apply the new technology.

IV. COST RELATED ISSUES ASSOCIATED INCREMENTAL COSTS, PAYBACK OPPORTUNITIES AND COSTS OF MONITORING AND VERIFICATION

51. The economic benefits of improving EE are well documented, and vary by equipment type, application, weather, time and by local factors such as discount rates, hours of use, electricity prices, transmission and distribution losses.[22]

52. The most frequently cited benefits of EE improvement are energy, cost and GHG saving and, for space cooling, peak load reduction. Transition to low-GWP refrigerants would further add to these savings.[23]

53. In addition, there is avoided morbidity and mortality caused by energy poverty, reduced days of illness, improved comfort, reduced pollution (SOx, NOx and particulate matter), and avoided CO_2 emissions. It has been estimated that these co-benefits can provide an additional 75 per cent to 350 per cent to the direct energy-savings benefits of EE.[24]

Methodology to calculate capital and operating costs

54. Various parties have established market transformation programmes for promoting EE including MEPS and labelling programmes. For example, the US DOE's Appliance and Equipment Standards Program and the preparatory studies for the EU Ecodesign Directive both use "bottom-up" engineering analysis based on data collection, testing and modelling of the more efficient equipment to identify the actual manufacturing cost (as opposed to the retail price) of efficiency improvement. This "bottom-up" approach usually uses industry standard equipment design software[25] and test data of higher efficiency equipment to identify design options for higher efficiency equipment from a "base case" model representing low or average efficiency on the market in question. Subsequently, the costs of these higher efficiency design options are surveyed by interviewing industry experts, manufacturers and component suppliers to build up a picture of the costs of higher efficiency equipment.

55. This methodology offers a "snapshot" of the cost of efficiency improvement at any given time and will tend to provide a conservative (i.e., higher) estimate of the cost of efficiency improvement. In actual practice, the prices of higher efficiency equipment have been found to decline over time in various markets as higher efficiency equipment begins to be produced at scale. This applies especially for small mass-produced equipment where manufacturers quickly absorb the initial development costs and try to get to certain "price points" that help them sell their equipment.

56. Similar processes have also been used to a more limited degree to support EE standards processes in countries such as China and India. While this methodology can be used generally to estimate the costs to the manufacturers of maintaining and/or enhancing EE for both Article 5 and non-Article 5 Parties with manufacturing capacity, the costs to the consumer of maintaining and/or enhancing EE are likely to be similar for all Parties with the additional costs of shipping for importing Parties.

Data collection

57. Due to the proprietary nature of business operations, there is limited publicly available data on capital and operating costs to the manufacturer attributable to improvements in EE for RACHP equipment.

[22] The US Energy Information Administration estimated that the average construction cost for new generators in 2016 is roughly US $2,000/kW of capacity, i.e., over US $2 billion per new power plant if financing costs are included. https://www.eia.gov/electricity/generatorcosts/
[23] This can be done simultaneous to introduction of high EE products.
[24] Ürge-Vorsatz et al., 2014.
[25] For example, [Fridley et al 2001] used the Oak Ridge National Laboratory (ORNL) Heat Pump Design Model, Mark V, version 95d [ORNL, 1996; Fischer & Rice, 1983; Fischer et al. 1988].

Furthermore, a glance at retail prices and efficiencies of equipment on the global market shows a wide variation in the prices of equipment at similar efficiency levels, indicating that retail prices alone are not a good indicator of the cost of maintaining and/or enhancing EE in new equipment.

58. Several examples of data collected in order to develop the methodology are presented below.[26]

(a) Retail prices are not sufficient to understand the cost of maintaining and/or enhancing EE: Figure 3 provides an example of small unitary variable speed air-conditioners with a cooling capacity of 3.5kW and EE level of about 4.5 Watt to Watt (W/W) (measured according to the Annual Performance Factor (APF) metric) in China.[27] Retail prices varies from approximately US $500 to US $2,000, i.e., a four-fold (400 per cent) variation. This effect of wide price variation at a single efficiency level holds for multiple cooling capacities, multiple efficiency levels and across both fixed-speed and variable speed air-conditioners;

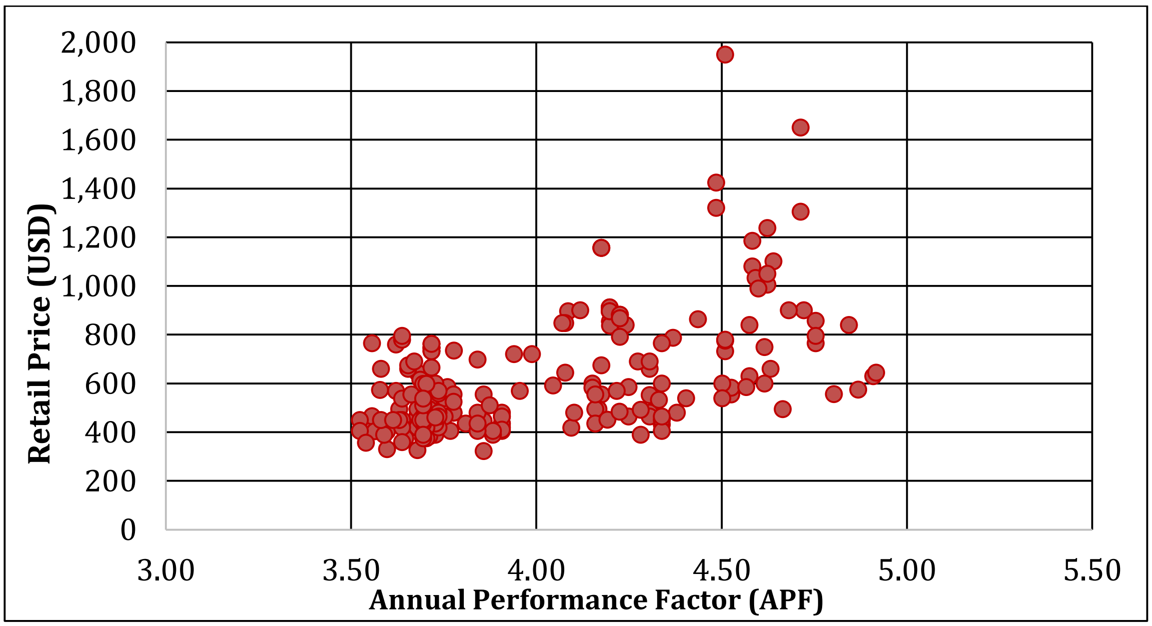

Figure 3. Retail price versus efficiency of 3.5kW mini-split air-conditioners on the Chinese market. Source: Shah, Park and Gerke, 2017

(b) A review of the air-conditioner market in Japan shows that air-conditioners on the market have a higher range of EE. Whilst there is a strong underlying association between the EE and the unit price, there remains a wide variation in price at a particular efficiency level. Figure 4 depicts the correlation between price and EE for all 3.5 kW models operating with HFC-32 as the refrigerant. The rate of price increase is roughly US $603 per EE (APF) point.

[26] Methodology for cost assessment was presented by the TEAP task force report based on data collected as presented in the document.

[27] Lawrence Berkeley National Laboratory's IDEA database and the Chinese National Institute of Standardization database.

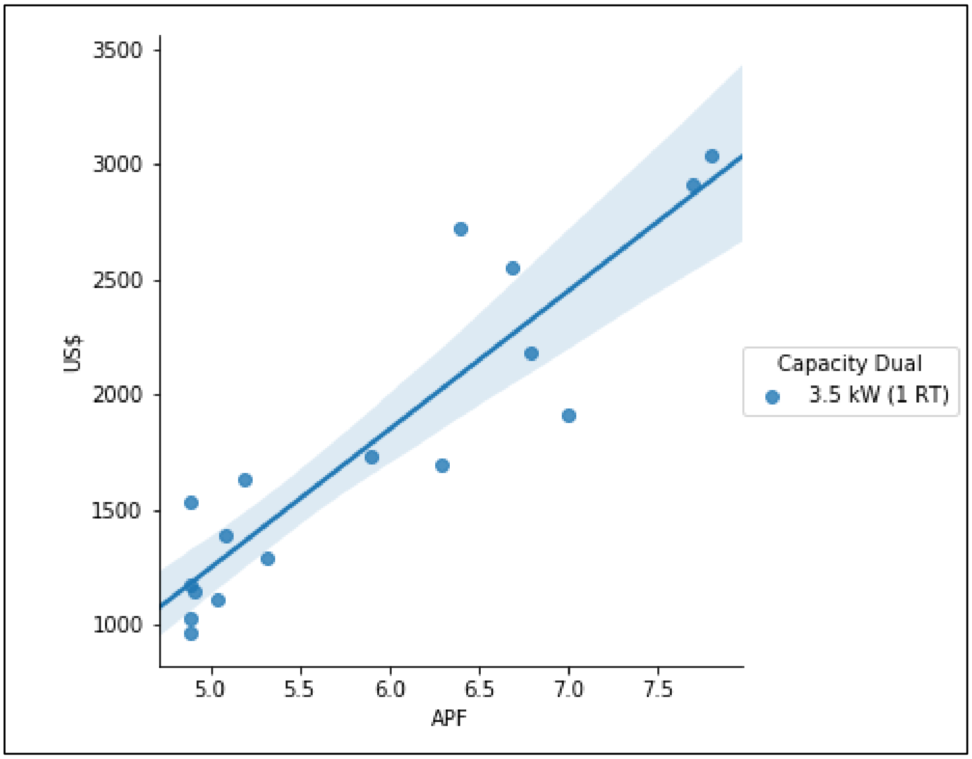

Figure 4. Survey of retail price vs EE in APF of mini-split air-conditioner in the Japanese market

(c) Costs and energy savings of various efficiency improvement options: Table 4 shows efficiency improvement options for various components for a 5.27 kW mini-split air-conditioner with expected energy savings from the "base case" model and their corresponding costs per unit in India.

Table 4. Efficiency improvement options, energy savings and manufacturing cost for a 5.27 kW mini-split air-conditioner in India

Technology	**Energy saving (%)**	**Incremental manufacturing cost (US $[28])**
Improved compressors	5.5 – 15.0	1.43 – 12.27
Variable speed compressors	21.0 – 23.0	25.67 -115.54
Variable speed drives for fans and compressors	26.0	44.93 – 134.79
Heat exchanger improvement	7.5 – 24.0	10.48 – 156.90
Expansion valve	3.5 – 6.5	1.78 - 32.09

(d) Price increase of efficiency with and without change in refrigerant: For one Chinese brand, the price increase for an approximately 13-15 per cent efficiency improvement for a 3.5 kW variable-speed air-conditioner using R-410A was about 6 per cent. However, when both the efficiency and refrigerant were updated (i.e. from 5-8 per cent improvement and from R-410A to HFC-32), the price increase was about 11 per cent.

Cost and payback period to the consumer for different efficiency levels

59. Table 5 shows the lifecycle cost (retail price plus installation cost plus energy cost over the lifetime of the equipment) and payback period (period of time over which the energy savings exceed the higher installation cost) to the consumer calculated using the above outlined methodology from a US DOE

[28] 1 US $ = INR 70.11

rulemaking document[29] for four efficiency levels above a base level considered for mini-split air-conditioner. The higher efficiency levels have higher installed costs, but lower lifetime operating costs. The data imply that at the current technology development that there is a ceiling of efficiency at which point the energy savings will not pay back the higher installed cost within the lifetime of the equipment.

Table 5. Installed cost, lifecycle cost and simple payback period to the consumer for various efficiency levels for mini-split air conditioners in the United States of America

SEER (W/W)	Average costs 2015 (US $)			Simple payback (years)	Average lifetime (years)
	Installed cost	Lifetime operating cost	Lifecycle cost		
4.1 (base)	3,714	4,758	8,472	N/A	15.3
4.3	+38	-93	-55	4.5	15.3
4.4	+105	-189	-84	4.8	15.3
4.7	+259	-295	-36	8.2	15.3
5.6	+1,105	-602	+503	16.6	15.3

60. Table 6 shows the breakdown of the lifecycle costs of typical 5 kW air-conditioner units at three EE levels in India (2 Star, 3 Star, and 5 Star), representing roughly 90 per cent of the total market. The refrigerant contribution to the lifecycle cost is minimal (less than 1 per cent). The lifecycle cost for the 2, 3, and 5 Star units are US $1,672, US $1,704, and US $1,540 respectively. This indicates that while the system price increases from 2 Star to 5 Star, it results in a net lifecycle cost saving of US $131.22.

Table 6. Breakdown of the lifecycle cost in percentage for 5 kW R-410A air-conditioner in India at different efficiency levels[30]

Star	System price	Refrigerant price	Installation cost	Lifetime energy cost
2 Star	25.9	0.5	1.3	72.3
3 Star	30.9	0.5	1.3	67.4
5 Star	42.8	0.7	1.4	55.1

<u>Capital and operating costs</u>

Stand-alone commercial refrigeration equipment

61. Transitioning from high-GWP HCFC and HFC to low-GWP options will require some investment in manufacturing and equipment. This is especially true when the transition is to flammable refrigerants such as A2L or A3 refrigerants. In general, data from the field indicates that the cost to the consumer for an R-290 stand-alone system can vary from 0 to 5 per cent over conventional systems. The higher price, if any, can often be recovered, with the lower power consumed by these newer systems.

62. The cost to implement the other efficiency improvement ideas will vary from small, as in the case of LED lighting, to high for the variable speed or higher efficiency compressors. Payback will depend on the cost of electricity in the respective region but since most regions regulate these systems, the market would be expected to adopt the lowest cost method to achieve the minimum efficiency required.

63. Transitioning to low-GWP refrigerant options will result in operating cost improvements from zero per cent up to 10 per cent depending on the refrigerant chosen. R-290 refrigerant could reduce electricity cost by 5 – 10 per cent compared to HCFC-22. Additional improvements with variable speed fans, compressors, LEDs and other efforts will further reduce the power consumption depending on the improvement that has been made.

[29] https://www.regulations.gov/document?D=EERE-2014-BT-STD-0048-0098
[30] Figure 2.15 on the TEAP Decision XXIX/10 task force report converted into a table.

Condensing units

64. Transitioning from high-GWP HCFC and HFC to low-GWP options will require some investment in manufacturing and equipment.[31] This is especially true when the transition is to flammable refrigerants such as A2L refrigerant blends or A3 refrigerants. Thermal load reduction through better insulation, especially in walk-in coolers and freezers, use of LED lights, and some other efficiency improvement are lower first capital cost and yield gains throughout the life of the equipment. Again, payback is a function of the local cost of electricity and can vary from region to region. Regulations play a key role in which efficiency improvement gets adopted.

65. Transitioning from high-GWP HCFC and HFC to low-GWP options can be expected to reduce or keep flat the operating energy costs depending on the refrigerant choice made. Thermal load reduction through better insulation, especially in walk-in coolers and freezers and the use of LED lights are some examples of EE methods that yield reduced power consumption, leading to lower operating costs.

Centralized and distributed systems

66. Market driven economics have justified many centralized and distributed systems to adopt efficiency methods. In the case of R-744 systems, for both cascade sub-critical and especially for transcritical systems, capital costs have prevented widespread adoption, particularly in warm climates. A recent study for a small store in Europe with ten refrigerated cases,[32] compared a distributed R-290 system to a transcritical CO_2 system. The efficiency of the R-290 system was about 5 per cent better on an annual basis and about 25 per cent less capital cost than the transcritical CO_2 system. In order to improve the performance of the CO_2 system, ejectors or parallel compressors could be added but the initial (purchase) cost will increase.

67. In the case of R-744 systems, for both cascade sub-critical and especially for transcritical systems, operating costs are flat to slightly higher in the case of transcritical, compared to R-404A. While the R-290 architecture could work for a small store format, it will be difficult to justify this in a store where the refrigeration systems are much larger.

Air-conditioning and heat-pump sector

68. There are technologies that are shown to be cost neutral, such as advanced heat exchanger designs, rotary compressors, and variable capacity centrifugal compressors. There are others that result in a cost premium that can be reduced with time due to the economies of scale, such as the micro-channel heat exchangers and the electronic expansion valves, or remain as a premium cost element such as the variable capacity compressors for room and packaged air-conditioners.

69. Previous studies indicated that lower GWP HFC/HFO blends can be readily used to replace R-410A while maintaining or improving the system performance of the RACHP. However, HCFC-22 alternative lower GWP refrigerants and refrigerant blends were not able to readily match the performance. A later study by Shen et al. 2017,[33] showed that with engineering optimization, HCFC-22 alternatives can match or exceed the performance of existing HCFC-22 units with efficiency increase of up to 10 per cent.

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[31] This is not expected to be high in case of condensing units as these equipment are generally not factory charged. Possibly some changes are made to the design, and some components for safety etc. may be needed.

[32] http://www.emersonclimate.com/europe/en-eu/About_Us/News/Documents/FFR196-Emerson-Fact-sheet-Integral-Display-Case-Technology-EN-1711.pdf

[33] Shen B, Abdelaziz O, Shrestha S, Elatar A. 2017 "Model-based optimization of packaged rooftop air-conditioners using low-GWP refrigerants," International Journal of Refrigeration, ISSN 0140-7007, available at https://doi.org/10.1016/j.ijrefrig.2017.10.028. Accessed 12 May 2018

70. Table 7 shows an example from a US DOE rulemaking document for capital costs of higher efficiency for four efficiency levels considered for mini-split air conditioning by the Unites States industry as a whole.

Table 7. Industry-wide capital conversion costs for various efficiency levels (2015)[34]

SEER (W/W)	Capital conversion costs (US $ million)	Shipments[35] (million units/year)
4.2	61.0	6.5
4.4	205.6	6.5
4.7	337.9	6.5
5.6	373.0	6.5

<u>Matrix of technical interventions to energy efficiency and associated costs</u>

71. Table 8 below presents a summary of matrix of technical interventions to improve EE and associated costs.

Table 8. Summary of matrix of technical interventions to achieve improved EE and associated costs

Equipment type	Baseline components	Technical interventions	Energy efficiency improvement	Associated costs
All	Evaporating temperature	Optimize evaporating temperature	Each 1°C increase result in 2 – 4 per cent	Low
All	Controls	Improved controls	10 – 50 per cent	Low - medium
Room air conditioners	Heat exchangers	Increase heat exchanger size, or use advanced designs (small diameter tubes or microchannel heat exchangers)	9 – 29 per cent.	Low - medium
	Compressors	Two-stage rotary compressors, high efficiency scroll compressors with DC motors	5 – 19 per cent	Medium
		AC, AC/DC or DC inverter driven compressors	20 – 30 per cent	Medium
	Expansion valve	Thermostatic or electronic expansion valve	5 – 9 per cent	Low
	Standby load	Reduced standby loads	2 per cent	Low
Packaged and large air conditioners	Compressors	Use multiple compressors to optimize part load performance	Up to 20 per cent	Medium
	Compressors	Use AC, AC/DC or DC inverter driven compressors	20 – 30 per cent	Medium – high
	Heat exchangers	Increase heat exchanger size, or use advanced designs (small diameter tubes or microchannel heat exchangers)	9 – 29 per cent	Low
	Crankcase heating	Optimize crankcase heating	9 – 11 per cent	0
	-	Fault detection and diagnosis	Up to 30 per cent	Low

[34] Trial standard levels 1,2,3 and 4 correspond to seasonal energy efficiency ratio (SEERs) of 14.5, 15.0, 16.0 and 19.0 BTU/hr/W respectively for 2 tonne mini-split air-conditioners. These "Trial standard levels" were defined differently for various product categories. (Source: DOE 2016).
[35] Total 2015 shipments included all types of central air-conditioners and heat pump systems shipped in the United States of America.

Equipment type	Baseline components	Technical interventions	Energy efficiency improvement	Associated costs
Commercial refrigeration	Condenser pressure control	Minimize head pressure control (replacing thermostatic expansion valves with electronic expansion valves)	Up to 20 per cent	Low
	Compressors	Variable speed control or efficient variable capacity controls	Up to 25 per cent	Medium
	Auxiliary fans and pumps	Variable speed controls for auxiliary fans and pumps	Up to 10 per cent.	Low
	Other controls	Defrost-on-demand and adjusted suction pressure controls.	Up to 10 per cent	Low
	Crankcase heating	Optimize crankcase heating	9 – 11 per cent	0

V. ENVIRONMENTAL BENEFITS IN TERMS OF CO_2-EQUIVALENT

72. While the Kigali Amendment focuses on energy efficient refrigerants,[36] the industry continues in parallel with its efforts to improve EE through system re-design and reducing the load through improved building design. These actions will reduce the refrigerant charge in air-conditioning systems, and reduce refrigerant emissions.

EE impact from indirect emission

73. There are several methodologies that estimate the total emissions from a system. Most common are Total Equivalent Warming Impact (TEWI)[37] and Life Cycle Climate Performance (LCCP) which attempts to quantify the total global warming impact by evaluating the RACHP systems during their lifetime from "cradle to grave".

74. The largest potential for EE improvement comes from improvements in design and components, which can yield efficiency improvements[38] of 10 to 70 per cent compared with 5-10 per cent for the refrigerant in most cases. Calculating lifecycle emissions at the country or regional level would require several steps and assumptions, such as product lifetime, refrigerant choice and leakage, that extend beyond considerations of the environmental benefits from EE. The environmental benefits from EE can vary by a factor of 1,000 depending on the hours of use and the emissions factor for electricity generation.

75. Calculating the environmental benefits of EE in RACHP equipment in CO_2-eq terms involves the following three steps:

(a) Determine the type of equipment (e.g., ductless split air conditioner, 3.5 kW cooling capacity), identify the baseline model unit energy consumption as a function of the current market in the country or territory or the units manufactured by a given facility, and determine the EE improvement to be evaluated;

(b) Calculate the energy savings for the higher efficiency model as a function of baseline unit energy consumption and hours of use. Hours of use vary significantly by country and climate and application; in some cases, national standards define the hours of use as part

[36] This is in the context of the phase-down of HFCs.
[37] Sometimes, a TEWI calculation may be simplified by neglecting broader effects including manufacture of the refrigerant and equipment, and disposal of the refrigerant and equipment after decommissioning. The impact of these components could be small.
[38] When EE improvements are referred to in this report we compare the energy used by an improved design to a baseline design. For example, if System A uses 10 units of energy and system B uses 8 units, there is a 20 per cent efficiency improvement.

of the EE metric (for example, the India Seasonal Energy Efficiency Ratio is defined using 1,600 hours of use annually). Actual energy performance of installed equipment may be lower than the designed efficiency due to poor installation or maintenance. Since the efficiency improvement is compared to a baseline unit, this approach assumes that performance degradation due to poor installation or maintenance or high temperatures would have a comparable effect on the baseline unit, so the relative energy savings are maintained. If hours of use increase in the case of the higher efficiency unit due to lower electricity bill costs, a form of rebound behaviour, the energy savings would be reduced due to “rebound” effect;

(c) Convert energy savings to CO_2-eq by multiplying by the end-use emission factor for electricity generation. Air-conditioners tend to run during the hottest times of day, and tend to coincide with peak electricity demand; for this reason, use of “marginal emission” factors, which represent the carbon intensity of the generators that produce power to meet peak demand, may be more accurate. Whether the carbon intensity of marginal generation is higher or lower than the annual emission factor depends on the grid composition of the country. However, as more renewable capacity is added, the trend is towards lower marginal emissions factors.

76. In the domestic refrigeration sector, savings due to EE appliances range from 55 per cent to nearly 70 per cent with technologies that are presently available. It is assumed in this case that refrigerators operate 24 hours per day and that HAT do not impact the performance of the devices, as they are placed indoor in environments with controlled temperature.

77. In case of commercial refrigeration, there is a very high energy saving potential. In some cases, as in open- versus closed-door freezers and coolers, savings can range from 70 to 80 per cent. In the case of ice cream freezers, the energy consumption was measured at 25°C and 31°C. The energy consumption increased 13 per cent at the higher ambient condition. However, the energy consumption was still much lower than an inefficient, vertical freezer. This shows that also in HAT conditions, the choice of the device is crucial.

78. Table 9 presents the summary of energy savings in kWh per year for specified hours of use of room air-conditioners and EE at the specified product EE level (higher efficiency level at 10-20 per cent and highest efficiency level 40-50 per cent compared to base unit energy use).

Table 9. Energy savings for a room air-conditioners unit

Case*	**Identify product-specific baseline unit energy consumption and efficiency improvement**					**Calculate per unit energy savings for efficient models**	
	Hours of use/year	**Unit type /cooling capacity (kW)**	**Base air-conditioners unit energy use (kWh/yr)**	**Higher EE**	**Highest EE**	**Higher EE (kWh/yr)**	**Highest EE (kWh/yr)**
Very low case **a** (very low hours, very low electricity emission factor)	350	Split unit / 3-4 kW	266	20 per cent	50 per cent	53	133
Low case **b** (low hours, low electricity emission factor)	1,200	Split unit / 3.5 kW	1,355	20 per cent	50 per cent	271	678

Case*	Identify product-specific baseline unit energy consumption and efficiency improvement					Calculate per unit energy savings for efficient models	
	Hours of use/year	Unit type /cooling capacity (kW)	Base air-conditioners unit energy use (kWh/yr)	Higher EE	Highest EE	Higher EE (kWh/yr)	Highest EE (kWh/yr)
High hours **c** (high hours, middle electricity emission factor)	2,880	Split unit / 3.5 kW	2,965	10 per cent	40 per cent	297	1186
High emission factor **d** (middle hours, high electricity emission factor)	1,600	Split unit / 5.275 kW	1,300	10 per cent	40 per cent	130	520
Highest case **e** (high hours, high electricity emission factor)	2,880	Split unit / 5.275 kW	5,759	25 per cent	40 per cent	1,440	2,304

(*) The five cases representing the situations that can be found in the actual scenario of climate zones and emission factors throughout the world.[39]

a Hours of use for cooling in Europe (Topten.eu); unit energy use from Topten.eu with inefficient (266 kWh/yr) and highest efficiency (122 kWh/yr).

b Hours of use and base air-conditioner unit energy consumption from United for Efficiency Country Assessment for Argentina (December 2016); percent improvement based on Topten.eu.

c Hours of use and base air-conditioner unit energy consumption from United for Efficiency Country Assessment for Thailand (December 2016); percent improvement based on India BEE 3-star and 5-star examples; emission factor for Thailand.

d Hours of use and base air-conditioner unit energy consumption from Indian ISEER standard and BEE 1-star level; percent improvement based on India BEE 3-star and 5-star examples.

e Hours of use for 8 hours for 360 days; base unit 2.6 W/W EER converted to energy consumption by dividing capacity by EER times hours of use; mid = 3.5 EER and highest = 4.5 EER.

79. In case of heat pumps, the energy savings for a heat pump unit in four cases representing the situations that can be found in the actual scenario of climate zones throughout the world is given in Table 10.

Table 10. Energy savings for a heat pump unit

Case*	Unit energy consumption								EE impro-vement (%)
	Base case				Best available technology (BAT)				
	Heat pump (GJ)	Electric backup (GJ)	Total (GJ)	Total (kWh/y)	Heat pump (GJ)	Electric backup (GJ)	Total (GJ)	Total (kWh/y)	
Cold climate and low emission factor	12.31	7.97	20.28	5,633	12.62	2.6	15.22	4,228	25
Cold climate and medium emission factor	12.31	7.97	20.28	5,633	12.62	2.6	15.22	4,228	25
Warm climate and medium emission factor	3.23	0.336	3.566	991	2.95	0.104	3.054	848	14

[39] CO_2 emission impact is provided in the TEAP task force report.

Case*	Unit energy consumption								EE improvement (%)
	Base case				Best available technology (BAT)				
	Heat pump (GJ)	Electric backup (GJ)	Total (GJ)	Total (kWh/y)	Heat pump (GJ)	Electric backup (GJ)	Total (GJ)	Total (kWh/y)	
Mild climate and high emission factor	8.08	2.48	10.56	2,933	6.42	0.4	6.82	1,894	35

(*) The four cases representing the situations that can be found in the actual scenario of climate zones and emission factors throughout the world.[40]

80. In case of mobile air-conditioning, based on a report on some passenger vehicle fuel economy standards that includes credits for high-efficiency air-conditioning, the GHG emission impact is identified as an indicator of the potential benefits and the range is from 0.9 grams CO_2-eq/km to 6.1 grams CO_2-eq/km.

VI. DEMONSTRATION PROJECTS FOR THE INTRODUCTION OF LOW-GWP TECHNOLOGIES AND HFC STAND-ALONE INVESTMENT PROJECTS

81. At its 74th, 75th and 76th meetings, the Executive Committee approved three feasibility studies for district cooling)[41] and 17 projects to demonstrate low-GWP technologies pursuant to decision XXV/5 and decision 72/40.[42]

82. Table 11 summarizes information on energy efficiency based on results available from the demonstration projects approved in line with decision 72/40, excluding refrigeration servicing sector projects.

Table 11: Feasibility studies and demonstration projects for the introduction of low-GWP technologies

Country	Project title (code)	Funding (US $)*	Meeting	Update on the progress in implementation
Refrigeration and air-conditioning and assembly sub-sector				
China	Demonstration project for ammonia semi-hermetic frequency convertible screw refrigeration compression unit in the industrial and commercial refrigeration industry at Fujian Snowman Co. Ltd. (CPR/REF/76/DEM/573)	1,026,815	82	The report mentioned that COP[43] of the new system designed in the project having refrigeration capacity of 56.7 kW, 167.1 kW and 216.3 kW systems is 1.57, 1.63 and 2.94, respectively.
Colombia	Demonstration of HC-290 (propane) as an alternative refrigerant in commercial air-conditioning manufacturing at Industrias Thermotar ltd (COL/REF/75/DEM/97)	500,000	81	The report mentions that an R-290 5-TR[44] split unit equipment (R-290 scroll compressor) consumes 13.1% less energy (kWh) than a similar R-410A unit.

[40] CO_2 emission impact is provided in the TEAP report. The information given in gigajoules (GJ) relates to annual consumption.
[41] The Dominican Republic, Egypt, and Kuwait.
[42] Including: seven projects in the refrigeration and air-conditioning and assembly sub sector (China, Colombia, Costa Rica, Kuwait, Saudi Arabia (two), a global (Argentina and Tunisia) and a regional (West Asia) project; six in the foam sector (Colombia, Egypt, Morocco, Saudi Arabia, South Africa, and Thailand); and three in the refrigeration servicing sector (Maldives, Europe and Central Asia region, and a global project (Eastern Africa and Caribbean regions).
[43] COP – Coefficient of Performance.
[44] TR – Tonne of Refrigeration.

Country	Project title (code)	Funding (US $)*	Meeting	Update on the progress in implementation
Refrigeration and air-conditioning and assembly sub-sector				
Costa Rica	Demonstration of the application of an ammonia/carbon dioxide refrigeration system in replacement of HCFC-22 for the medium-sized producer and retail store of Premezclas Industriales S.A. (COS/REF/76/DEM/55)	524,000	82	The final report indicated that comparison of average monthly bills for October / November 2017 (prior to installation of the new refrigeration system) and January / February 2018 (after installation of new refrigeration system) shows that the average monthly bills decreased by 10.23 per cent. This consumption decrease was expected to grow after system is stabilised and better operations practices to about 20 per cent.
Saudi Arabia	Demonstration project at air-conditioning manufacturers to develop window and packaged air-conditioners using low-GWP refrigerants (SAU/REF/76/DEM/29)	1,300,000	83	The results of demonstration projects show higher EER of HFC-32 and R-290 compared to R-410A at 52 degrees centigrade; EER decreases for all refrigerants when the outdoor temperature increases from 35 to 52 degrees centigrade.
Saudi Arabia	Demonstration project on promoting HFO-based low-GWP refrigerants for air-conditioning sector in high ambient temperatures (SAU/REF/76/DEM/28)	796,400	Not available	
Regional (West Asia), PRAHA-II	Promoting alternative refrigerants in air-conditioning for high ambient countries in West Asia (PRAHA-II) (ASP/REF/76/DEM/59 and 60)	700,000	Not available	
Foam sector				
Colombia	Demonstration project to validate the use of hydrofluoro-olefins for discontinuous panels in Article 5 parties through the development of cost-effective formulations (COL/FOA/76/DEM/100)	248,380	81	Results on energy efficiency were not directly reported; however, results show thermal conductivity levels for formulations using HFO-1233zd(E) and HFO-1336mzz(Z) co-blown with water were similar to HCFC-141b based formulations.
Egypt	Demonstration of low-cost options for the conversion to non-ODS technologies in polyurethane foams at very small users (EGY/FOA/76/DEM/129)	295,000	83	The report did not provide information on energy efficiency of the equipment.
Morocco	Demonstration of the use of low cost pentane foaming technology for the conversion to non-ODS technologies in polyurethane foams at small-and medium-sized enterprises (MOR/FOA/75/DEM/74)	280,500	Not available	

Country	Project title (code)	Funding (US $)*	Meeting	Update on the progress in implementation
Refrigeration and air-conditioning and assembly sub-sector				
Saudi Arabia	Demonstration project for the phase-out of HCFCs by using HFO as foam blowing agent in the spray foam applications in high ambient temperatures (SAU/FOA/76/DEM/27)	96,250	Not available	
South Africa	Demonstration project on the technical and economic advantages of the vacuum assisted injection in discontinuous panels plant retrofitted from HCFC-141b to pentane (SOA/FOA/76/DEM/09)	222,200	81	Results on energy efficiency were not directly reported; however, results show thermal conductivity levels comparable to HCFC-141b.
Thailand	Demonstration project at foam system houses to formulate pre-blended polyol for spray polyurethane foam applications using low-GWP blowing agent (THA/FOA/76/DEM/168)	352,550	83	Results on energy efficiency were not directly reported; however, results show thermal conductivity levels for formulations using HFO-1233zd(E) and HFO-1336mzz(Z) co-blown with water had marginally higher thermal conductivity. This could change with improvements in the formulations.
Feasibility study for district cooling				
The Dominican Republic	Feasibility study for district cooling in Punta Cana (DOM/REF/74/TAS/57)	91,743	81	Energy efficiency was a key benefit from the project; Actual energy efficiency performance gains is not available.**
Egypt	Feasibility study for district cooling in New Cairo (EGY/REF/75/TAS/127 and 128)	27,223	82	The reports contain techno-economic feasibility of the district cooling configurations and return calculations. Actual energy efficiency performance gains is not available.**
Kuwait	Feasibility study comparing three not-in-kind technologies for use in central air-conditioning (KUW/REF/75/TAS/28 and 29)	27,223	82	The reports contain techno-economic feasibility of the district cooling configurations and return calculations. Actual energy efficiency performance gains is not available.**

* This value does not include project preparation fund and agency support cost.
** TEAP task force report mentions that district cooling systems reduce power demand by 55 to 62 per cent in comparison to conventional air conditioning systems and consume 40 to 50 per cent less energy

83. Table 12 lists the ten stand-alone HFC investment projects so far approved. While the report on energy efficiency performance of the redesigned equipment is required in the final report, the results of these projects is not available as of date.

Table 12. Stand-alone HFC investment projects so far approved

Country	Agency	Project title
Argentina	UNIDO	Conversion project for replacement of HFC-134a with isobutane (R-600a)/propane (R-290)-based refrigerant in the manufacture of domestic and commercial refrigeration equipment at Briket, Bambi and Mabe-Kronen
Bangladesh	UNDP	Conversion from HFC-134a to isobutane as refrigerant in manufacturing household refrigerator and of reciprocating compressor of HFC-134a to energy efficient compressor (isobutane) in Walton Hi-Tech Industries Limited
China	UNDP	Conversion from C5+HFC-245fa to C5+HFOs in a domestic refrigerator manufacturer (Hisense Kelon)
Dominican Republic (the)	UNDP/Canada	Conversion of a commercial refrigerator manufacturing line at Fábrica de Refrigeradores Comerciales, SRL (FARCO) from HFC-134a and R-404A to propane (R-290) as refrigerant
Jordan	UNIDO	Conversion of large commercial unitary roof top air-conditioning units of up to 400kW manufacturing facility from HFC (R134a, R-407C, R-410A) to propane R290 as refrigerant at Petra Engineering Industries Co.
Lebanon	UNIDO	Conversion from HFC-134a and HFC-404A to R-600a and R-290 in domestic refrigeration at Lematic Industries
Mexico	UNIDO	Conversion of commercial refrigeration manufacturing in two facilities from the use of HFC-134a and R-404A as the refrigerants to propane (R-290) and isobutane (R-600a) at Imbera
Mexico	UNDP/Canada	Conversion of domestic refrigeration manufacturing facility from HFC-134a to isobutane as a refrigerant and conversion of compressors manufacturing facility from HFC-134a-based to isobutane-based at Mabe Mexico
Thailand	IBRD	Conversion from HFC to propane (R-290) and isobutene (R-600a) as a refrigerant in manufacturing commercial refrigeration appliances in Pattana Intercool Co. Ltd.
Zimbabwe	UNDP/ France	Conversion from HFC-134a to isobutane in the manufacture of domestic refrigerators at Capri (SME Harare)

Recommendation

84. The Executive Committee may wish to consider the summary of the report by the Technology and Economic Assessment Panel on matters related to energy efficiency with regard to the issues identified in decision 82/83(e) (decision 82/83(f)) contained in document UNEP/OzL.Pro/ExCom/83/42 during its deliberations relating to ways to operationalize paragraph 22 of decision XXVIII/2, and paragraphs 5 and 6 of decision XXX/5.

Annex I

GLOSSARY OF TERMS USED IN THE PRESENT DOCUMENT

APF: Annual Performance Factor (see Seasonal Energy Efficiency Ratio)

Coefficient of performance (COP, sometimes CP or CoP): For a heat pump, refrigerator or air conditioning system, this is a ratio of useful heating or cooling provided to work required. Higher COPs equate to lower operating costs.

Cooling capacity: A measure of a system's ability to remove heat. Measured in kW, Btu/h, or refrigeration ton (RT), where 1 RT = 3.5 kW = 12,000 Btu/h.

Cooling/heating load: The amount of energy needed to heat or cool to a desired level of service. Improving insulation in a building is a strategy for reducing heating and cooling load while providing the same level of comfort to the occupant.

Coefficient of Performance (COP): COP is defined as the ratio between the cooling capacity and the power consumed by the system. COP is also used for heat pumps and in this case it is defined as the ratio between the heating capacity and the power consumed by the system.

CSPF: Cooling season performance factor (see Seasonal Energy Efficiency Ratio).

Design efficiency: The energy performance of equipment as designed or as shipped, same as nameplate efficiency.

Energy Efficiency (EE): Energy efficiency is an attribute of a device or process, which can be either high or low.

Energy Efficiency Ratio (EER): Ratio of the cooling output divided by the electrical energy input when measured at full load (i.e., at the maximum cooling capacity or the design point) and is measured in W/W or Btu/h/W (1 W = 3.412 Btu/h).

Energy performance: The amount of energy consumed for a piece of equipment or system to perform a specific level of service. EE improvements referred to in this report, compare the energy used by an improved design to a baseline design. For example, if System A uses 10 units of energy and System B uses 8 units, there is a 20 per cent efficiency improvement.

HSPF: Heating Seasonal Performance Factor (see Seasonal Energy Efficiency Ratio)

Installed efficiency: The energy performance of equipment as installed.

ISEER: Indian Seasonal Energy Efficiency Ratio.

Kilowatthour (kWh): A measure of electricity defined as a unit of work or energy, measured as 1 kilowatt (1,000 watts) of power expended for 1 hour. One kWh is equivalent to 3,412 British Thermal Units (Btu) or 3.6 MJ.

Manufacturing cost: cost to manufacture the equipment.

Million tonnes oil equivalent (Mtoe): 1 Mtoe = 11.63 billion kWh

Nominal design point: represents the set of conditions (e.g. indoor and outdoor temperatures) used to design the system

Operating cost: The cost to the equipment user to operate the equipment.

Part-load operation: condition that happens when the system has to face a load lower than nominal (nominal conditions are used for the design of the system). RACHP systems usually operate at part-load conditions for most part of their life cycle.

Peak Load: The highest electricity demand occurring within a given period on an electric grid.

Percent energy efficiency improvement: percent change in energy consumption of an efficient unit compared with a base unit.

Refrigeration Ton (RT): Measure of cooling capacity, where 1 ton refers to 12,000 Btu, equivalent to the energy required to freeze 2000 pounds of water in 24 hours. 1 RT = 3.52 KW.

Retail price: Price to purchase the equipment.

Seasonal Energy Efficiency Ratio (SEER): Ratio of cooling output divided by the electrical energy input, measured at full and part-load, and weighted to represent the overall performance of the device for the weather over a typical cooling season in each given country. An alternative name to SEER is the **Cooling Seasonal Performance Factor (CSPF)**. **Heating Seasonal Performance Factor (HSPF)** is used for heating mode. **Annual Performance Factor (APF)** is a metric used for reversible heat-pump room air conditioners that heat and cool.

Unit energy consumption: The amount of energy consumed by a unit of equipment, usually over one year.

Variable speed drives (VSD): A type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor, also known as inverter.