Guidance Report on net benefits and cost for energy efficient refrigeration design options

- Guidance on incremental capital and operating costs for improved energy efficiency (EE) in domestic and commercial refrigeration and the associated emission reduction calculation
- Study of market barriers; incl. potential increase in sales prices for higher EE products
- Technical and financial evaluation of options for enhancing EE in new models; including impact on production lines of more EE, lessons learned, and estimates of average costs based on case studies as well as summary of field visits and events attended

Project funded by:	United Nations Industrial Development Programme (UNIDO) and Kigali Cooling Efficiency Program (K-CEP)
Project implemented by:	International Copper Association (ICA)

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Table of Contents

List of Figures

List of Tables

List of Acronyms

ADL	Arthur D. Little
AHAM	Association of Home Appliance Manufacturers
ANSI	American National Standards Institute
BAT	Best Available Technology
BAU	Business as Usual
CERA	Commercial EPA Refrigerator Analysis
CFC	Chlorofluorocarbon
CLASP	Collaborative Labelling and Appliance Standards Program
CNC	Computer Numerical Control Machine
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CR	Commercial Refrigeration
DC	Direct Current
DP	Differential Pressure or Pressure Drop
DSM	Demand Side Management
ECM	Electronically Commutated Motor
E_r	Direct refrigerant emission
E_m	Refrigerant emissions during manufacturing
E_o	Refrigerant emissions operation,
E_{eol}	Refrigerant emissions end-of-life
E_{ind}	Indirect emissions
EF_{el}	Electricity emission factor (tCO_2/MWh)
EC_i	Yearly electricity consumption for refrigeration model i (MWh)
ER	emissions reduction
EE	Energy Efficiency
EEV	Electronic Expansion Valve
EER	Energy Efficiency Ratio
GHG	Greenhouse Gas
GWP	Global Warming Potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HT	Heat Transfer
ICC	Incremental capital cost

IEA	International Energy Agency
IEC	International Electrotechnical Commission
IGU	Insulated Glazing Unit
IIR	International Institute of Refrigeration
IOC	Incremental operational cost
IOT	Internet of Things
IPCC	Intergovernmental Panel for Climate Change
IR	Infrared
K-CEP	Kigali Cooling Efficiency Program
LCCP	Lifecyle Climate Performance
LED	Light Emitting Diode
MCHX	Microchannel Heat Exchanger
MDI	Manufacturer Development Index
MEPS	Minimum Efficiency Performance Standard
MLF	Multi-Lateral Fund
MSP	Manufacturing Selling Price
NOAA	National Oceanic and Atmospheric Administration
ODP	Ozone Depleting Potential
ODS	Ozone Depleting Substances
OEM	Original Equipment Manufacturer
RACHP	Refrigeration, Air-Conditioning, and Heat Pumps
RTOC	Refrigeration and Air Conditioning Technical Options Committee
R&D	Research and Development
TEAP	Technology and Economic Assessment Panel
TEWI	Total Equivalent Warming Impact
TSD	Technical Support Documents
U4E	United for Efficiency
UNEP	United Nations Environmental Program
UNIDO	United Nations Industrial Development Organization
US DOE	The US Department of Energy
VIP	Vacuum Insulated Panels
XPS	Expanded Polystyrene

Subscripts

eq	Equivalent

EE	Due to Energy Efficiency
GWP	Due to GWP
RC	Due to Refrigerant Conversion
100	GWP assessed over 100 years

About the project

The Kigali Cooling Efficiency program (K-CEP), supported by 18 foundations and individual donors contributing to help increase the EE of cooling in developing countries, approved the UNIDO's project of "Assessment of incremental capital and operating costs for improved EE in domestic, commercial and retail refrigeration in Guatemala, Ecuador, Uganda, Lebanon, Jordan, Morocco and Tunisia". The project component under which this cost guideline was developed assessed potential incremental capital and operating cost based on ongoing or planned projects related to EE improvements within the domestic and commercial refrigeration in the countries selected and submitted to the Multilateral Fund (MLF).

The project includes also assessing respective markets in terms of barriers and advice on ways forward, offering inputs and recommendations. The results obtained in the project and lessons learned will be applied to future country projects for domestic and commercial refrigeration sectors in the most cost-effective way. Additionally, it will demonstrate the EE contributions to accelerate the climate benefits of the Kigali Amendment to phase down hydrofluorocarbons (HFCs).

The project includes technical assistance and field visits to companies producing domestic and commercial refrigerators in Guatemala, Ecuador, Uganda, Lebanon, and Morocco and will develop cost analysis based on conversion of technical solutions.

We would like to acknowledge UNIDO Staff: Mr. Fukuya Iino, Ester Cristina Monroy Gonzalez, Jude Sentongo Kafeero, Mary Najjuma, and Bojan Bogomirovic. We would also like to acknowledge support from the local UNIDO offices and National Ozone Unit officers in Ecuador, Guatemala, Lebanon, Morocco, and Uganda for their support and the active participation from the domestic and commercial refrigeration unit manufacturers in these 5 countries. Finally, we would also like to acknowledge the great effort of the expert reviewers: Prof. Roberto Peixoto, Mr. Alex Pachai, Mr. Farzi Irannejad, and Mr. Osama Said Mostafa.

1 Introduction

Global warming is accelerating faster than originally expected, and more dire impacts are expected based on the most recent scientific studies as shown in the latest IPCC special report on "Global Warming of 1.5°C"[1]. The IPCC estimates that the global average temperature increase is likely to reach 1.5°C between 2030 and 2052 based on current business-as-usual (BAU) case. The IPCC showed that long-lasting or irreversible impacts may be experienced if temperature increase exceeds 2°C. The 1.5°C-consistent pathways require rapid reduction in CO_2 emissions and other greenhouse gases (GHGs). In 2015, the International Institute of Refrigeration estimated that the global stock of refrigerators is consuming roughly 4% of global electricity[2]. Furthermore, RTOC 2018 assessment report estimated the global installed stock of domestic refrigerators to be between 2 and 2.3 billion units in 2018[3]. As such, the use of HFCs and the rapid urbanization are expected to further increase the share of buildings related GHG emissions.

The Kigali Amendment to the Montreal Protocol[4] focuses primarily on the reduction of the global warming impact of refrigerants, including a phase-down schedule for the use of HCFCs. Recent discussions amongst the parties of the Montreal Protocol have reinforced the need to consider a life-cycle climate performance (LCCP) approach and consider both refrigerant transition (to lower GWP gases) and efficiency improvement simultaneously. Previous refrigerant transitions have demonstrated that the RACHP sectors' energy efficiency may be improved while selecting the next generation refrigerants. Various examples have been seen, especially in the domestic refrigerators where the transition from CFC-12 to HFC-134a and HC-600a have shown successful introduction to more efficient appliances.

NOAA's periodic report on global climate states that the 2019 Northern Hemisphere meteorological summer (June through August) was the hottest in 140-years of climate records, tied with 2016.[5] The 2019 Northern Hemisphere land and ocean surface temperatures for the period were 1.13°C (2.03°F) above average.

Meanwhile, this same period (June through August) is the Southern Hemisphere's winter, and this year's Southern Hemisphere winter was tied with 2015 as the planet's second warmest, after 2016. This year's Southern Hemisphere winter was at 0.74°C (1.33°F) above the 20th century average. Extreme high air temperatures contribute directly to deaths from cardiovascular and respiratory disease, particularly among elderly people. In the heat wave of summer 2003 in Europe for example, more than 70 000 excess deaths were recorded.[6]

Against this background the use of cooling devices in buildings including commercial properties will inevitably grow in order to improve human comfort, health and productivity. Whilst there have been significant GHG emission reductions made since the 1980s, this is unlikely to be enough to offset the

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[1] https://www.ipcc.ch/sr15/. Accessed April 26th, 2020.

[2] https://www.coursehero.com/file/23918862/NoteTech-29-EN/. Accessed April 26th, 2020.

[3] UNEP (2018). Assessment report of the Refrigeration and Air conditioning Technical Options Committee (RTOC). https://ozone.unep.org/sites/default/files/2019-04/RTOC-assessment-report-2018_0.pdf. Accessed April 26th, 2020.

[4] https://www.unenvironment.org/news-and-stories/news/kigali-amendment-montreal-protocol-another-global-commitment-stop-climate. Accessed April 2020.

[5] https://www.ncei.noaa.gov/news/global-climate-201908. Accessed April 26th, 2020.

[6] Robine, Jean-Marie, Siu Lan K. Cheung, Sophie Le Roy, Herman Van Oyen, Clare Griffiths, Jean-Pierre Michel, and François Richard Herrmann. "Death toll exceeded 70,000 in Europe during the summer of 2003." Comptes rendus biologies 331, no. 2 (2008): 171-178.

increased demand from new appliances. Further innovation, design and engineering solutions will need to be implemented on the short term and at scale to improve the refrigeration equipment efficiency, optimize their utility, and enable lower GHG emission energy sources (e.g. renewable energy). Moves to reduce GHG emissions from the electricity grid and to develop alternative renewable technologies for cooling have not yet achieved economic feasibility for mass market uptake.

This report provides a review of energy efficiency options while phasing down high global warming potential refrigerants for the domestic refrigerator sector and light commercial refrigeration applications. It includes guidance for incremental capital and operation cost for the manufacturers that participated. The report also summarizes our findings on market barriers for energy efficient domestic and light commercial refrigerators across the countries studied. These findings reflect interviews conducted during the site visits.

2 Evaluation Methodology of Incremental Cost Assessment and Estimations

The global domestic refrigeration market was estimated to have an annual global production of 80 million units, with an installed stock of 1.5 billion units and a lifetime of 20 years, by 2005 during the Ozone Depleting Substances (ODS) Phase-Out activities[7]. This market grew to an approximate annual production of 170 million domestic refrigerators and freezers in 2014.[8] The estimated 20-years product life and growing markets result in an estimated 2.0 to 2.3 billion units of global installed inventory. The IPCC/TEAP Special Report[7] indicates that HFC-134a and HC-600a were the primary refrigerants used during the CFC phase-out transition. The HFC-134a had larger market share amongst the frost-free and larger capacity refrigeration units. Domestic refrigeration unit designs vary from region to region; however, it is becoming a global commodity with more features entering developing economies. For domestic refrigeration units manufactured in emerging economies energy efficiency is strongly influenced by configuration, component hardware selection (cabinet insulation, heat exchange design, control algorithms, refrigerant systems, heat losses, parasitic power demands such as fans and anti-sweat heaters and product safety), and whether the product complies with national and international initiatives (e.g. global and regional harmonization of MEPS, CLASP[9], AHAM, 2012[10]). The ODS phase-out in the domestic refrigeration industry was completed worldwide by 2008.[5] HC-600a (isobutane) and HFC-134a emerged as the only viable alternatives to the CFC refrigerants for new production.

The comparison between baseline and improved energy efficiency performance should be based on a comprehensive Life Cycle Climate Performance (LCCP) or Total Equivalent Warming Impact (TEWI) of domestic refrigeration design options. LCCP or TEWI consider two general types of GHG emissions: direct, which for discussion of the refrigerant choice are limited to the refrigerant itself; and indirect, which depends on the refrigerator design, the infrastructures of supporting services in the use environment, and other GHG emissions related to running the refrigerator.

According to IPCC/TEAP special report 2005[7], the direct GHG emissions, that are related to direct refrigerant release to the atmosphere, are attributed to:

- Refrigerant emissions during manufacturing: refrigerant transfer and storage, charge station operations, maintenance protocols, and factory process efficiencies
- Key refrigerator design variables: hermetic-system internal volume, number of joints, mechanical fatigue, and abuse tolerance and, the refrigerant GWP
- Variables influencing emissions during service: refrigerant recovery procedure usage and efficiency, charge technique employed, technician training and technician work standards

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[7] IPCC/TEAP Special Report: Safeguarding the Ozone Layer and the Global Climate System, Chapter 4 Refrigeration IPCC, Cambridge Press, 2005. https://www.ipcc.ch/report/safeguarding-the-ozone-layer-and-the-global-climate-system/. Accessed April 26th, 2020.

[8] Montreal Protocol on Substances that Deplete the Ozone Layer, UNEP, Report of the Technology and Economic Assessment Panel, May 2018, Volume 5, Decision XXIX/10: Task Force Report on Issues Related to Energy Efficiency while Phasing Down Hydrofluorocarbons. ISBN: 978-9966-076-42-7

[9] https://clasp.ngo/. Accessed April 26th, 2020.

[10] AHAM (2012). Association of Home Appliances Manufacturers Voluntary Standard AHAM 7001-2012/CSA SPE-7001-12/UL 7001, “Sustainability Standard for Household Refrigeration Appliances”

- End-of-life refrigerant emissions: this is the typical release of refrigerant stored in the equipment when it is disposed-off at the end of its useful life

Whilst indirect GHG emissions, that are related to GHG emissions from manufacturing and recycling processes and electricity production, are attributed to:

- CO_2 emissions during the manufacturing and assembly of the equipment (electricity consumption and other direct GHG emissions other than refrigerants)
- Operating efficiency (electricity consumption)
- GHG emissions during recycling process (depend on the ease of refrigerator disassembly and separation for recycling)

2.1 Energy Efficiency Design Options for Domestic Refrigerators

Domestic refrigerator energy efficiency (EE) may be improved through modifications to the refrigerator configuration and component hardware selection (cabinet insulation, gaskets, heat exchanger design, controllers, refrigerant systems, parasitic power demands such as fans and anti-sweat heaters, and product safety). Such areas of EE opportunities are listed in detail in the Refrigeration and Air Conditioning Technical Options Committee (RTOC, 2018) report[3], the International Energy Agency energy efficiency policy profiles report (IEA, 2003)[11], the Arthur D. Little global comparative analysis of HFC and alternative technologies (ADL, 2002)[12], the Technical Support Documents of the US Department of Energy rulemakings for domestic refrigerators and freezers[13], and the ecodesign support documents[14]

According to International Institute of Refrigeration (IIR)[15], the refrigerant choice is a trade-off between many factors including ease of manufacture, cost, toxicity, flammability, environmental impact, corrosiveness, and thermodynamic properties as well as energy efficiency. Higher critical temperature results in improved energy efficiency and better transport properties that improve heat transfer and reduce the compressor temperature lift. Additionally, energy efficiency is also impacted by:

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[11] IEA (2003), Cool Appliances, Policy Strategies for Energy Efficient Homes. International Energy Agency (IEA), Paris, France.

[12] ADL (2002), Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications. Final Report to the Alliance for Responsible Atmospheric Policy, March 21, 2002, Acorn Park, Cambridge, Massachusetts, USA, 150pp.

[13] EERE (2009), 2010-09-23 Technical Support Document: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers, https://www.regulations.gov/document?D=EERE-2008-BT-STD-0012-0060. Accessed April 26th, 2020.

[14] VHK and ARMINES (2016). Commission Regulation (EC) No. 643/2009 with regard to ecodesign requirements for household refrigeration appliances and Commission Delegated Regulation (EU) No. 1060/2010 with regard to energy labelling of household refrigeration appliances – final report. Preparatory/Review Study. https://www.eup-network.de/fileadmin/user_upload/Household_Refrigeration_Review_FINAL_REPORT_20160304.pdf. Accessed April 26th, 2020.

[15] IIR (2003), 17th Informatory Note on Refrigerating Technologies How to improve energy efficiency in refrigerating equipment, November 2003 (prepared by S. Forbes Pearson, winner of the IIR Gustav Lorentzen Medal awarded at the 21st IIR International Congress of Refrigeration in Washington DC in August 2003)

- Compressors: part load performance has detrimental impact on the system efficiency – use of variable speed or variable capacity compressors with improved controls can minimize the energy penalty but increases capital costs
- Condenser: keeping the condenser clean and free from fouling allows plenty of fresh air and protection against recirculation. The use of advanced designs and implementation of advanced sub-coolers is also desirable
- Expansion devices: use of electronic expansion valves will improve system and part load controls
- Evaporators: design heat exchanger with optimum trade-off between cost and temperature difference. Refrigerant distribution and circuiting, air flow distribution, use of enhanced surfaces, and refrigerant and airside pressure drops can all significantly affect energy efficiency
- Defrost: regular defrosts are required to restore performance. Electric timed defrost is simple but is least efficient. It is important to optimize the frequency and duration of defrost to avoid unnecessary defrosting
- Interconnecting piping: wrong size or bad piping arrangement (e.g. excessive bends and fitting) may cause unnecessary pressure drops or inhibit oil return
- Controls: improved controls allow the refrigeration system to run more efficiently even during part-load performance.

The refrigerant choice has certain but lower impact on energy efficiency compared with system load, system design, component selection, and use of effective controls.[16] It is important to consider safety and reliability during the transition towards flammable refrigerants such as HC-600a.[17] Indicative ranges for energy savings from EE options are summarized below[18]:

- Refrigerant choice: 5 – 10%
- Components and controls: 30 – 70%
- Minimizing cooling load: 30 – 60%

A summary of refrigerant choices and their impacts is provided in Table 1 below. In this table we only consider the two viable refrigerants that emerged as alternatives for new refrigerator production during the phase-out of CFCs.

Mature EE design options for domestic refrigerators and freezers include:

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[16] UNEP (2018a), "Briefing Note B: The Potential to Improve the Energy Efficiency of Refrigeration, Air-conditioning and Heat Pumps", https://ozone.unep.org/sites/default/files/2019-08/briefingnote-b_potential-to-improve-the-energy-efficiency-of-refrigeration-air-conditioning-and-heat-pumps.pdf. Accessed April 26th, 2020.

[17] UNEP (2017), TEAP TF report under Decision XXVIII/4 "Safety Standards for Flammable Low Global Warming Potential (GWP) Refrigerants". Available at https://ozone.unep.org/sites/default/files/2019-05/TEAP-XXVIII_4-TF-Report-May 2017.doc. Accessed April 26th, 2020.

[18] UNEP (2018b), "Briefing Note A: The Importance of Energy Efficiency in the Refrigeration, Air-conditioning and Heat Pump Sectors", http://conf.montreal-protocol.org/meeting/workshops/energy-efficiency/presession/breifingnotes/briefingnote-a_importance-of-energy-efficiency-in-the-refrigeration-air-conditioning-and-heat-pump-sectors.pdf. Accessed April 26th, 2020.

- Efficient compressors
- High efficiency heat exchangers
- Improved low thermal loss cabinet structures and gaskets
- Less variable manufacturing processes

Application of these options is constrained by available capital funds and product cost trade-off.

Table 1 Domestic Refrigerator Refrigerant Choice and Implications[19]:

Refrigerant	**HFC-134a**	**HC-600a**
ODP	0	0
GWP	1300	3
Safety Designation	A1	A3
Energy Efficiency	NA (baseline)	About 3% better
Safety Implications	None	Precautions necessary for appliance design, manufacture, servicing, and disposal
Design Issues	None	Reduce leakage and ensure no sparks can ignite leaked refrigerant
Cost Difference	NA (baseline)	About 2% more expensive compared with HFC-134a
Service and Maintenance implications	None	Trained technicians and special equipment to handle flammable gas
End of Life	Must be recovered and destroyed or recycled	safe venting or recovery
Prospects for future use and availability	Phased out in EU; Kigali amendment to the Montreal Protocol phase-down of HFCs	Safety reasons might impact use in some economies

Additionally, there are other design options that might be introduced in premium-cost models or where strict minimum energy performance standards are in place such as:

- Variable speed compressors,
- Intelligent controls,
- System reconfigurations (e.g. dual evaporators),
- Advanced insulation systems and cabinet design,

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[19] U4E (2017), Accelerating the Global Adoption of Climate-Friendly and Energy-Efficient Refrigerators, UN Environment – Global Environment Facility, United for Efficiency (U4E), https://united4efficiency.org/resources/accelerating-global-adoption-energy-efficient-climate-friendly-refrigerators/, English version, page 66. Accessed April 26th, 2020.

- Demand Side Management (DSM) initiatives requiring interactive communication with energy providers in order to implement the Smart Grid concept.

The different energy test standards might not be able to capture the energy savings from the different options presented above. Thus, product manufacturers need to understand and test their product developments against internal development tools, using where possible standardised tests. It is important to consider the use of a comprehensive international test standard such as IEC 62552-3:2015[20] to be able to evaluate the potential of such developments. A more detailed list of EE technology options based on the US DOE technical support document is listed in Appendix 3.

Based on the information presented above, we may conclude that replacing HFC-134a with HC-600a would have a small positive impact on equipment efficiency. When, comparing the same generation HFC-134a and HC-600a compressors, we find that their performance was comparable. However, due to the demand for higher efficiency HC-600a compressors and their increased market share, HC-600a compressors became more efficient than baseline HFC-134a compressors. The main efficiency improvements will come from using advanced and variable capacity compressors, improved evaporator fans using electronically commutated motor (ECM), improved cabinet design and insulation, and high-performance heat exchangers designs. Advanced controls and system designs is an evolving area of research and development and may yield additional significant improvements. It is important to always consider the trade-off between energy efficiency gains and incremental cost when considering the different technology options.

2.2 Energy Efficiency Design Options for Commercial Refrigerators (CR)

CR equipment need to operate continuously and reliably as they often hold many thousands of USD worth of product and a failure of the system can result in product and financial loss. Furthermore, they need to maintain perishable goods at a temperature to avoid spoilage and ensure it remains edible and of acceptable quality (taste, texture, colour, etc.). Finally, the functionality and construction of CR equipment differs widely:

- Operating temperature range from below -20°C (ice cream) to over +10°C (vegetables)
- May be configured as vertical, horizontal, corner, and combined orientations equipment
- May be open or with doors
- Operation may be continuous or intermittent (e.g. bottle coolers being unplugged at nigh time)
- Ambient conditions vary depending on installation location, weather, etc.

Hence, CR products require more customization. Consequently, the production volume may be considered small, in the range (100), to medium scale, in the range (1000), per model per year. The heat load in CR equipment depends largely on construction type (thermal conduction, infiltration), and internal heat loads (product perspiration, defrost heat, fan/motors, lighting, etc.).

CR EE depends on system design, components, and equipment construction. Cost of EE design options may vary widely, depending upon the type of appliance, its size, and its function. EE options have been broadly categorised according to function, e.g., improving airflow, improving fan energy, reducing heat load and so on. During product developments, engineers work on several aspects of CR equipment including manufacturability, reliability, cost, performance, and of course EE. However, it is

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[20] IEC 62552-3:2015, “Household refrigerating appliances - Characteristics and test methods - Part 3: Energy consumption and volume”, https://webstore.iec.ch/publication/21803. Accessed April 26th, 2020.

important to consider cost-neutral EE upgrades first. Cost-neutral or cost-saving options for manufacturers to improve EE include:

- Micro-channel heat exchangers or small diameter tubes
- Improved fan designs
- Optimized air flow distribution
- Higher efficiency compressors
- Evaporator and Condenser design optimization (within certain limits)

Holistic investigations of EE measures are important as they may increase or decrease costs elsewhere within the system. Fans with brushless DC motors, or ECM, used in CR equipment would require more expensive electrical conductor (3- or 4-wires DC conductor instead of 2-wires AC conductor). In contrast, a higher efficiency commercial refrigerator requires less electrical power and thus smaller electrical wire gauge and switches with a lower total installed cost. Another example of holistic impact is that of all aluminium micro-channel heat exchangers they result in several cost reducing aspects including:

- Reduce material cost
- Reduce refrigerant charge/cost
- Reduce chassis cost due to being smaller and lighter
- Reduce cover cost
- Reduce packaging cost
- Reduce transportation and storage costs.

Below is a more detailed discussion on some of the most relevant EE design options for CR equipment:

- Compressors

Compressors vary depending on temperature lift, capacity, refrigerant type, and construction type. Incremental efficiency improvements can be obtained from enhanced oil distribution, reduced valve losses, improved motor efficiency, reduced internal leakage, reduced flow path pressure losses, etc.). Further improvement can be achieved through improved manufacturing tolerances, use of high efficiency designs (rotary instead of reciprocating), and use of variable speed technology using inverter technology. Variable speed technology allows refrigerant mass flow rate to suit the system’s cooling load (optimal balance point for the surrounding temperatures).

- Cabinet airflow

Cabinet airflow has significant impact on energy use and product quality. Improvement can be achieved by changing the air duct configuration or using baffles and plates to guide the airflow. These improvements are mostly cost-neutral; however, they require detailed research and development (R&D).

- Fan/motors

ECM fan motors have resulted in a quantum shift in efficiency which in turn resulted in significant reduction in corresponding internal heat load. The benefit is double fold: reduce electric consumption and reduce internal cabinet heat load. Furthermore, fan structure and blade shape can offer additional energy savings.

- Cabinet lighting

CR equipment typically used to employ fluorescent lamps. However, with the advent and proliferation of light emitting diode (LED) technology, they became more widely used. LEDs offer double benefit: use less power and reduce heat load.

- Defrost techniques

Several defrost techniques have been investigated in CR equipment including reverse cycle, hot gas, cool gas, electrical resistance heaters, and “off-cycle”. Reverse cycle, hot gas and cool gas defrost technologies are efficient but tend to be more expensive and impact system reliability. Other relevant technique is to optimize the defrost cycle by use on-demand technology.

- Controls

Modern control technologies offer significant EE improvement potential. Electronic expansion valve (EEV) and associated control have significant potential for EE improvements. However, EEV technology is currently limited due to the relatively high cost. Other advanced controllers linking compressor modulation, EEVs, defrost-on-demand, lighting, trim-heaters, fan airflow rates, fault detection (leaks), and occupancy have a major influence on energy consumption.

- Heat exchanger design

Heat exchanger design features impact CR equipment performance differently. It is important to minimise the heat exchanger approach temperature difference (~5 K), for both evaporator and condenser. Wire-on-tube condensers are used, which are low cost and provide sufficient levels of EE. The major disadvantage is however, that degradation due to dust accumulation over time is substantially. Microchannel heat exchangers (MCHX) or small diameter copper tubing used as condensers reduce refrigerant charge and improve heat exchanger effectiveness.

2.3 Conversion and Abatement Costs for Domestic Refrigerators

In order to develop higher EE refrigeration equipment, additional capital investments and operating costs are incurred at the production facility and are reflected in the appliance selling price. However, the price premium is often offset by the reduced operating cost due to lower electricity consumption and reduced maintenance cost. Meanwhile, there are cases with tremendous potential for EE improvement with minimum to no price premium on the consumer is witnessed. As EE technologies mature, the market will benefit from the cost curve (mass-production), and prices will become more competitive versus the baseline technology. As an example, the domestic refrigerator appliance industry in the USA has successfully reduced the annual energy consumption by almost four-folds between 1972 and 2015 with an overall price reduction trend as shown in Figure 1. A breakdown of the lifetime CO_{2eq} emissions of a typical residential fridge-freezer in developed economies over time is shown in Figure 2. The significant reduction between a 1980 refrigerator and the 2015 global Best Available Technology (BAT) is primarily due to the reduction in indirect emissions associated with electricity consumption and direct emissions due to the phase-out of high GWP CFC refrigerants.

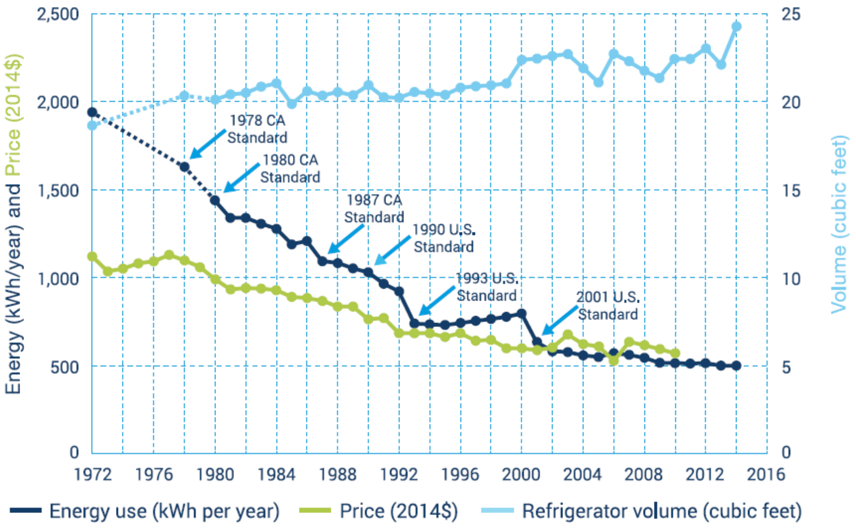

Figure 1: Average Household Refrigerator Energy Use, Volume, and Price Over Time

In Figure 1 above, data includes standard size and compact refrigerators; energy consumption and volume data reflect the current US DOE test procedure; the adjusted volume is equal to fresh food volume + 1.76 × freezer volume; and the prices present the manufacturers selling price in the U.S.

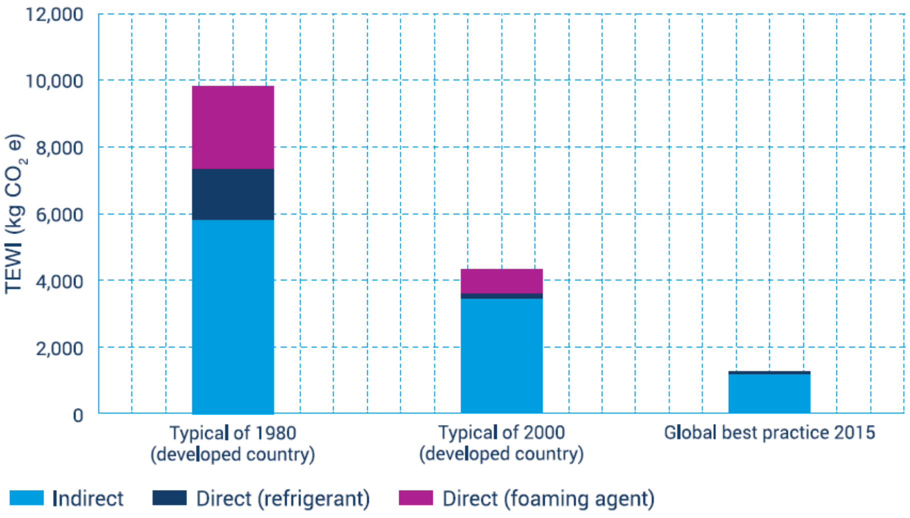

Figure 2: GHG emissions from domestic refrigerators[18]

2.4 Availability of Technology and Equipment for Domestic Refrigeration

Table 2 summarizes the conversion cost and abatement of HFC-134a refrigerators to HC-600a based on the baseline technology in the three most common domestic refrigerator configurations based on estimated manufacturing cost premiums, development costs, required implementation investments, and other abatement opportunities.[7] More recent investigations suggest that the manufacturing cost premium is significantly reduced due to the reduction of HC-600a compressor cost. Capital investment depends greatly on the manufacturing capacity; for a manufacturing capacity of 300k units per year the capital investment is under 1,000,000 USD.

Table 2: Domestic refrigeration, status and abatement options (as of 2005)[7]

Product Configuration	**Cold Wall**	**Open Evaporator, Roll Bond**	**No-Frost**
HC-600a manufacturing cost premium	No Premium	3 – 5 USD per unit	8 – 30 USD per unit
Worldwide Capital Investment	0	45 – 75 M USD	400 – 1,500 M USD
Worldwide GHG Emissions Reduction	1,432 tons	1,253 tons	6,086 tons

Several studies have investigated the LCCP or TEWI of domestic refrigeration and the refrigerant choice for small sealed equipment. The overall conclusion is that the indirect emissions are dominant and well over 95% of lifetime GHG emissions.[18]

Schwarz et al., 2013[21] estimated the mitigation costs for domestic refrigerators conversion to HC-600a 1.0 €/tCO_{2eq}. The 1.0 €/tCO_{2eq} marginal cost estimated by Schwarz et al. 2013 is primarily to account for the additional safety systems in relation to flammability. The higher efficiency of HC-600a systems results in lower running costs compared with HFC-134a systems, and subsequently lower lifetime cost. There are no significant technical barriers to the use of HC-600a. There is an estimated 800 million HC-600a domestic refrigerators installed worldwide.

The proprietary nature of business operations limits the availability of public data on capital and operating costs to the manufacturer related to EE improvements. Furthermore, retail prices and efficiencies of equipment on the global market lack correlations as there are other factors impacting product costs including design features, finish, advanced/premium features, commercialization, branding, and marketing. Field data suggests a price premium of 0 – 5% for HC-290 stand-alone commercial refrigeration units compared with conventional systems[8]. Furthermore, the UNEP 2015[22] desk study on evaluating HCFC Phase-out projects in the refrigeration and air conditioning manufacturing sector presented additional details on specific conversion costs such as refrigerant charging machines, safety requirements, etc. The majority of projects with tasks related to safety, flammability, and toxicity included:

- Additional safety-related equipment with the corresponding changes in project costs
- Training and operational procedures within the manufacturing plant
- Training related to the proper installation and servicing
- Coordination with responsible bodies regarding standards and codes for the use of the chosen technologies for design, manufacturing, installation, servicing, and transport

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[21] Schwarz W, Leisewitz A, Gschrey B, Herold A, Gores S, Papst I, Usinger J, Colbourne D, Kauffeld M, Pedersen PH and Croiset I, 2013. “Preparatory study for a review of Regulation (EC) No 842/2006 on certain fluorinated greenhouse gases”. Annexes to the Final Report Prepared for the European Commission in the context of Service Contract No 070307/2009/548866/SER/C4.

[22] UNEP 2015, “Desk Study on the Evaluation of HCFC Phase-Out Projects in the Refrigeration and Air-Conditioning Manufacturing Sector”, UNEP/OzL.Pro/ExCom/75/9, 19 October 2015.

Shah et al 2014[23] presented a study on potential refrigerator efficiency improvements showing cost-efficiency trade-off for the Indian market. While this study is not related to the countries involved in the present project, the results presented are quite relevant as it followed a similar methodology to the one adopted in our project. Furthermore, these results provide additional data for policy makers and product developers in developing countries. The summary of efficiency improvements is presented in Table 3 below. The options listed in Table 3 are cumulative; i.e. option 6b employs the highest efficiency compressor (EER = 6.67), the maximum use of vacuum insulated panels (VIP), the optimized thermal insulation design and improved gaskets. The expected energy savings may range from 65% to 85% depending on the final system integration at a total cost premium of up to 225 USD. Park et al 2018[24] provide incremental manufacturing costs for off-grid electric refrigerators subject to various EE technology options as shown in Table 4. Modelled data suggest up to 52% energy savings at a manufacturer selling price incremental cost increase of 60 USD with a maximum potential energy savings of 70% at a manufacturer cost premium of 213 USD. A detailed list of cost-efficiency trade-off based on the Technical Support Documents (TSD) of US DOE is listed in Appendix 4.

Table 3: Efficiency improvement options and corresponding energy savings for India[23]

Option #	**Change from previous option**	**Energy Consumption, kWh/yr.**	**% Energy Savings from baseline**	**Incremental Cost from Baseline (USD)†**
Baseline	Samsung RT35BD (fresh-food compartment=239 litres, frozen food compartment= 80 litres)	580.7	0%	0
1	Insulation in freezer walls/door = 60mm.	529.6	9%	1
2	Insulation in freezer walls/door = 80mm and in fresh-food compartment doors/walls to 60mm.	405.9	30%	1.5
3	Replacement of EER = 4.4 compressor with EER=6.0 compressor	202.2	65%	48
4b	90mm in freezer compartment and 65mm in fresh-food compartment and with optimized gaskets for doors or apertures	138.3	76%	53
5b	Maximum VIPs	95.6	84%	65
6b	EER=6.57 compressor	86.1	85%	225

* Options 4b, 5b, and 6b have less certain impacts

† The original study was done using pricing information in the local Indian market based local currency. The incremental cost is presented here in USD based on an average currency conversion assuming 1 Rs = 0.014 USD

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[23] Shah, N., Park, W.Y., Bojda, N., and McNeil, M., 2014 "Superefficient Refrigerators: Opportunities and Challenges for Efficiency Improvement Globally", 2014 ACEEE Summer Study on Energy Efficiency in Buildings, https://aceee.org/files/proceedings/2014/data/papers/8-1072.pdf. Accessed April 26th, 2020.

[24] Park, W.Y., Shah, N. & Phadke, A. Enabling access to household refrigeration services through cost reductions from energy efficiency improvements. Energy Efficiency 12, 1795–1819 (2019). https://doi.org/10.1007/s12053-019-09807-w. Accessed April 26th, 2020.

Table 4: Energy-efficiency improvement options for small off-grid refrigerators (not cumulative)[24]

Energy-efficiency improvement option	% Energy Savings		Incremental Manufacturing Cost (USD)	
	50 L	**100L**	**50L**	**100L**
2 cm increase in wall thermal insulation	18	25	10	15
6 cm increase in wall thermal insulation	34	40	30	45
Increase compressor coefficient of performance (COP) from 1.4 to 1.7	20	20	15	15
DC variable-speed compressors	23	23	27	27
Use Vacuum Insultation Panels (VIPs)	10	20	24	36

2.5 Availability and Cost of Technology and Equipment for Commercial Refrigeration

CR products that encompass the entire refrigeration system (compressors, expansion devices, evaporators, condensers, and ancillaries) in one packaged unit are considered here. Details of the equipment characteristics can be found in the latest RTOC Assessment Report (UNEP, 2018). Table 5 provides a summary of the potential EE improvement and indicative additional cost for different types of CR equipment. Some of these EE technology options are mainly attributed to the refrigerant changeover to HC-290 or HC-600a such as

- EE fan motors. These are required to minimise the sources for ignition within the system; this is especially important when working with flammable refrigerants
- Compressors. Compressors working with hydrocarbon refrigerants are readily available with higher efficiency than legacy compressors being replaced. This provides a unique opportunity for EE
- Heat exchangers. When working with flammable refrigerants, it is important to minimise the refrigerant charge to ensure that the equipment complies with the safety regulations when operating with flammable refrigerants. This is usually achieved using small diameter tube heat exchangers or micro-channel heat exchangers that offer a simultaneous improvement in efficiency
- Leak minimisation. CR equipment working with flammable refrigerant should operate with minimum leaks in order to minimise risks of deflagration. This results in a collateral benefit of operating the system closer to its design charge over its lifetime which results in improved EE.

Table 5: Overview of technical options for reducing energy consumption in self-contained commercial refrigeration units[25, 26]

Option	Potential EE improvement	Indicative additional cost	Applicable to†	Remarks
Anti-fogging glass	Minimal	<5%	GD F†	Avoids heating elements, as option
Improved cabinet air flow				
- air deflectors/guides	15%	neg.	OM†	Reduces cold spillage
- shelf risers and weir plates	4%	neg.	OM	Reduces cold spillage
- short air curtains	30%	Neg.	OM	Reduces cold spillage
- strip/night curtains	60%	$100	OM	Reduces cold spillage
Energy efficient fan/motors				
- EC fan motors	10%	15%	All	Less energy & heat load
- variable speed	10%	15%	All	e.g., 2-speed fixed
- optimised fan blades	5%	Neg.	All	
- tangential fans	5%	<10%	All	
- diagonal compact fans	5%	<10%	All	Match press drop of cabinet
- improved axial fans	5%	<10%	All	
Cabinet doors				
- doors on cabinets	45%	$300 per m	All	Reduces heat load and infiltration
- door gaskets	15%	$30	All	Reduces heat load and infiltration
Compressors				
- higher efficiency	20% (MT), 30% (LT)	Neg.	All	Increased by 20% over past 20 years
- Inverter driven	40%	2 × non-inverter	All	Better PL efficiency; with/out PFC
- motor efficiency controllers	10%	n/k	All	Regions having poor mains power; not needed for inverter driven
Cabinet lighting				
- LEDs	50% on lighting	<0%	All	Now standard
- occupancy sensors	10%	<0%	NP†	On demand lighting

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[25] Foster, A, Hammond, E, Brown, T, Maidment, G and Evans, J (2018). Technological options for retail refrigeration. Paris International Institute of Refrigeration/ London South Bank University. https://openresearch.lsbu.ac.uk/item/8688y. Accessed April 26th, 2020.

[26] Montreal Protocol on Substances that Deplete the Ozone Layer, UNEP, Report of the Technology and Economic Assessment Panel, May 2019, “Volume 4: Decision XXX/3 Task Force Report on Cost and Availability of Low-GWP Technologies/Equipment that Maintain/Enhance Energy Efficiency”, ISBN: 978-9966-076-66-3

Option	Potential EE improvement	Indicative additional cost	Applicable to[†]	Remarks
Defrost techniques				
- hot gas, reverse cycle	5%	3%	F	Increases leaks, faults
- off-cycle	10%	<0%	HT[†]/MT	Eliminates defrost energy
- on demand control	10%	<5%	All	Defrosts when needed
Control				
- dynamic demand controllers	40%	var	All	Manages energy use
- electronic expansion valves	20%	$200	All	Modulates evaporator pressure
- optimisation of capillary	Anything	Neg.	All	
- suction pressure control	2% per K increase	$40 - $400	All	Modulates evaporator pressure
Heat exchanger design			All	
- optimised configuration	0 to 40%, from baseline	neg	All	Better Heat Transfer (HT), lower pressure drop (DP)
- optimised air fins	10%	neg	All	Better HT, lower DP
- internal rifling	5%	neg	All	Better HT, lower DP
- internal fins	5%	neg	All	Better HT, lower DP
- hydrophobic coating	5%	neg	All	Mainly for condensers, reduces dust and corrosion
- hydrophilic coating	5%	neg	All	Anti-corrosion; reduce water layer thickness
Other heat load			All	
- radiant reflectors	8%	neg	All	Reflects infrared (IR)
- night blinds and covers	20%	$300	All	Can reduce IR and infiltration
- improved glazing	5%	5%	All	Reflects IR
- anti-sweat heater control	3%	Neg.	All	Minimise heat load
- refrigerant line trim heaters	10% to 25%	Neg.	All	Instead of resistance heaters
- vacuum insulated panels (VIP)	15%[27]	$\$400/\text{m}^2$	All	Reduces thermal conduction
Heat pipes	12%	n/k	All	In cabinet shelves, improv product temp
Leak minimisation			All	
- improved leak tightness	20%	10%	All	Degrees of improvement
- leak detection	15%	10%	All	Previously on large sys
Pipe insulation	3%	n/k	All	Normal practice

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[27] Clodic, D. and Zoughaib, A., "Technical and Economical Evaluation of Vacuum Insulated Panels for A European Freezer" (2000). International Refrigeration and Air Conditioning Conference. Paper 501. http://docs.lib.purdue.edu/iracc/501. Accessed April 26th, 2020.

Option	Potential EE improvement	Indicative additional cost	Applicable to[†]	Remarks
Higher efficiency refrigerant	Varies	+/-	All	See RTOC 2014[28], 2018[3]
Nanoparticles in refrigerant	20%	$20 – 100	All	Experimental, concerns

[†] OM: Open Multideck, F: Freezer, NP: Non-Perishables, GD: Glass Door, HT: High temperature, MT: Medium Temperature

2.6 Cost-Efficiency Model

An approach has been developed for evaluating cost-efficiency trade-off similar to the US DOE engineering analysis approach.[13] The main reason we adopted this approach is due to the availability of public lifecycle cost analysis tools for the different types of refrigerators, the availability of a refrigerator modelling framework with appropriate cost and efficiency information for the different EE technology options. We considered information from literature, manufacturers, vendors, and product catalogues to update the manufacturing cost and energy use reduction characteristics of different design options. Energy models based on a publicly available tool called Commercial EPA Refrigerator Analysis (CERA) were developed and used to evaluate the energy performance based on the various design options. Further, we developed a simplified manufacturing cost models for the original equipment manufacturer (OEM) and the corresponding incremental cost estimates based on the available worksheet developed by US DOE[29]. Finally, the results of the energy models and incremental cost estimates were used to develop the cost-efficiency curves as shown in Figure 3.

This activity was conducted during the site visits for the OEMs participating in this project. Additional data collection was performed after the site visits based on the forms shown in Appendices 1 and 2 (presented to the OEMs during the site visits) and Appendices 3 and 4 (with information based on public literature).

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[28] UNEP (2014). Assessment Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC).

[29] https://www.regulations.gov/docket?D=EERE-2008-BT-STD-0012. Accessed April 26th, 2020.

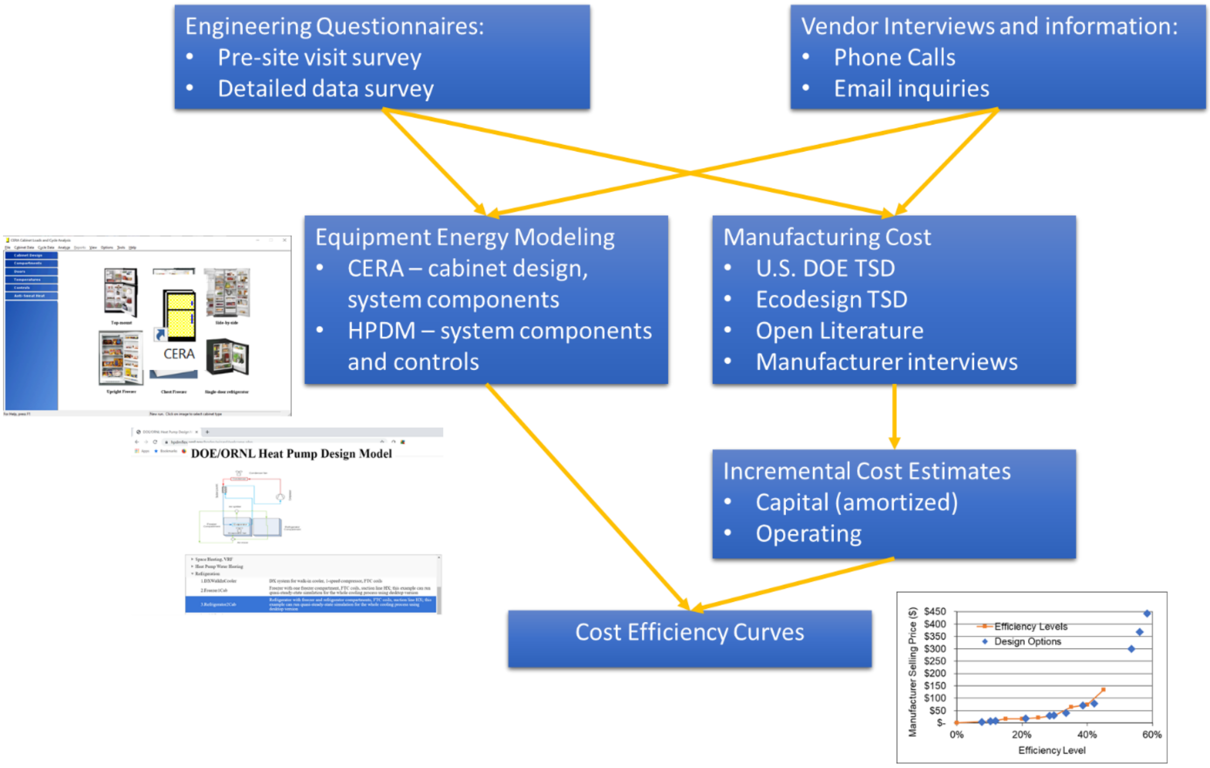

Figure 3: Cost-Efficiency Curves Architecture

2.7 Definitions

Incremental capital cost (ICC): this is the costs related to the conversion of the production line to handle the new technology. In this report, we refer to ICC related to converting the production lines to improve energy efficiency while converting the refrigerants to hydrocarbon flammable refrigerants.

Incremental operational cost (IOC). IOC is the recurring incremental cost to run the manufacturing line to produce the energy efficient equipment operating with the low GWP flammable refrigerants. This is not to be confused with the electricity and maintenance cost.

Energy Efficiency (EE). EE is the improvement in equipment energy efficiency, in this case it is the reduction in energy consumption to operate the equipment. It is calculated based on the applicable Minimum Efficiency Performance Standard (MEPS) for the different countries.

2.8 Manufacturer Development Index (MDI)

In this report we worked with six manufacturers in 5 countries. In order to maintain confidentiality, the manufacturers were rated according to the following equally weighted criteria:

- Manufacturer development capacity. This is based on their capacity to develop new energy efficient products while converting to natural refrigerants. The rating is based on the manufacturer's product development capacity: up to 3 points for having modelling capabilities, up to 4 points for having adequate experimental facilities, and up to 3 points for the product development team capabilities and management. This score for the manufacturers evaluated varied between 1 and 9.
- Manufacturer production volume. This rating is based on the percentage of the volume produced compared to the local or regional market. Manufacturers with regional leadership

were rated as 10, manufacturers; with national leadership with rated at 8; medium scale manufacturer were rated as 5 and small producing manufacturers were rated as 2.

- Manufacturer proximity to and relationship with component's OEM. This is rated based on the ease of access to components and the ability to work with the supplier to provide the most optimised solutions. Up to 4 points are given for relationship with OEMs, up to 3 points are given for distance to OEM's and border/custom issues to account for transportation cost, and up to 3 points are given for ease of placing an order and securing foreign currency. This score for the manufacturers evaluated varied between 3 and 10.
- Market maturity. This is rated based on the consumer awareness (up to 3 points), having MEPS in place, either national or regional (up to 3 points), and product competition (up to 4 points). This score for the manufacturers evaluated varied between 2 and 9.
- Country's energy efficiency score[30]. This score was obtained directly from World Bank RISE index[31] and normalised to a value of 10.

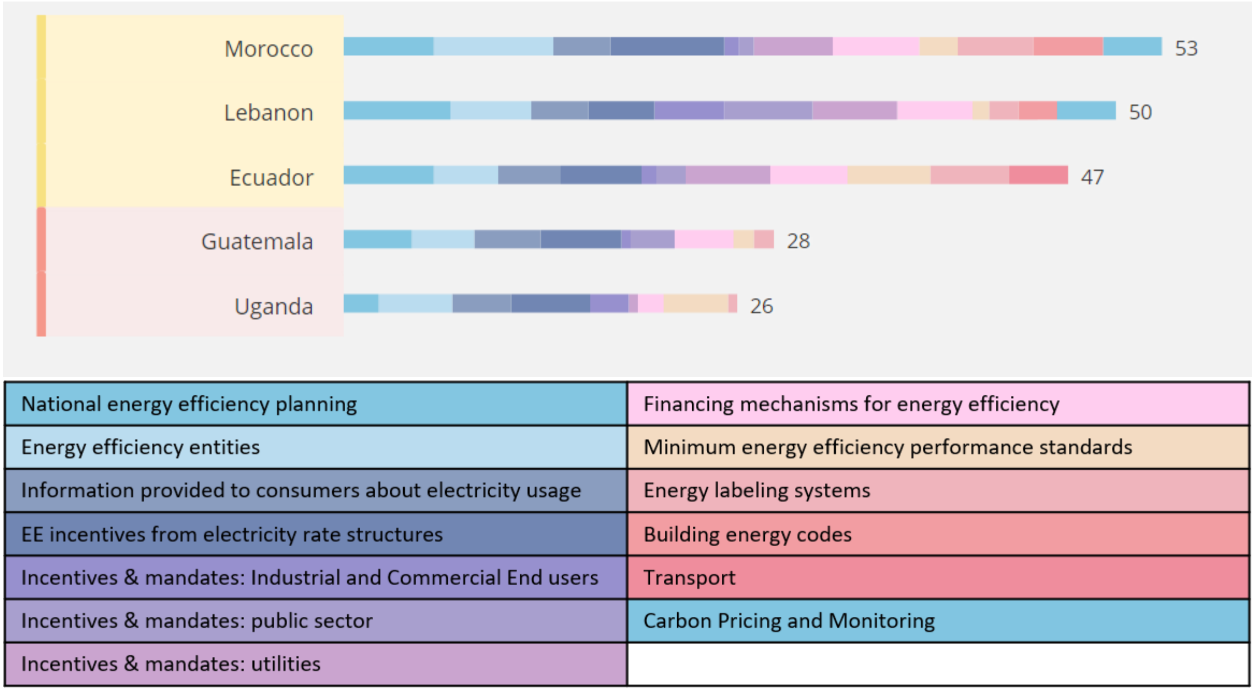

Figure 4: Country's Energy Efficiency Scores[31]

The manufacturers' development index (MDI) varied between 0.212 to 0.814 for the 6 manufacturers studied.

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[30] https://rise.worldbank.org/scores. Accessed April 26th, 2020.
[31] https://rise.worldbank.org/indicators#pillar-energy-efficiency. Accessed April 26th, 2020.

3 Cost-Efficiency (increasing EE vs. Cost) Case Studies

Several case-studies were conducted with the participating manufacturers. In these case studies, we have developed a relationship between equipment energy efficiency improvement and incremental manufacturing selling price. First, we started by modelling the baseline equipment in CERA using physical dimensions and engineering data (compressors, heat exchangers, fans, foam, etc.). The baseline models are then calibrated against experimentally measured performance to ensure that it is a true representation of the equipment performance. Next, we initiated a series of design modifications to achieve improved EE. Below are some details on these case studies along with the manufacturer development index for each case.

Unfortunately, we were not able to have a reliable case-study with the manufacturer having the lowest MDI. This was primarily due to the lack of required information on performance of the baseline unit and the cost of different energy efficiency options. For the 2nd manufacturer with MDI = 0.52, we also lacked information on the baseline model. As such, we could not model the baseline equipment in order to study cost-efficiency relationship.

The 3rd manufacturer (MDI = 0.534) worked with us on 2 case studies: one for domestic refrigerator and another for CR. The results for the CR unit are shown in Figure 5. This figure shows that 57% efficiency improvement can be achieved with a manufacturing selling price (MSP) increase of $50.55. The most cost-effective EE improvement was the design of the evaporator which reduced the MSP while increasing the unit efficiency. Next, changing the evaporator fan motor proved to be another cost-effective option which increased EE by 15% with an $7.69 MSP increase only.

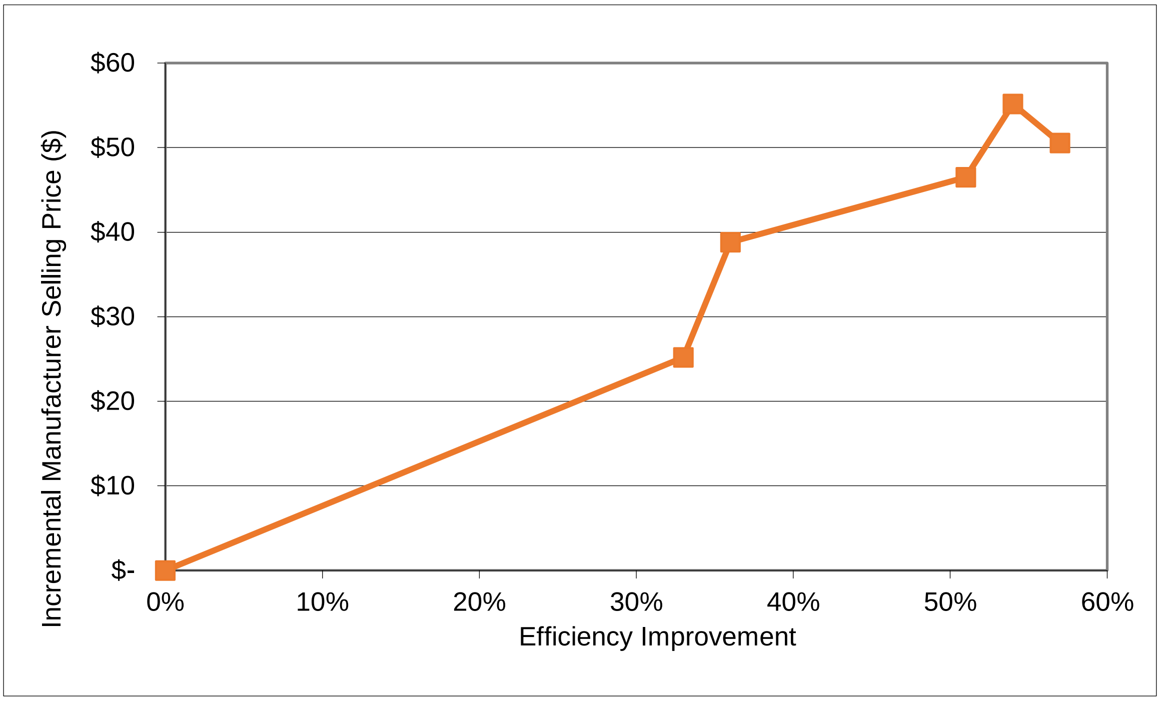

Figure 5. Cost-efficiency curve for Upright self-contained glass door merchandiser from 3rd manufacturer

The 4th manufacturer (MDI = 0.566) has only domestic refrigerators. We worked with them on their baseline system and studied different energy efficiency design options. The results of the case-study are summarised in Figure 6 showing that up to 45% efficiency improvement may be achieved at an incremental MSP of only $25.4.

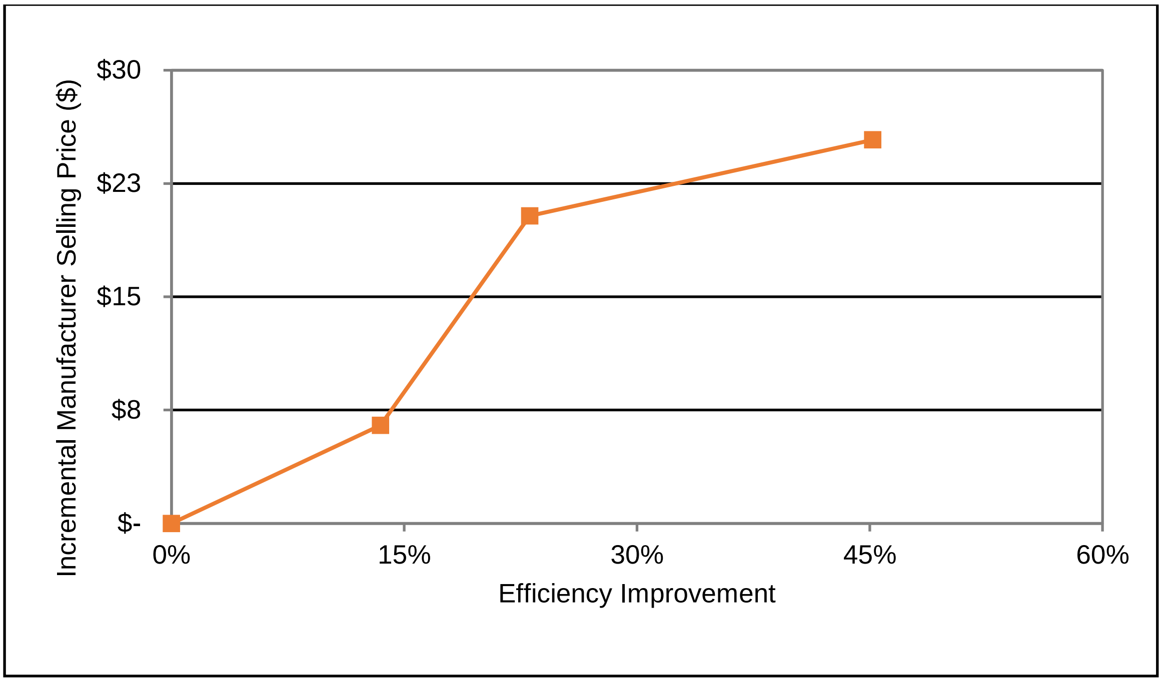

Figure 6. Cost Efficiency Curve for domestic refrigerator from 4th manufacturer

The 5th manufacturer (MDI = 0.776) only works with commercial refrigeration equipment. We believe that they are amongst the group of most competent manufacturers and have all the relevant information to enable good investigation of the cost-efficiency trade-off. The cost-efficiency curves for the 4 case studies we worked with them on are shown in Figure 7. Case 1 resulted in the most energy efficiency improvement, 40%, at only $13.68. On the other hand, Case 2 resulted in the most challenging to achieve the required EE levels. It could only achieve 32% efficiency improvement at the incremental manufacturing selling price of $30.27.

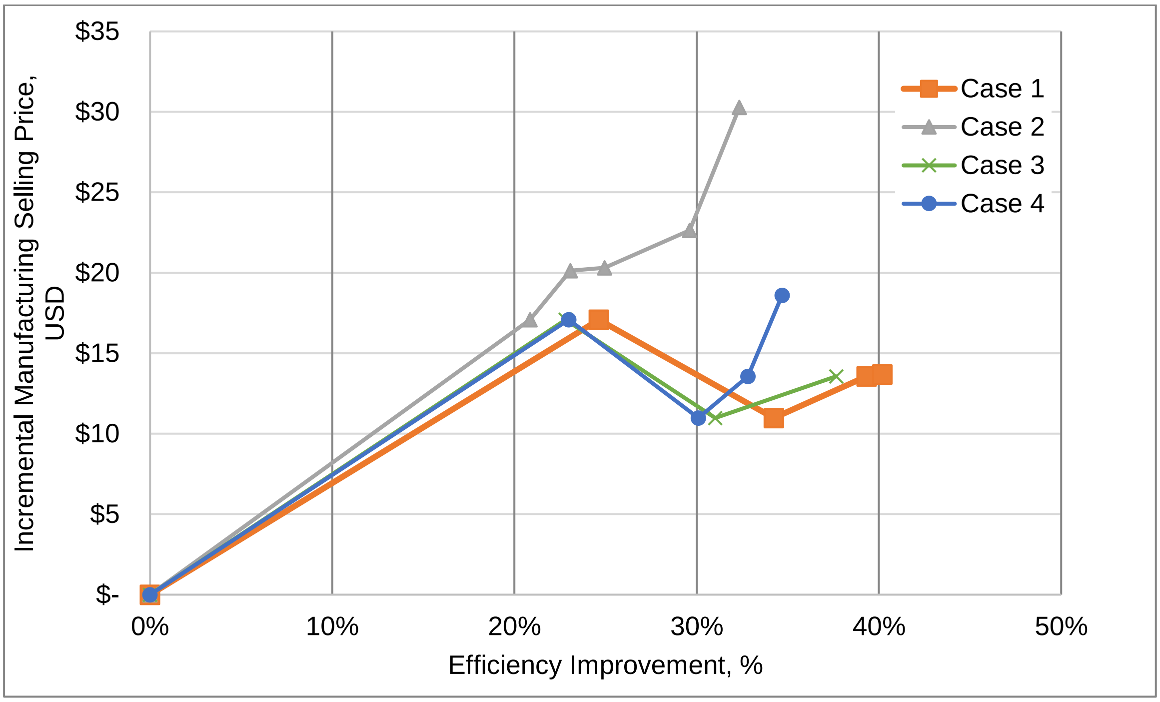

Figure 7. Incremental cost versus efficiency improvement for 4 case studies of commercial refrigerators from 5th manufacturer.

Finally, the 6th manufacturer (MDI = 0.814) was the most advanced and best prepared to work on the cost-efficiency activities. They have well-established product development plans and capable multi-disciplinary departments supporting their activities. We analysed the energy efficiency – cost trade-off for one of their baseline top-mount refrigerators. The cost-efficiency curve is shown in Figure 8. As can be seen from the figure; cost effectiveness ($/EE increase) is reflected by the slope of the curve. The slope is almost constant for the first 4 EE measures and is sharply increased (poor EE – cost effectiveness) for the last measure. The analysed top-mount refrigerator can achieve 27% energy savings at an incremental manufacturing selling price of $26.5 up and up to 30% energy savings at an incremental manufacturing selling price of $38.17.

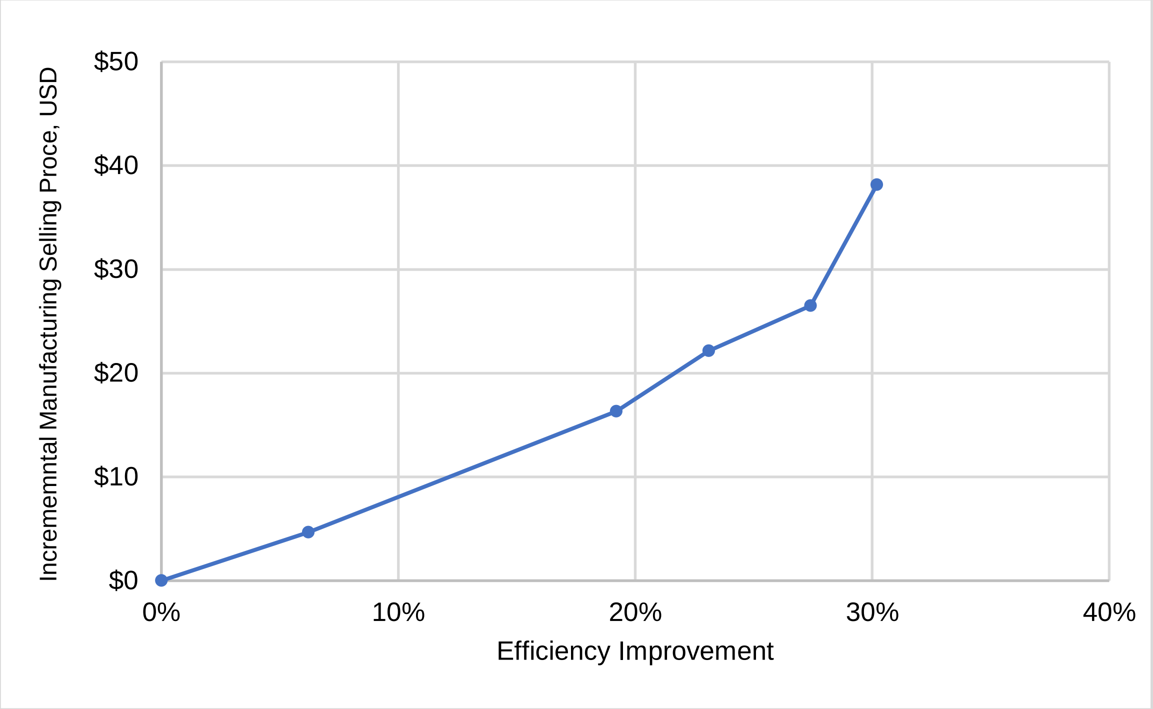

Figure 8. Cost-efficiency curve for Top-Mount Domestic Refrigerator from 6th manufacturer

The summary of these case studies conducted with the 4 participating manufacturers can be found in Table 6.

Table 6. Summary of Case Studies

Case Study #	MDI	EE below $20, %	Incremental Manufacturing Selling Price, USD	Max EE	Incremental Manufacturing Selling Price, USD
1	0.534	NA	NA	57%	$55.55
2	0.566	13.5%	$6.5	45.2%	$25.4
3	0.776	40.2%	$13.7	40.2%	$13.7
4	0.776	20.9%	$17.1	32.3%	$30.3
5	0.776	37.7%	$13.6	37.7%	$13.6
6	0.776	34.7%	$18.6	34.7%	$18.6
7	0.814	19.2%	$16.3	30.2%	$38.2

4 Energy Efficiency Cost Guidelines

Using data provided during the case-studies and further information provided by the manufacturer we were able to provide more generalized cost estimates on the EE design options using the MDI. Table 7 provides a summary of EE and corresponding IOC per unit for the manufacturers with different MDIs. As shown in the table, there is no correlation between MDI and IOC or expected EE improvements. The only generalization was that the manufacturer with highest MDI showed the least EE improvement for the different technologies, suggesting that their baseline systems are already more optimized. Furthermore, this manufacturer has a good relationship with supplier and thus strong purchasing power. This resulted in the least IOC per unit.

Table 7. IOC and EE improvement potential for different technologies in domestic refrigerators

Technology	MDI									
	EE improvement potential (%)					IOC (USD$/unit)				
	0.814	0.566	0.534	0.52	0.212	0.814	0.566	0.534	0.52	0.212
Change insulation Thickness	4%	5%	9.50%			3.72	2.5	17	6	
Change of air circulation									3	
High efficiency evaporator fan	16%	11%	18.5%			-1.21	5	6	4	
Inverter compressor	12.5%	29%	30%			-3.54	16.35	45	5	
Use defrost timer	2.75%					3			1	
Optimize Gasket		6.5%					6.5		1	
Refrigerant switch							-1.5			0.22
Improved Compressor	11.5%	25.5%	6.50%			1.44	1.05	6.5		6.375
Improved Evaporator	12.5%		3%			3.89		-4.65		
Improved Condenser	4%									
High Efficiency Condenser Fan	11%					0.71				

Table 8 provides a summary for commercial refrigeration technology options and corresponding IOC per unit. Unfortunately, the data available between manufacturers is sparser and it is difficult to infer any correlation except that manufacturers with high MDI tend to be more progressive with EE technology options and have stronger purchase power that allows them to achieve lower IOC.

Table 8. IOC and EE improvement potential for different technologies in commercial refrigerators

Technology	MDI							
	EE (%)				IOC (USD/Unit)			
	0.814	0.776	0.534	0.52	0.814	0.776	0.534	0.52
High Performance Insulated Glazing Unit (IGU) for doors		23%	33%			22	20	
Use High Efficiency Compressor		8%				-5		
Increase Insulation Thickness		5%				0.76		6
Optimize Gasket		1.5%				4		1
MCHX		2%				5		0
Smart Controller	12.5%		5%	10%	10.71		6	22.5
VIP	4%				5.33			35
ECM Motors and Improved Fan Designs	26.5%	4%			33.53	2		
Digital Controller with Internet of Things (IOT)	30%		30%		39.74		55	
Use LED Lighting	2%				3.14			

5 Impact of Energy Efficiency Technology Options on Production Lines

In this section we present a summary of the required capital investment to adopt energy efficiency measures while phasing down HFC refrigerants for domestic and commercial refrigeration equipment with manufacturers of different MDI.

5.1 Impact of increasing insulation thickness

Changing the insulation thickness may be achieved by modifying the internal cabinet dimensions, the outer cabinet dimensions, or a combination of both. Different manufacturers have different product development strategies; furthermore, customer acceptance varies significantly according to region and end-use. This is summarized in Table 9 below.

Table 9. Summary of equipment and ICC related to increased insulation thickness for different manufacturers in million USD.

MDI	0.814	0.776	0.566	0.534	0.52	0.212
Bending Machine			\$0.85 – \$2.5			
Moulds	\$4.1 for the complete product lines	<\$0.05 per base model	\$0.5 per base model	<\$0.05 per base model	<\$0.05 per base model	

5.2 Impact of improving the door gaskets

Door gaskets can be optimized to reduce the heat leak. However, this requires changing the welding jigs and additional development costs. Furthermore, there might be a need to change the refrigerator doors liner design. Hence, this change should be integrated with new thermoforming and foaming mould discussed in section 7.1 to ensure cost effectiveness.

Table 10. Summary of equipment and ICC related to improved gaskets for different manufacturers in thousands USD.

MDI	0.776	0.566
Welding jigs	\$3 each	\$9 × 6

5.3 Impact of using low GWP HC flammable refrigerants

Changing the from the non-flammable HFC-134a to the flammable HC-600a or HC-290, rated as A3, requires new refrigerant charging stations, new leak detectors, changes in infrastructure and training. The itemized cost of changing refrigerant to A3 is listed in table 11. Note, the number of production lines has a significant impact and is listed accordingly.

Table 11. Summary of equipment and ICC related to refrigerant conversion in thousands USD.

MDI	0.814	0.776	0.566	0.534	0.52	0.212
Number of Production Lines	2	2	2	1	1	1
HC detectors	$35 × 4	$13.6 × 4	$15 × 9	$12	$12.5 × 2	
Portable HC detectors	$1.25 × 4	$8.1 × 4				$2.5 × 5
Helium charging and recovery	$20 × 6	$51 × 3			$45	
Safety systems	$195	$121.43	$218	$50.8	$52	$70
Charging machines	$120 × 4 + $70 × 1	$43 × 4	$50 × 4	$92.5	$65	$40
Storage and distribution	$222		$90		$5	$45
Transfer pumps		$6.5 × 2	$27.6 × 2		$10 × 2	
Ultrasonic welding	$27 × 5		$30.5 × 4		$25	
Accessories for charging unit					$10	
Refrigerant extraction unit	$13.2 × 4	$9.4 × 2		$20	$5	
Calibrated leaks		$7.8			$2.5	
Vacuum pumps	$16 × 8			$8.1 × 6		
Upgrade functional testing	$116.7 × 3 + $84			$55		$35
Installation, commissioning, and training		$19.8	$20	$11.5	$10	$5
After sales			$30			
Total	**$1,982**	**$592.475**	**$870.1**	**$290.4**	**$264.5**	**$207.5**

5.4 Impact of using variable speed compressors

Using variable speed compressors provides significant energy savings due to the higher EER compared to the baseline compressor EER. However, further energy savings may be achieved with appropriate integration with advanced unit controllers. The development of high-performance advanced control units requires capacity building and investment in the order of 100,000 USD for the manufacturer with MDI = 0.566.

The manufacturer with MDI = 0.834 plans to develop in-house advanced control unit to achieve additional energy savings. Their estimated development cost is in the order of 120,000 USD. Furthermore, the same manufacturer has identified the need to improve the wiring termination to reduce the termination to 1 instead of 5-6 for baseline technology. The cost of implementing this improvement is 100,000 USD.

Another option for using variable speed compressors is to rely on the complete solution provided by the compressor OEM. In this case, the compressor OEM will supply the variable speed compressor and the associated controller; the manufacturer would just use the compressor OEM best practices and integrate the complete solution in their systems. This was the preference of the manufacturer with MDI = 0.534. As such, their expected incremental operational cost for the variable capacity compressor was significantly higher than other manufacturers as it accounted for the cost of the controller.

As discussed above, the choice of the company to either develop or depend on the compressor OEM controller can have a significant impact on the ICC and IOC as summarized in Table 12. The more developed the manufacturer, the more they prefer to develop in-house capabilities to ensure that the IOC is minimized.

Table 12. ICC and IOC for variable capacity compressor

MDI	ICC, USD	IOC, USD	Comments
0.534	Negligible	High	The company will depend on OEMs to provide the relevant capacity building and the control solution provided by them
0.566	$100,000	Medium	The company will rely on the control solution provided by the OEM
0.814	$220,000	Negligible	The company will develop in-house advanced controller and will change wiring termination to optimize operation

5.5 Impact of using triple pane higher insulation glass doors

In order to replace the double pane insulating glass door with a higher performance triple pane glass door, a manufacturer suggested the need to replace the door hinges and the plastic moulds. The estimated capital cost for this is in the order of $50,000.

5.6 Impact of using microchannel heat exchangers

One of the CR manufacturers has identified that the use of microchannel heat exchanger would require $25,000 ICC for product engineering and to develop the required moulds and computer numerical control machine (CNC) codes for the heat exchanger bracketing. However, the energy efficiency improvement ranked too low to implement.

It is important to consider that developed economies have identified microchannel heat exchanger technologies or small diameter copper tube heat exchangers to be cost neutral as indicated in section 2.2. while the manufacturer here focused solely on the ICC; this manufacturer has not considered potential savings from charge reduction, potential chassis cost reduction, potential packaging cost reduction, and reduced transportation and storage costs.

5.7 Other Production Facility Energy Efficiency Upgrades

The manufacturer with MDI of 0.52 made several plant upgrades to improve their plant energy consumption including:

- Upgraded the boilers for a higher efficiency steam cycle.
- Used servo motors for injection machines.

- Changed the generator to a green generator ($800/ton Diesel which translates into 0.15 to 0.20 $/kWh instead of 0.25$/kWh from the grid).
- Replaced plant lighting to LED.
- Employed the best efficiency possible for thermoforming.

They have also done preliminary investigations for the use of PV. However, they acknowledged that PV cannot provide enough capacity for the plant's 3 MW operation capacity.

The most developed manufacturer (MDI = 0.814) has also identified potential plant upgrades to reduce their plant's energy consumption. These included:

- Changing their current thermoforming machines to replace 4 of the old machines with 2 new ones and keep one of the old machines. This comes at an incremental capital cost of $1,528,000 and is expected to reduce the annual energy consumption by 400,000 kWh.
- Changing the injection moulds for polyurethane (PU) in order to reduce the insulation overpacking (improve thermal properties and reduce PU consumption). This would result in an incremental capital cost of $473,000.
- Changing the cleaning process from water basin technology to cleaning tunnels technology. This is expected to provide greater than 50% water savings (an associated energy savings) at an incremental capital cost of $350,000.
- Upgrade roll forming for metal parts (2 machines $775,000 each). This would result in reduction in adhesive tape and silicone usage.
- Install a new laboratory with safety system to enable product development, $150,000.

6 Incremental Capital and Operation Cost

We worked with the different manufacturers using information obtained during the case-studies, the development of EE cost guidelines, and the understanding of the EE technologies' impact on manufacturing facility to develop realistic ICC and IOC for conversion projects that would provide both direct refrigerant abatement (conversion from high GWP HFC refrigerants to low GWP flammable HC refrigerants) and indirect emissions reduction due to energy savings. Table 13 provides a summary of our findings. Table 13 also shows a large variation in ICC between the different manufacturers. In general, we can see that more developed manufacturers require advanced manufacturing equipment; as such, the ICC related to refrigerant conversion (ICC_{RC}) is typically costlier. On the other hand, there is no considerable correlation between ICC_{RC} and production volume. As for the ICC related to energy efficiency upgrades (ICC_{EE}), there are no considerable correlation with either MDI or production volume.

The IOC related to refrigerant conversion (IOC_{RC}) are well correlated with production volume and inversely correlated with the manufacturer's MDI. Well-developed Manufacturers (MDI > 0.7) have no or negative IOC_{RC}. This is mainly because compressors (lower pressure) and refrigerants (natural) are provided at lower cost or at parity with current technology. Furthermore, these manufacturers were able to further optimize their systems which enabled other cost saving options (e.g. capillary tubes). On the other hand, less developed manufacturers have lower purchase power and were not able to negotiate the compressor or the refrigerant price. As such, the IOC_{RC} was more significant and was also dependent on the production volume.

Finally, the IOC related to energy efficiency upgrades (IOC_{EE}) showed good correlation with manufacturer's MDI and production volume. In general, developed manufacturers can negotiate with OEM to obtain EE technologies at lower cost than less developed manufacturers. Furthermore, the production volume showed to have a good impact, as IOC_{EE} correlates linearly with production volume.

Table 13: Incremental Capital and Operating Cost for refrigerant conversion and energy efficiency upgrades

MDI	0.814	0.776	0.566	0.534	0.52	0.212
Production volume	140k	90k	150k	30k	300k	8.5k
ICC_{RC}	$1,982k	$593k	$870k	$291k	$265k	$208k
ICC_{EE}	$4.3M	$101k	$1M to $2.7M + $500k per base model	<$50k per base model	$100k + <$50k per base model	
IOC_{RC}	$(339k)	NA	$266k	$195	$4,511k	$53k
IOC_{EE}	$2M	Up to $2M	Up to $4.6M	Up to $2M	Up to $6M	NA

7 Emission Reduction Calculations

Refrigeration equipment contributes to CO_{2eq} emissions directly through the release of refrigerant to the atmosphere during the equipment life cycle or indirectly through electricity consumption. In this section we calculate the life cycle climate impact potential (LCCP) for the baseline case – before any refrigerant or energy efficiency conversion process and after the proposed conversion project to estimate the equivalent GHG emission reductions for the different manufacturers. Below is a description of the methodology employed and results obtained.

7.1 Direct Emissions

The direct refrigerant emission (E_r) is the sum of the refrigerant emissions during manufacturing (E_m), operation (E_o), and end-of-life(E_{eol}) in metric tons of equivalent CO_2 emissions (tCO_{2eq}). These are calculated as shown in the following equations:

$$E_r = E_m + E_o + E_{eol}$$

$$E_m = \sum_i n_i \times \frac{IC_i}{1000} \times GWP_i \times \left(EF_{m,i} + ED\right)$$

Where i is the model number, n_i is the number of manufactured refrigeration units of model i, IC_i is the initial charge (kg), GWP_i is the GWP of refrigerant used in the refrigeration model i, $EF_{m,i}$ is the refrigerant emission factor during the manufacturing for the refrigeration model i, and ED is the refrigerant emission factor associated with the refrigerant distribution in the facility.

$$E_o = \sum_i n_i \times \frac{IC_i}{1000} \times GWP_i \times EF_{o,i} \times L_i$$

Where $EF_{o,i}$ is the refrigerant emission factor due to leakage during operation of refrigeration model i and L_i is the effective operation life span of refrigeration model i (years).

$$E_{eol} = \sum_i n_i \times \frac{IC_i}{1000} \times GWP_i \times \left(1 - EF_{o,i} \times L_i\right)\left(1 - R_i \times EF_{r,i}\right)$$

Where R_i is the fraction of the units recovered at the end of life and $EF_{r,i}$ is recovery efficiency at the end of life of refrigeration model i.

7.2 Indirect Emissions

The indirect emission (E_{ind}) considered in our analysis is only related to the electricity consumption. It is the sum of the energy consumption over the effective operation span of the manufactured refrigeration units multiplied by the electricity emission factor (tCO_2/MWh) which can be expressed as:

$$E_{ind} = EF_{el} \times \sum_i L_i \times n_i \times EC_i$$

Where EF_{el} is the electricity emission factor (tCO_2/MWh) and EC_i is the yearly electricity consumption for refrigeration model i (MWh).

Table 14 provides a summary of direct and indirect emission factors for the manufacturers with different MDI. In this table we notice that more developed manufacturers have more detailed information about the detailed direct emissions during the production. It is also important to note that in the 5 countries studied there is no program for refrigerant reclaim and recycling at the refrigerators' end of life. Finally, the electricity GHG emission rate varied significantly and was the least in countries with the highest penetration of hydroelectric power generation. The lower electricity GHG emission rates can have a significant impact on the LCCP CO_{2eq} abatement costs.

Table 14. Emissions Factors from manufacturers with different MDI

Emission Factor (s)	MDI				
	0.814	0.776	0.566	0.52	0.212
n_i, IC_i, GWP_i, EC_i	Varies by model number, Detailed tabulated data provided in Appendix 1.				
$EF_{m,i}$	data provided in Appendix 1	1.1%	10%	2.5%	<1%
ED		NA	5%	1%	NA
$EF_{o,i}$		1%	1%	1%	<1%
L_i	10	10	10	15	NA
R_i	0	NA	0	2%	NA
$EF_{r,i}$	NA	NA	NA	NA	NA
EF_{el}[32]	0.262	0.336	0.718	0.705	0.532[33]

7.3 Emissions Reduction

The emissions reduction (ER) is calculated by subtracting the estimated direct and indirect emissions after the planned refrigerant conversion and energy efficiency upgrades from the baseline direct and indirect emissions:

$$ER = [E_r + E_{ind}]_{Baseline} - [E_r + E_{ind}]_{project}$$

Using the provided information from the manufacturers we were able to estimate ER based on the 3-years average production volumes as shown in Table 15. Furthermore, we also applied maximum available technologies to achieve the maximum energy efficiency. The summary of this finding is shown in Table 16. It is important to note that the average refrigerator/freezer size and the temperature setting varies significantly for different markets. This has a major impact on the product average annual energy consumption.

Table 15. Emissions Factors from manufacturers with different MDI

Emissions, tCO_{2eq}	MDI		
	0.814	0.566	0.52
$[E_r]_{Baseline}$	16,529	29,443	111,622
$[E_{ind}]_{Baseline}$	278,000	357,230	2,902,394
$[E_r]_{project}$	3,813	22	28
$[E_{ind}]_{project}$	154,452	321,507	2,401,029
ER	136,263	65,145	612,959

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[32] https://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf. Accessed April 26th, 2020.

[33] https://iges.or.jp/en/pub/list-grid-emission-factor/en. Accessed April 26th, 2020.

Table 16. Emissions Factors from manufacturers with different MDI applying maximum EE potential

Emissions, tCO_{2eq}	MDI		
	0.814	0.566	0.52
$[E_r]_{project}$	12	22	28
$[E_{ind}]_{project}$	136,841	196,476	1,936,983
ER	157,675	190,175	1,077,005

Based on these results we can see that the baseline indirect emissions $[E_{ind}]_{Baseline}$ are at least one order of magnitude higher than the direct emissions $[E_r]_{Baseline}$. As such, EE plays more dominant role in emissions reduction compared with refrigerant conversion except for the manufacturer with MDI = 0.566; for this manufacturer, the emission reduction due to energy efficiency (ER_{EE}) is roughly 55% of the total emissions reduction (ER). This is due to the fact that this manufacturer focuses primarily on refrigerant conversion and not so much on efficiency upgrades. On the other hand, the most developed manufacturer showed that the ER_{EE} is responsible to 91% of the total ER of the project. Finally, when we considered the maximum potential for the 3 manufacturers, the ER_{EE} is shown to be responsible for 85 to 90% of the total ER of the projects in the three manufacturers.

It is also important to note that one of the manufacturers visited has become a carbon neutral facility by purchasing carbon credit – 200 tons of CO_2 per year. Furthermore, this manufacturer is one of the most progressive in terms of environmental stewardship. They were the second company in the developing world to switch over from CFC-12 to HFC-134a in 1996, CFC-11 to HCFC-141b in 1996 and then to cyclopentane in 2006. They had an awareness campaign to instruct technicians not to vent HFC-134a and they donated recovery machines to technicians and then bought a reclaimer for HFC-134a to recycle old machines in order to be able to reuse the old HFC-134a. They continue to improve EE; HC-290 transition provided a good opportunity as with the new refrigerant and new compressors, they see 10 to 20% improvement in EE. Also, working with HC-290, they worked on reducing refrigerant charge. They started using improved condensers which further improved their HFC-134a equipment efficiency. There is also an interest in long term options like creating a carbon neutral cooler; starting with a very efficient cooler that has the lowest daily energy consumption and then buying carbon credits (plant trees, etc.) to get to neutral emissions throughout the lifetime of the unit.

Finally, the E_{ind} calculated earlier relied on annual energy consumption that are mostly measured according to standards in the respective countries. However, a more accurate value for annual energy consumption is not available since it varies significantly by end-use. It is important to note that in Latin America, consumers are used to turning off the coolers at night. A survey by Wellington controller confirmed that 70% of coolers on the market were unplugged at night. Furthermore, many customers use the controllers they have in energy saving mode; hence the actual field energy consumption would be exceedingly difficult to identify and would be unrepresentative across a diversified set of conditions. Hence the prediction and calculation provided here may be considered as worst-case scenario in terms of emissions and best-case scenario in terms of emissions reduction.

8 Market Barriers for EE Refrigerators

One important task to this project was to define the local or regional market barriers for EE technologies in the residential and commercial sectors in the 5 participating countries. These barriers were primarily identified by conducting interview questions with the local manufacturers and national ozone unit officers as discussed in the following subsections.

8.1 Market barriers for EE residential refrigerators

8.1.1 Consumer behaviour and retail price

The most relevant barrier identified was consumer behaviour. In general, amongst most developing regions, consumers are driven mainly, or exclusively, by first cost of replacement of new appliances rather than the lifetime cost. They are not aware of the benefits of energy efficiency to themselves or society. The energy labels, if available, are not well appreciated due to the small annual refrigeration electricity cost that makes the payback for typical energy efficiency options unacceptable. Furthermore, consumers taste for luxury and high-end refrigerators is primarily driven by advanced imported technologies. Some markets are characterised by unstable electric grid or limited electricity penetration. In these markets, consumers are looking for more reliable refrigerators that can remain resilient during periods of extended power outage and/or are not impacted by the poor power quality. In addition, most developing markets prefer 3 stars appliances, those with a default freezer setpoint -18°C freezer. These appliances are known to be less energy efficient. Finally, some of the marketing teams interviewed have identified that consumers generally appreciate aesthetics, odour control, quality and reliability, ease of service, capacity, and ease of use over energy efficiency and environmental friendliness. As such, it is difficult to roll-out EE features in high-end products that can bear the incremental selling price.

8.1.2 Lack of consumer awareness

As identified in section 8.1.1, energy labels are not well appreciated in most developing countries. This is primarily because in most developing countries, electricity is subsidized by local governments. In this case, it would be difficult for the consumer to realize payback for energy efficiency within acceptable time (less than 3 years according to most interviews). Furthermore, the consumers are not aware of the additional societal and environmental benefits of energy efficiency. These benefits include reduced government spending on electrical subsidies, improved air quality, well-being, etc. As such, there is a growing need for educational campaigns to educate the local consumers about the energy labels and EE benefits beyond utility cost savings. Finally, there is a general lack of campaigns to promote EE amongst refrigeration manufacturers, technicians, and salesforce.

8.1.3 Relentless market competition and political instability

Another important barrier to the development of EE refrigerators is the increasing pressure from international white goods manufacturers who produce millions of units per year and have better production economies of scale. In some markets, trade agreements have opened the markets with little to no protection; this along with limited market growth resulted in an overall reduction in market share and subsequently profitability of the local producers. In addition, regional turmoil, and market development near some of the studied economies have affected the production volumes. Regional markets that are more price sensitive opt for the affordable products, while other more developed regional markets have growing certification requirements – making market expansion more complicated.

8.1.4 Lack of technical capacity

Most of the local manufacturers visited in the developing countries participating in this project lack the required technical product development R&D for cost-effective efficiency improvement. They need support from their respective local governments as well as international stakeholders in EE in order to enable cost-effective equipment efficiency upgrades while remaining competitive and compliant with new local and regional MEPS. Most manufacturers would like EE upgrades to be cost neutral or with minimal cost increase since consumers are price conscious as discussed earlier. Furthermore, most, if not all, equipment needed to manufacture higher EE products are not locally produced and must be imported.

8.1.5 Absence and poor implementation of Minimum Energy Performance Standards (MEPS)

Another important market barrier to EE technology adoption is the varying degree of MEPS implementation (if available). EE adoption generally follows an “S” curve as shown in “maroon” in Figure 9.[34] Early adopters take the risk to invest in new and more expensive technology resulting in small market penetration. With time, the technology becomes more established and the production economies of scales makes it more cost effective; increasing its market penetration rates. Eventually, the market penetration stabilizes and only market laggard resist EE technology adoption. There are several market interventions that can help accelerate the adoption of EE refrigerators and permanently unlock its potential as shown by the different arrows and the updated blue dashed “S” curve. Amongst these interventions, MEPS has the greatest impact.[26]

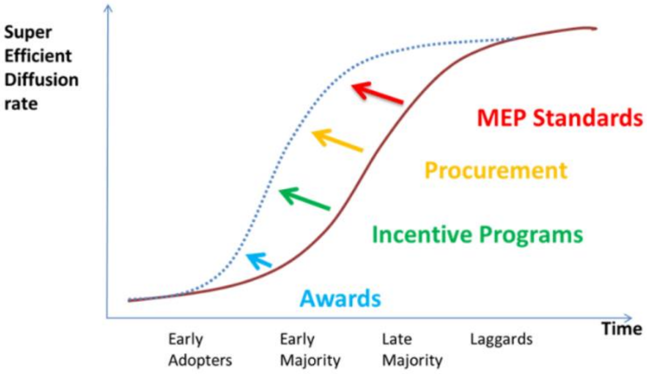

Figure 9. Impact of Market Interventions on Highly Efficient Technology Diffusion Rate[34]

As such, the lack of MEPS in some regions is considered a significant barrier to EE refrigerators. The need to comply with different regional MEPS which are not harmonized and require different testing methodologies can be construed as a barrier as well. In the latter case, the manufacturers’ test laboratory resources are completely occupied by the compliance requirements and little room is available for the product development cycle. As such, there is a growing need for model regulation and harmonization (e.g. the model regulation efforts lead by united for efficiency[35] and unified equipment performance test procedure[36]). Furthermore, obtaining the ISO 17025[37] Testing and Calibration Laboratory certification is important to guarantee testing quality; however, it is not

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[34] de la Rue du Can, S., G. Leventis, A. Phadke, A. Gopal. 2014. “Design of Incentive Programs for Accelerating Penetration of Energy-Efficient Appliances.” Energy Policy, v. 72, September, pp. 56–66

[35] https://united4efficiency.org/products/refrigerators/. Accessed April 26th, 2020.

[36] IEC 62552-1:2015 test procedure: https://webstore.iec.ch/publication/21805. Accessed April 26th, 2020.

[37] https://www.iso.org/ISO-IEC-17025-testing-and-calibration-laboratories.html. Accessed April 26th, 2020.

always cost effective for manufactures in developing countries. Some manufacturers resort to correlation unit testing as an alternative to ISO 17025. The expected 2020 IEC 62552 updates focus on more stringent EE requirements. As such, it is important that energy efficiency and refrigerant changeover support compliance over the next 10 years. Some manufacturers expected the need to improve EE by 20 to 50% to maintain an “A” status.

8.1.6 Lack of access to finance

As presented earlier in section 6, the incremental capital and operating costs associated with energy efficiency (ICC_{EE} and IOC_{EE}) are quite significant. These capital investments are difficult to raise under most market conditions. Hence, there is a need for appropriate financing mechanisms to further enable EE. Furthermore, we found a lack of governmental financial incentives for EE appliances. In some cases, governments would subsidise electricity which would further hurt EE technology adoption. Electric subsidies, lower electricity rates, result in increased payback periods and as such have an adverse impact on EE adoption.

8.2 Market barriers for EE commercial refrigerators

Unlike domestic refrigerators that can be manufactured at limited locations in high volumes and exported to all over the world, most commercial refrigerators are manufactured or assembled regionally and locally as specifications are more localized, the volume is lower, and the size of each equipment is larger. The following sub-sections illustrate the main market barriers for EE commercial refrigerators.

8.2.1 Buyers’ purchase power

Commercial refrigeration sales are largely controlled by institutional or business-to-business (B-to-B) sales. These sales are mainly driven by client’s specifications/guidelines and test methods which are usually more progressive than national or regional MEPS, if they exist. Recent customer consolidation rendered the commercial refrigerator market a primarily “buyers” market. This resulted in increased purchase power for the clients leading to smaller margins but guaranteed volumes. Manufacturers are currently looking for additional customers who can afford larger margins (unique features, or technologically advanced features) even if with lower (baseline) margins. For example, restaurants and kitchens refrigeration equipment may benefit greatly from variable speed compressor technology due to improved temperature controls within the refrigerated space. As such, this technology could be added to premium models for market introduction. However, there would need to be a campaign to educate the market of these benefits.

The fierce competition and low margins associated with the B-to-B market makes it extremely difficult for manufacturers to introduce EE components unless they are specified by the B-to-B customers. Some of the B-to-B customers already require HC-290, ECM fan motors, and advanced electronic components to improve EE. This is mainly to support corporate environmental footprint goals as part of their corporate social responsibility (CSR), and to support the point of sale customers by running cost during operation. There is an increasing interest of beverage producers in more energy efficient coolers on the market a so called “super-efficient cooler”.

8.2.2 Shorter payback time by Non-institutional customers

Non-institutional customers are primarily driven by first cost and have limited appreciation of the lifecycle monetary and societal benefits of EE. Overall, the acceptable payback for these consumers is 18 months simple payback. In some markets, shop owners sometimes put electricity sub meters ($20 per device) on their vending machines to check the cost associated with running them.

8.2.3 Resilient equipment specification

Another important barrier in developing markets is that electric grid is not stable and as such, consumers tend to favour refrigerators that are more resilient to poor electric grid quality. This usually comes at the cost of poor EE performance.

8.2.4 Absence and poor implementation of MEPS

As discussed earlier in section 8.1.5, MEPS plays an important role in the adoption of EE technologies. This is also the case for commercial refrigerators. The Super-Efficient Appliance Equipment and Appliance Deployment Initiative (SEAD) preliminary analysis indicated that ~90TWh could be saved by 2030 through MEPS for commercial refrigeration systems in participating SEAD economies.[38] However, in most of the visited countries participating in this study there is a lack MEPS for commercial refrigeration. Some manufacturers developed their own test protocols that are a mix of several regional standards while others strived to comply with MEPS and test standards to all the markets they serve. Unfortunately, in the latter case, there might some conflicts in the energy performance methodology, testing methodology, or equipment characterization between the different markets. An example of the conflicting methods is the performance evaluation for the deli cases and ice-cream freezers; the ANSI/AHAM is based on the display area- while other calculation methods are based on the gross volume. This is an inefficient, costly, and counter-productive process that delays the uptake of EE; laboratory resources become mostly tied up with equipment certification and less-so with EE product development. As such, it is particularly important to develop a harmonized commercial refrigerator model regulation to alleviate such strain on manufacturers in developing countries and requirements for testing for the different countries they supply to. They must comply with over 50 country schemes.

8.2.5 Lack of training capacities to generate qualified technicians and certifications

Qualified technicians and servicing technicians are important for the widespread use of higher EE equipment operating with HC refrigerants. Limited national capacity to nurture qualified technicians may be considered as an additional barrier to EE.

There is a need for more recognised laboratories to support EE development activities and highly trained technicians. There are some regional and national programs to certify technicians and servicing contractors based on course attendance or awarded by the technician association in other instances, as well as training of trainers' programs[39].

From the technology perspective, most components needed to manufacture higher EE equipment are imported, and local manufacturers generally need support during the refrigerant conversion and EE upgrades to identify the most cost-effective technologies.

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[38] https://superefficient.org/efficient-products/refrigeration/commercial-refrigeration. Accessed April 26th, 2020.

[39] https://www.giz.de/en/downloads/giz2016-en-flyer-cool-training.pdf. Accessed April 26th, 2020.

8.2.6 Lack of access to finance

Another important barrier to EE is the high incremental capital and operating costs associated with energy efficient commercial refrigerators (ICC_{EE} and IOC_{EE}) depicted in section 6. Currently, there is no financial support for higher EE, and it is difficult to raise capital for such projects under current market conditions. Large scale investment beyond what the market can offer may be needed to improve commercial refrigeration products EE performance and set a new market norm.

Some of the companies participating in this project have indicated that an open source variable speed compressor would reduce the IOC_{EE}. This would make the variable speed compressor cheaper for all refrigerator manufacturers and scale-up its use. This is an example project that could be financed by an international organization to support EE in commercial refrigerators.

8.2.7 Availability and Affordability of EE components

While some of the EE components are now widely available, their affordability and availability vary. For example, the variable speed compressor technology is available – but not in high enough volumes from all suppliers. As such, the affordability varies significantly by geographical location, purchase volume, and the collaboration framework with the compressor suppliers. Another example of a proven EE technology is the 3-way bypass valves for defrost. This technology, while available, is still not cost effective. Finally, some countries still put import restriction on HC-290.

9 Conclusions

In this report, we investigated the potential for simultaneously improving energy efficiency while transitioning towards more sustainable low global warming refrigerant solutions for the domestic and commercial refrigeration industry. The study analysed products and production lines of the 6 manufacturers of varying degree of development capacity, production volume, proximity to and relationship with component's OEM. Furthermore, the five countries studied had various degrees of market maturity and energy efficiency policies. A Manufacturer Development Index (MDI) was compared to describe the manufacturer's ability to develop energy efficient appliances. The MDI ranged from 0.212 for the least capable manufacturer to 0.814 for the most capable manufacturer. It is important to note that this index did not consider the ability of the manufacturer's financial ability to invest in energy efficiency and refrigerant conversion projects.

Development of a cost efficiency model: A cost efficiency model was developed to help manufacturers evaluate potential design trade-off between energy efficiency gains and cost. First, the baseline equipment physical characteristics are modelled using CERA. This model is then checked against measured performance data provided by the manufacturer. The different energy efficiency technology options are evaluated such as:

- Increased insulation thickness
- Improved gasket
- Using ECM evaporator fan
- Improved compressor efficiency
- Heat exchanger optimization
- Air flow optimization

Based on the evaluation of these design options, and considering the different cost elements (materials, labour, overhead, depreciation, etc.), cost-efficiency curves were developed for the different manufacturers and different products. With feedback from the site visits and design workshops, it was clear that the refrigerant conversion offers up to 10% efficiency improvement due to the availability of more efficient HC compressors replacing the old HFC compressor technologies. Furthermore, we have performed 7 detailed case-studies showing the potential for up to 57% energy savings. Our findings show that more developed manufacturers had lower potential for energy efficiency improvement as their refrigerators are already considerably more developed than others compared in the study. One of the most cost-effective options amongst the case-studies considered was the replacement of the evaporator fan motor with more efficient Electronically Commutated Motors (ECM) technology.

Several energy efficiency technologies were considered for domestic refrigerators, the use of the inverter compressor had the highest potential energy savings – up to 30%, however the incremental operating cost (IOC) per unit varied significantly between manufacturers based on their MDI. The most developed manufacturers showed cost savings while less developed manufacturers showed IOC as much as 45 USD per produced unit. Furthermore, higher efficiency compressor technology was highlighted to be another cost-effective technology with up to 25.5% energy savings for IOC of up to 6.4 USD per produced unit. Replacing the evaporator fan with higher efficiency ECM technology can result in up to 18.5% efficiency improvement with a cost increase of up to 6 USD. Again, more developed manufacturer showed cost savings with this technology. Finally, increasing the insulation thickness provides marginal efficiency gains at marginal IOC; however, they require significant incremental capital cost.

Similarly, several technologies were considered for commercial refrigeration equipment; the highest potential energy savings was attributed to high performance insulated glazing for glass door self-contained display units with up to 33% energy savings at an estimated IOC of 22 USD. Digital controllers with IOT showed to have significant potential energy savings with up to 30% efficiency improvement at a cost of up to 55 USD. Higher efficiency fan motors had significant potential energy savings as well – up to 26.5% at a cost of 33.5 USD. Finally, increasing the thermal insulation showed quite a marginal energy benefit at marginal IOC.

This report also summarised the impact of different energy efficiency technology options on the production line and incremental capital cost (ICC). The ICC related to refrigerant conversion varied significantly between manufacturers due to production volume, technology maturity, and health and safety systems enforcement practices. ICC was highest for the most developed manufacturer at approximately 2 million USD and lowest for the least developed manufacturer at approximately 0.2 million USD. Increasing the insulation thickness proved to be a capital-intensive measure due to the need for expensive moulds for commercial refrigerators. The most developed manufacturer was able to develop a complete estimate at roughly 4.1 million USD for its planned energy efficiency upgrades. One of the manufacturers showed the need for new metal bending machine which alone would cost up to 2.5 million USD. The least developed manufacturer showed the potential for modest ICC as most of the moulds were hand-made and developed by trial and error. Improving the gasket requires the use of new welding jigs which may cost 3 to 9 thousand USD each. On the other hand, incorporating higher performance insulation glass door requires modest capital investment to re-engineer the door hinges and plastic moulds with an estimated ICC of 50 thousand USD. Finally, the use of the variable speed compressor technology requires some level of capacity buildings and controller development which require ICC in the order of 100 thousand USD for each manufacturer.

Three of the six manufacturers were able to provide enough information to estimate the emissions reduction under planned and maximum energy efficiency scenarios. The emission reductions varied significantly due to the production volume, average annual electricity consumption, and electricity emission rate. Our analyses confirmed that the indirect emissions contribute to more than 90% of the total emissions in HFC systems and more than 99% of the total emission in low GWP systems. As such, energy efficiency (EE) plays a more dominant role in emission reduction (ER) compared with refrigerant conversion except for the manufacturer with MDI = 0.566; for this manufacturer, the emission reduction due to energy efficiency (ER_{EE}) is roughly 55% of the total emissions reduction (*ER*). This is because their project focuses primarily on refrigerant conversion and not so much on efficiency upgrades. On the other hand, the most developed manufacturer showed that the ER_{EE} is responsible to 91% of the total *ER* of the project. Finally, when we considered the maximum potential for the 3 manufacturers, the ER_{EE} is shown to be responsible for 85 to 90% of the total *ER*.

It is important to consider the potential barriers to introducing energy efficient low-GWP refrigeration technologies to the market. For the domestic sector, the most relevant barrier identified was consumer behaviour; that are driven mainly by first cost of replacement or new appliances rather than the lifetime cost and in addition consumers were not aware of the benefits of energy efficiency to themselves or the environment. Another important barrier to the development of EE refrigerators is the increasing pressure from international white goods manufacturers who have better production economies of scale. In addition, regional turmoil, and market development near some of the economies studied have affected the production volumes. Most of the local manufacturers visited in the developing countries participating in this project lack the required technical product development R&D for a cost-effective efficiency improvement. Furthermore, most, if not all, components needed to manufacture higher EE products are not locally produced and must be imported. These components require significant ICC_{EE} and IOC_{EE} that is difficult to raise or justify under most market conditions especially where regulations and awareness in the market are lacking.

Another important market barrier to EE technology adoption is the varying degree of MEPS implementation (if available). In general, we found a lack of governmental financial incentives for EE appliances and thus limited access to financing for investing for EE. In some cases, governments would subsidise electricity which would further discourage EE technology adoption. Generally, there is a lack of educational campaigns that can improve consumer appreciation for energy labels and EE as well as campaigns to promote EE amongst refrigeration manufacturers, technicians, and salesforce.

Finally, we found that commercial refrigerators market is largely controlled by institutional or business-to-business (B-to-B) sales. These sales are mainly driven by client's specifications/guidelines and test methods which are usually more progressive than national or regional MEPS, if they exist. There is some interest from beverage producers to claim to have the best Energy Efficient cooler on the market a so called "super-efficient cooler". Non-institutional customers are primarily driven by first cost and have limited appreciation of the lifecycle monetary and societal benefits of EE. Overall, the acceptable payback for these consumers is 18 months simple payback.

In some markets, shop owners sometimes put electricity sub meters ($20 per device) on their vending machines to check the cost associated with running them. Another important barrier in these markets is that electric grid stability is quite variable and as such, consumers tend to favour refrigerators that are more resilient to poor electric grid quality. This usually comes at the cost of poor EE performance.

Most of the visited countries participating in this study lack MEPS for commercial refrigeration and often local manufacturers were not adequately protected from low cost imported products. Qualified technicians and servicing technicians are important for the widespread use of higher EE equipment operating with HC refrigerants. Limited national capacity may be considered as an additional barrier to EE.

Another important barrier to EE is the high ICC_{EE} and IOC_{EE}. Currently, there is No financial support for higher EE, and it is difficult to raise capital for such projects under current market conditions. Finally, the limited supply of EE technology components, their higher cost, or importation barrier should be closely considered.

10 References

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Appendix 1

Factory Information

MDI	0.212		0.52		0.566		0.776		0.814	
Baseline/Post conversion	Baseline	Post	Baseline	Post	Baseline	Post	Baseline	Post	Baseline	Post
Certified technicians, #			600	550	35	35	44	44	28	28
Uncertified technicians, #	10	12	50	70	16	16	8	8	402	402
Female technicians, #	3	4	0	0	10	10	0	0	20	20
Female employees, #	20	30	0	0	36	36	27	27	288	288
HFC-134a consumption, kg/yr.	40	0	40,000	2,000	23,000	0	10,500	0	12,000	3,000
R404A consumption, kg/yr.	50	0	12,000	10,000			1,750	0	0	0
HC-600a consumption, kg/yr.	220	600	500	15,000	0	7,700	0	20	0	2,700
HC-290 consumption, kg/yr.		130	500	5,000			3050	8,600		1,350
Other refrigerants, kg/yr.	60 (HCFC-22)								90	0
Annual Electric consumption, kWh	20,300	82,000			4,250,000		1,700,000		675,623	
Fossil energy	Diesel	Diesel			Fuel7		Diesel/LPG/Gasoline		Diesel	
Annual fossil consumption	500 litres	2500 litres			370,000 kg		2,934/19,589/3,497 Gal		4,428 Gal	
Foaming agent	HCFC-141b	CYCLOPENTANE	CYCLOPENTANE		ISOCYCLOPENTANE		CYCLOPENTANE		CYCLOPENTANE	
Foaming agent consumption, kg	30,450	60,000			62,000		26,100	29,000	60,000	

Appendix 2

Emissions Data for MDI = 0.212

Product # (n_i)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Product type/category														
2015 production, units/yr.	x	x	x	x	x	x	x	x	x	x	x	x		
2016 production, units/yr.	x	x	x	x	x	x	x	x	x	x	x	x		
2017 production, units/yr.	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Annual energy consumptions (measured), kWh/year	135	219	256											
Baseline Refrigerant	HC-600a							HFC-134a		HC-600a		HFC-134a	R404	
Refrigerant charge, g/unit	70	80	120	155	130	140	150	160	180	230	260	340	360	140
Alternative Refrigerant	HC-600a												HC-290	
Alternative Refrigerant Charge, g/unit	70	80	120	155	130	140	150	54	60	230	260	115	120	50
Expected annual energy consumptions, kWh/year														

Emissions Data for MDI = 0.52

Product # (n_i)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Product type/category	Domestic Refrigerator				Domestic Refrigerator				Domestic Refrigerator					Domestic Refrigerator			
2015 production, units/yr.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2016 production, units/yr.	x	x	x		x	x	x	x	x	x	x	x	x	x		x	x
2017 production, units/yr.	x	x	x		x	x	x	x	x	x	x	x	x	x		x	
Annual energy consumptions (measured), kWh/year	400	440	460	480	510	550	620	650	540	600	640	700	700	560	580	620	640
Baseline Refrigerant	HFC-134a																
Refrigerant charge, g/unit	70	80	120	155	130	140	150	160	180	230	260	340	360	140	150	160	160
Alternative Refrigerant	HC-600a																
Alternative Refrigerant Charge, g/unit	36	40	56	68	50	55	62	68	68	86	100	126	126	50	60	66	66
Expected annual energy consumptions, kWh/year	320	340	380	400	360	400	500	530	400	450	540	600	600	440	470	520	525

Product # (n_i)	18	19	20	21	22	23	24	25	26	27
Product type/category	Freezer					Cooler				
2015 production, units/yr.	x	x	x			x	x	x		x
2016 production, units/yr.		x	x	x	x	x	x	x		x
2017 production, units/yr.	x	x	x	x	x	x	x	x	x	x
Annual energy consumptions (measured), kWh/year	540	560	600	630	720	850	900	1100	1000	1700
Baseline Refrigerant	HFC-134a									
Refrigerant charge, g/unit	160	180	200	225	330	120	195	270	215	400
Alternative Refrigerant	HC-600a									HC-290
Alternative Refrigerant Charge, g/unit	58	64	72	80	84	50	54	64	60	105
Expected annual energy consumptions, kWh/year	440	460	500	520	650	700	750	900	850	1400

Emissions Data for MDI = 0.566

Product # (n_i)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Product type/category	Refrigerator/Freezer													
2015 production, units/yr.	x	x	x	x	x	x	x	x		x	x	x	x	x
2016 production, units/yr.	x	x	x	x	x	x	x	x		x	x	x	x	x
2017 production, units/yr.	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Annual energy consumptions (measured), kWh/year	241.5	284.4	302.4	367.2	352.8	342	363.6	468	518.4	414	450	482.4	475.2	522
Baseline Refrigerant	HFC-134a													
Refrigerant charge, g/unit	105	110	120	141	127	138	145	121	110	150	160	127	170	132
Alternative Refrigerant	HC-600a													
Estimated alternative Refrigerant Charge, g/unit	35	38	40	47	42	46	48	40	37	50	53	40	57	44
Expected annual energy consumptions, kWh/year	217.4	256	272.2	330.5	317.5	307.8	327.2	421.2	466.6	372.6	405	434.2	427.7	469.8

Emissions Data for MDI = 0.776

Product # (n_i)	1	2	3	4	5	6	7	8	9	10	11
Product type/category	Glass Door Cooler (GDC)				Solid Door Freezer (F)		GDC	F	GDC	F	GDC
2015 production, units/yr.	x	x	x	x	x	x	x	x		x	x
2016 production, units/yr.	x	x	x	x	x	x	x	x		x	x
2017 production, units/yr.	x	x	x	x	x	x	x	x	x	x	x
Annual energy consumptions (measured), kWh/year	1551	1660	1639	438	1686	3212	504	1387	1974	3176	1533
Baseline Refrigerant	HC-290										
Refrigerant charge, g/unit	105	105	105	55	75	120	65	58	116 x 2	80	105
Alternative Refrigerant	HC-290										
Estimated alternative Refrigerant Charge, g/unit	105	105	105	55	75	120	65	58	116 x 2	80	105
Estimated annual energy consumptions, kWh/year	1077	1186	1263	314	1599	3022	369	1259	1887	2606	1270

Emissions Data for MDI = 0.814

Product # (n_i)	1	2	3	4	5	6	7	8	9	10	11	12	13
Product type/category	Refrigerator-Freezer				Cooler		Cooler-sub zero		Freezer				
2015 production, units/yr.	x	x	x	x	x	x	x	x	x	x	x	x	x
2016 production, units/yr.	x	x	x	x	x	x	x	x	x	x	x	x	x
2017 production, units/yr.	x	x	x	x	x	x	x	x	x	x	x	x	x
Annual energy consumptions (measured), kWh/year	365.2	398.8	491.1	503.7	1828.9	2350.6			671.6	889.9	881.5	1217.3	1842.7
Baseline Refrigerant	HFC-134a												
Refrigerant charge, g/unit	75	90	90	90	100	140	250	250	140	180	140	180	260
Alternative Refrigerant	HC-600a				HC-290		HC-290		HFC-134a				
Estimated alternative Refrigerant Charge, g/unit	31	36	49	49	37	52	37	52	140	180	140	180	260
Estimated annual energy consumptions, kWh/year	205.2	224.1	232.7	237.5	1026	1050.5	1436.5	1470.7	649.7	1181.9	912.5	1168	1428.1

Appendix 3

Technology Options for Refrigerators, Refrigerator-Freezers, and Freezers

1. **Insulation**

    - Improved resistivity of insulation: using carbon black additives may lower k-factors by 6-9%. This option has been screened-out by US DOE due to the lack of potential suppliers.
    - Increased insulation thickness: adding 0.5 – 1 inch of insulation thickness may result in up to 10% reduction in energy consumption "investments would be required in foaming systems, tooling, and moulding to accommodate thicker insulation. Increased packaging and shipping costs must also be considered. Greater insulation thickness results in either decreased interior volumes, increased exterior dimensions, or some combination of both. Since kitchen dimensions and designed spaces for refrigerator-freezers are limited, there are restrictions on increasing the exterior size of the product. Reducing interior volume is considered undesirable because it impacts consumer utility. [23]
    - Vacuum-insulated panels: may result in 35% reduction in energy use compared with PU foam insulation, however several practical limitations should be considered including its reliability and performance over its lifetime.
    - Gas-filled panels (GFPs): GFPs have better thermal performance than PU foam insulation, however, they lack structural integrity. The US DOE has screened-out this technology option as research has suggested that GFPs are as expensive as VIP while providing less improvement in resistivity.

2. **Gasket and Door Design (screened-out by US DOE due to limited or no reduction in load)**

    - Improved gaskets: research on improved gaskets is quite dated and indicate a diminishing return on EE
    - Double door gaskets: it is an additional inner seal to reduce leakage and infiltration, practical limitations related to ice formation and aesthetics limit its use
    - Improved door face frame: using a plastic cover on the internal flange can reduce the edge-effect heat losses by 50% (up to 3.5% reduction in energy consumption)
    - Reduced heat load for through the door (TTD) feature

3. **Anti-Sweat Heater**

    - Condenser hot gas or warm liquid: this technology is already part of nearly all standard-size refrigerator freezers. This option has been screened-out by US DOE as it is currently considered part of the baseline.
    - Electric heater sizing: ensure proper sizing to avoid any unnecessary heating. This option has been screened-out by US DOE as it is currently used in a limited class of appliances (French-door) and is considered part of the baseline.

- Electric heater controls: use of advanced controls based on ambient temperature and humidity to avoid moisture build-up on the refrigerator sides

4. **Compressor**

   - Improved compressor efficiency: replace baseline compressors with high efficiency compressors available from OEMs
   - Variable-speed compressors: replace baseline compressors with high efficiency variable speed compressors that provide better part load performance, this might result in up to 30% energy savings
   - Linear compressors: linear compressors provide capacity modulation and can achieve high efficiencies due to the free piston configuration; it is 9% more efficient compared with the best available technology. This technology option has been screened-out by US DOE due to the proprietary design of the LG compressors that leads to high uncertainty in widespread use.

5. **Evaporator**

   - Increased surface area: increasing the surface area of the evaporator is limited by the appliance design – adding more heat transfer area results in reduced temperature difference between the cabinet temperature and the evaporating temperature, thereby reducing the compressor temperature lift
   - Improved heat exchange: this may be achieved using enhanced fins and/or tubes, though expected impact is limited due to other practical design consideration. A novel concept is to incorporate phase-change material within the heat exchanger to enable higher average evaporating temperature compared with conventional designs. This option has been eliminated by US DOE due to the issues associated with frost management.

6. **Condenser**

   - Increased surface area: same as for the evaporator – in general increased surface area reduces the temperature difference and thus the compressor lift; however, this is limited by practical design consideration
   - Improved heat exchange: this may be achieved using enhanced fins and/or tubes, though expected impact is limited due to other practical design consideration, other novel design options include microchannel heat exchangers and electrohydrodynamic enhancement
   - Forced-convection condenser: replace hot wall condensers in standard-size appliances with forced convection design to improve airside heat transfer coefficient and reduce condensing temperature. This option has been eliminated by US DOE due to the issues associated with cleaning and dust handling.

7. **Fans and Fan Motor**

   - Evaporator fan and fan motor improvements: efficient fans and fan motors contribute to the energy savings in 2 ways: 1) by reducing the parasitic electricity consumption, and 2) by reducing the heat dissipated into the cabinet which results in additional thermal load to be removed by the compressor

- Condenser fan and fan motor improvements: condenser fan and fan motor improvements reduce the parasitic electricity consumption
- Fan blade improvements cost of fabrication is expected to be low except for paying for the blade development and/or licensing fees. US DOE was not able to obtain credible calculation of savings and costs associated with improved fan blades. Hence, US DOE has eliminated this option from further consideration.

8. Expansion Valve

- Improved expansion valves: adjustable thermostatic or electronic expansion valves improve part load performance. These valves are available but are oversized for residential refrigeration. While they could provide optimum performance for a wider range of operating conditions, this performance improvement would not be captured under in current testing conditions, as such US DOE has eliminated this option.

9. **Cycling Losses**

- Fluid control or solenoid valve: install a fluid control or solenoid valve after the condenser to prevent refrigerant migration during the off-cycle; however, this configuration results in increased compressor starting torque and result in a negative impact on system reliability. US DOE has eliminated this option.

10. **Defrost System**

- Reduced energy for automatic defrost: use smaller heater, reduce heater on-time, reduce defrost frequency, or any combination of these. It is unlikely to achieve relevant energy savings without compromising defrost performance; hence US DOE eliminated this option.
- Adaptive defrost: control the defrost time and heat based on moisture introduced into the cabinet; this technology can reduce energy consumption by 3 – 4%
- Condenser hot gas: eliminates the electric heater and uses a valve to allow the compressor hot gas to flow through the evaporator to initiate defrost. This technology option has limited documentation and results in concerns regarding reliability of the required valve; hence it was screened-out by US DOE.

11. **Control System**

- Temperature control: use electronic thermostats to allow precise control, these controllers can also account for additional parameters to reduce compressor run times. Due to the lack in supporting data on energy savings claims, US DOE has eliminated this option.
- Air-distribution control: better air distribution the freezer and fresh food compartments can improve temperature control and reduce energy consumption. There is insufficient information regarding the designs of air flow distribution systems to quantify potential energy savings.

12. **Other Technologies**

- Alternative refrigerants: use of low GWP refrigerants such as HC-600a result in 0-5% energy savings. Due to the refrigerant charge limit of 50 g for flammable refrigerants in USA – US DOE has limited this option to compact refrigerators.
- Component location: optimize the component location to minimize parasitic energy. No options for relocation of components have been identified which merit further consideration in the engineering analysis.

13. **Alternative Refrigeration Cycles**

- Lorenz-Meutzner cycle
- Dual-loop system
- Two-stage system
- Control valve system
- Ejector refrigerator

- Tandem system

14. Alternative Refrigeration Systems

- Stirling cycle
- Thermoelectric
- Thermoacoustic

Appendix 4

Incremental Cost Details for different appliance classes as per US DOE Technical Support Document

This Appendix provides a sample of the incremental cost details for the different design options considered during the US DOE Rulemaking process for the development of the MEPS for refrigerators and freezers.

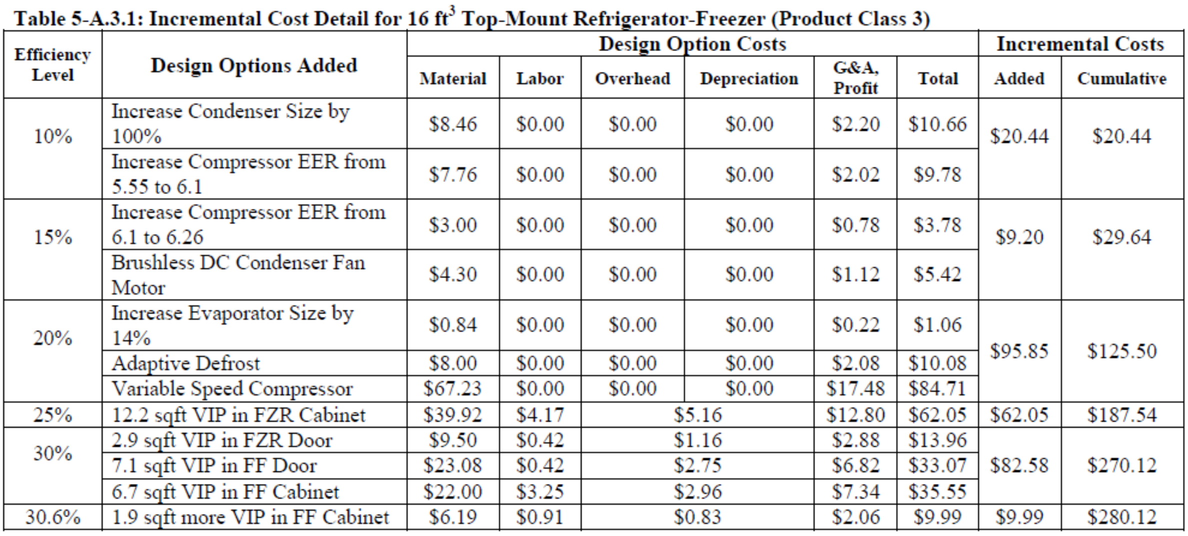

Table 5-A.3.1: Incremental Cost Detail for 16 ft^3 Top-Mount Refrigerator-Freezer (Product Class 3)

Efficiency Level	Design Options Added	Design Option Costs						Incremental Costs	
		Material	Labor	Overhead	Depreciation	G&A, Profit	Total	Added	Cumulative
10%	Increase Condenser Size by 100%	$8.46	$0.00	$0.00	$0.00	$2.20	$10.66	$20.44	$20.44
	Increase Compressor EER from 5.55 to 6.1	$7.76	$0.00	$0.00	$0.00	$2.02	$9.78		
15%	Increase Compressor EER from 6.1 to 6.26	$3.00	$0.00	$0.00	$0.00	$0.78	$3.78	$9.20	$29.64
	Brushless DC Condenser Fan Motor	$4.30	$0.00	$0.00	$0.00	$1.12	$5.42		
20%	Increase Evaporator Size by 14%	$0.84	$0.00	$0.00	$0.00	$0.22	$1.06	$95.85	$125.50
	Adaptive Defrost	$8.00	$0.00	$0.00	$0.00	$2.08	$10.08		
	Variable Speed Compressor	$67.23	$0.00	$0.00	$0.00	$17.48	$84.71		
25%	12.2 sqft VIP in FZR Cabinet	$39.92	$4.17	$5.16		$12.80	$62.05	$62.05	$187.54
30%	2.9 sqft VIP in FZR Door	$9.50	$0.42	$1.16		$2.88	$13.96	$82.58	$270.12
	7.1 sqft VIP in FF Door	$23.08	$0.42	$2.75		$6.82	$33.07		
	6.7 sqft VIP in FF Cabinet	$22.00	$3.25	$2.96		$7.34	$35.55		
30.6%	1.9 sqft more VIP in FF Cabinet	$6.19	$0.91	$0.83		$2.06	$9.99	$9.99	$280.12

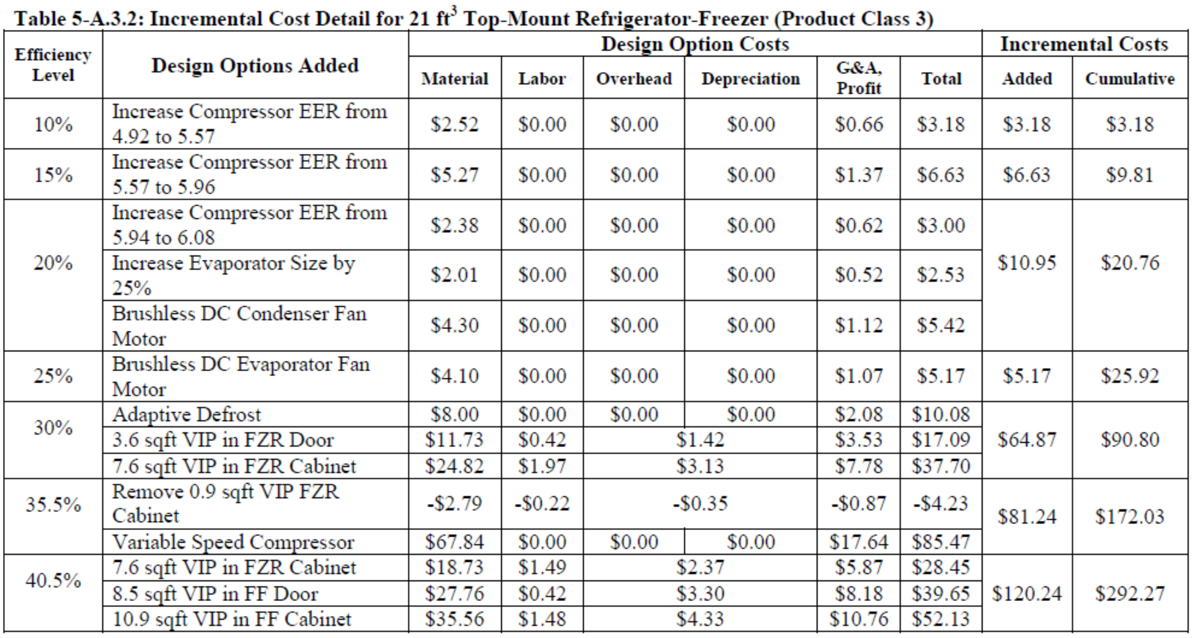

Table 5-A.3.2: Incremental Cost Detail for 21 ft^3 Top-Mount Refrigerator-Freezer (Product Class 3)

Efficiency Level	Design Options Added	Design Option Costs						Incremental Costs	
		Material	Labor	Overhead	Depreciation	G&A, Profit	Total	Added	Cumulative
10%	Increase Compressor EER from 4.92 to 5.57	$2.52	$0.00	$0.00	$0.00	$0.66	$3.18	$3.18	$3.18
15%	Increase Compressor EER from 5.57 to 5.96	$5.27	$0.00	$0.00	$0.00	$1.37	$6.63	$6.63	$9.81
20%	Increase Compressor EER from 5.94 to 6.08	$2.38	$0.00	$0.00	$0.00	$0.62	$3.00	$10.95	$20.76
	Increase Evaporator Size by 25%	$2.01	$0.00	$0.00	$0.00	$0.52	$2.53		
	Brushless DC Condenser Fan Motor	$4.30	$0.00	$0.00	$0.00	$1.12	$5.42		
25%	Brushless DC Evaporator Fan Motor	$4.10	$0.00	$0.00	$0.00	$1.07	$5.17	$5.17	$25.92
30%	Adaptive Defrost	$8.00	$0.00	$0.00	$0.00	$2.08	$10.08	$64.87	$90.80
	3.6 sqft VIP in FZR Door	$11.73	$0.42	$1.42		$3.53	$17.09		
	7.6 sqft VIP in FZR Cabinet	$24.82	$1.97	$3.13		$7.78	$37.70		
35.5%	Remove 0.9 sqft VIP FZR Cabinet	-$2.79	-$0.22	-$0.35		-$0.87	-$4.23	$81.24	$172.03
	Variable Speed Compressor	$67.84	$0.00	$0.00	$0.00	$17.64	$85.47		
40.5%	7.6 sqft VIP in FZR Cabinet	$18.73	$1.49	$2.37		$5.87	$28.45	$120.24	$292.27
	8.5 sqft VIP in FF Door	$27.76	$0.42	$3.30		$8.18	$39.65		
	10.9 sqft VIP in FF Cabinet	$35.56	$1.48	$4.33		$10.76	$52.13		

Table 5-A.3.4: Incremental Cost Detail for 18.5 ft^3 Bottom-Mount Refrigerator-Freezer (Product Class 5)

Efficiency Level	Design Options Added	Design Option Costs						Incremental Costs	
		Material	Labor	Overhead	Depreciation	G&A, Profit	Total	Added	Cumulative
10%	Increase Compressor EER from 5.61 to 6.26	$9.98	$0.00	$0.00	$0.00	$2.60	$12.58	$20.89	$20.89
	Brushless DC Evaporator Fan Motor	$4.10	$0.00	$0.00	$0.00	$1.07	$5.17		
	Increase Evaporator Size by 25%	$2.50	$0.00	$0.00	$0.00	$0.65	$3.15		
15%	Adaptive Defrost	$8.00	$0.00	$0.00	$0.00	$2.08	$10.08	$12.35	$33.24
	Brushless DC Condenser Fan Motor	$4.30	$0.00	$0.00	$0.00	$1.12	$5.42		
	Remove Evaporator Size Increase	-$2.50	$0.00	$0.00	$0.00	-$0.65	-$3.15		
20%	Variable Antisweat Heat Control	$17.48	$0.00	$0.00	$0.00	$4.54	$22.02	$25.17	$58.42
	Increase Evaporator Size by 25%	$2.50	$0.00	$0.00	$0.00	$0.65	$3.15		
25%	Variable Speed Compressor	$60.02	$0.00	$0.00	$0.00	$15.60	$75.62	$86.84	$145.26
	2.4 sqft VIP in FZR Door	$7.76	$0.21	$0.93		$2.31	$11.22		
30%	6.8 sqft VIP in FF Door	$22.09	$0.42	$2.63		$6.54	$31.68	$111.75	$257.01
	2.4 sqft more VIP in FZR Door	$7.76	$0.21	$0.93		$2.31	$11.22		
	13.7 sqft VIP in FZR Cabinet	$44.76	$4.17	$5.72		$14.21	$68.86		
32%	7.2 sqft VIP in FF Cabinet	$23.49	$4.17	$3.24		$8.03	$38.93	$38.93	$295.94

Table 5-A.3.5: Incremental Cost Detail for 25 ft^3 Bottom-Mount Refrigerator-Freezer (Product Class 5)

Efficiency Level	Design Options Added	Design Option Costs						Incremental Costs	
		Material	Labor	Overhead	Depreciation	G&A, Profit	Total	Added	Cumulative
10%	Increase Compressor EER from 5.00 to 5.67	$4.04	$0.00	$0.00	$0.00	$1.05	$5.08	$5.08	$5.08
15%	Increase Compressor EER from 5.67 to 5.97	$3.93	$0.00	$0.00	$0.00	$1.02	$4.95	$4.95	$10.03
20%	Increase Compressor EER from 5.97 to 6.26	$5.27	$0.00	$0.00	$0.00	$1.37	$6.64	$6.64	$16.67
25%	Brushless DC Evaporator Fan Motor	$4.10	$0.00	$0.00	$0.00	$1.07	$5.17	$17.11	$33.78
	Variable Anti-Sweat Heater Control	$9.48	$0.00	$0.00	$0.00	$2.46	$11.94		
30%	Brushless DC Condenser Fan Motor	$4.30	$0.00	$0.00	$0.00	$1.12	$5.42	$59.30	$93.09
	Variable Speed Compressor	$42.77	$0.00	$0.00	$0.00	$11.12	$53.89		
40.5%	9.2 sqft VIP in FF Door	$30.12	$0.42	$3.57		$8.87	$42.98	$197.92	$291.01
	5.9 sqft VIP in FZR Door	$19.34	$0.42	$2.31		$5.74	$27.81		
	14.8 sqft VIP in FZR Cabinet	$48.43	$4.17	$6.15		$15.28	$74.03		
	10.3sqft VIP in FF Cabinet	$33.57	$4.17	$4.41		$10.96	$53.10		

Table 5-A.3.7: Incremental Cost Detail for 22 ft^3 Side-Mount Refrigerator-Freezer with TTD Ice (Product Class 7)

Efficiency Level	Design Options Added	Design Option Costs						Incremental Costs	
		Material	Labor	Overhead	Depreciation	G&A, Profit	Total	Added	Cumulative
10%	Increase Compressor EER from 5.51 to 5.85	$4.45	$0.00	$0.00	$0.00	$1.16	$5.60	$12.54	$12.54
	Brushless DC Condenser Fan Motor	$4.30	$0.00	$0.00	$0.00	$1.12	$5.42		
	Increase Evaporator Area 19%	$1.21	$0.00	$0.00	$0.00	$0.31	$1.52		
15%	Increase Compressor EER from 5.85 to 6.22	$6.09	$0.00	$0.00	$0.00	$1.58	$7.68	$7.68	$20.22
20%	Increase Compressor EER from 6.22 to 6.26	$0.75	$0.00	$0.00	$0.00	$0.20	$0.95	$41.92	$62.14
	Increase Condenser Size by 27%	$3.91	$0.00	$0.00	$0.00	$1.02	$4.92		
	Variable Anti-Sweat Heater Control for Ice Dispenser	$9.48	$0.00	$0.00	$0.00	$2.46	$11.94		
	5.1 sqft VIP in FZR Door	$16.71	$0.42	$2.00		$4.98	$24.11		
25%	Remove 5.1 sqft VIP FZR Door	-$16.71	-$0.42	-$2.00		-$4.98	-$24.11	$47.49	$109.64
	Variable Speed Compressor	$44.71	$0.00	$0.00	$0.00	$11.62	$56.34		
	3.0 sqft VIP in FZR Cabinet	$9.66	$1.19	$1.27		$3.15	$15.27		
30%	7.4 sqft more VIP in FZR Cabinet	$24.15	$2.98	$3.17		$7.88	$38.17	$139.49	$249.13
	5.1 sqft VIP in FZR Door	$16.71	$0.42	$2.00		$4.98	$24.11		
	8 sqft VIP in FF Door	$26.28	$0.42	$3.12		$7.75	$37.57		
	7.8 sqft VIP in FF Cabinet	$25.60	$2.56	$3.30		$8.18	$39.64		
31%	4.9 sqft more VIP in FF Cabinet	$16.08	$1.61	$2.07		$5.14	$24.89	$24.89	$274.02

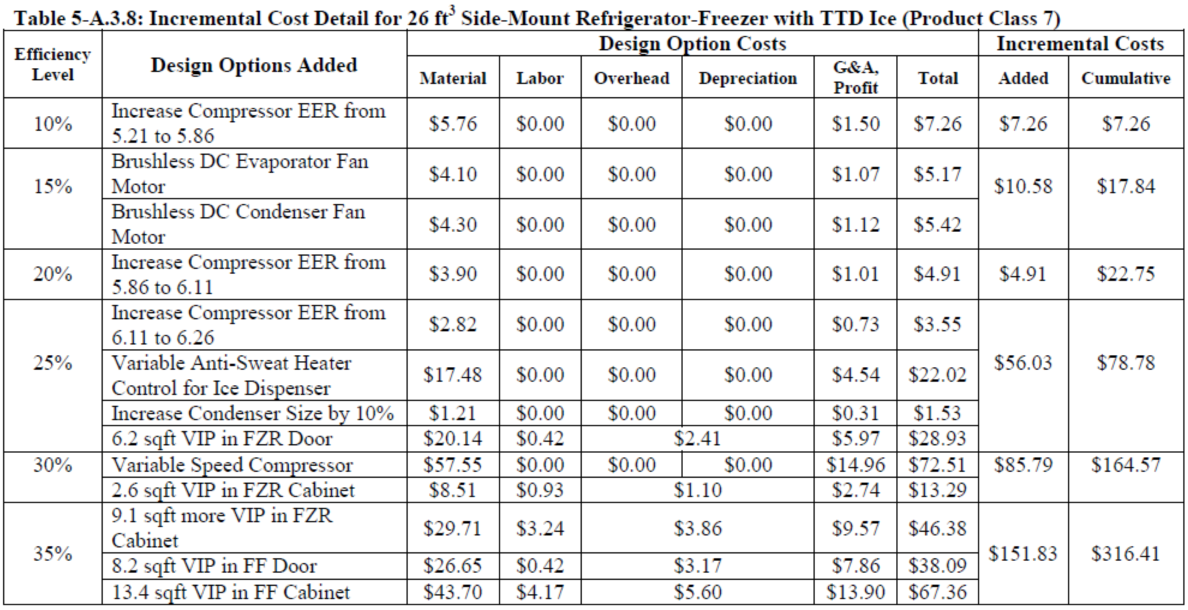

Table 5-A.3.8: Incremental Cost Detail for 26 ft^3 Side-Mount Refrigerator-Freezer with TTD Ice (Product Class 7)

Efficiency Level	Design Options Added	Design Option Costs						Incremental Costs	
		Material	Labor	Overhead	Depreciation	G&A, Profit	Total	Added	Cumulative
10%	Increase Compressor EER from 5.21 to 5.86	$5.76	$0.00	$0.00	$0.00	$1.50	$7.26	$7.26	$7.26
15%	Brushless DC Evaporator Fan Motor	$4.10	$0.00	$0.00	$0.00	$1.07	$5.17	$10.58	$17.84
	Brushless DC Condenser Fan Motor	$4.30	$0.00	$0.00	$0.00	$1.12	$5.42		
20%	Increase Compressor EER from 5.86 to 6.11	$3.90	$0.00	$0.00	$0.00	$1.01	$4.91	$4.91	$22.75
25%	Increase Compressor EER from 6.11 to 6.26	$2.82	$0.00	$0.00	$0.00	$0.73	$3.55	$56.03	$78.78
	Variable Anti-Sweat Heater Control for Ice Dispenser	$17.48	$0.00	$0.00	$0.00	$4.54	$22.02		
	Increase Condenser Size by 10%	$1.21	$0.00	$0.00	$0.00	$0.31	$1.53		
	6.2 sqft VIP in FZR Door	$20.14	$0.42	$2.41		$5.97	$28.93		
30%	Variable Speed Compressor	$57.55	$0.00	$0.00	$0.00	$14.96	$72.51	$85.79	$164.57
	2.6 sqft VIP in FZR Cabinet	$8.51	$0.93	$1.10		$2.74	$13.29		
35%	9.1 sqft more VIP in FZR Cabinet	$29.71	$3.24	$3.86		$9.57	$46.38	$151.83	$316.41
	8.2 sqft VIP in FF Door	$26.65	$0.42	$3.17		$7.86	$38.09		
	13.4 sqft VIP in FF Cabinet	$43.70	$4.17	$5.60		$13.90	$67.36		