Techno-Economic Analyses of the Incremental Cost of Super Efficiency for Refrigerators in India

August, 2012

An initiative supported by SHAKTI SUSTAINABLE ENERGY FOUNDATION

Date: August 2012

Disclaimer

Table of Contents

List of Figures 5

List of Tables 6

1. Background, Scope and Methods 4

1.1. Energy efficiency in domestic appliances 9

1.2. Super-efficient Appliances 15

1.3. Techno-economic analysis of super efficiency in appliances 16

1.4. Objectives 16

1.5. Methodology 17

1.6. Organization of this report 18

2. Market Assessment 14

2.1. Product classes in refrigerators 19

2.2. Product classes in refrigerators defined by BEE 19

2.3. Refrigerator Market in India 20

2.3.1. Market share: By category 21

2.3.2. Market share: By storage volume 22

2.3.3. Market share: By Brand 23

2.3.4. Market share: By star label 24

2.4. Standards Labeling Program in India for refrigerators 27

2.4.1. MEPS and star labelling for Refrigerators 29

2.4.2. Test Procedure for Direct Cool and Frost Free refrigerators 31

3. Technology Assessment 28

3. 1. Basic refrigeration technology 33

3.1.1. Working of a Vapor-compression type refrigerator 33

3.1.2. Main components of a refrigerator 34

3.2. Factors affecting energy consumption in a refrigerator 36

3.3. Defrost system in Frost free refrigerators 37

3.4. Refrigerator storage volume 38

3.5. Technologies for improving refrigerator efficiency: Review of global studies 39

3.5.1. Insulation 41

3.5.2. Gasket and Door design 44
3.5.3. Heat Exchanger Improvements 44
3.5.4. Compressor Improvements 46
3.5.5. Defrost systems 47
3.5.6. Other technological options 48
3.6. Summary of technologically feasible options from global studies 49
4. Techno-economic and Consumer Impacts Analysis 46
4.1. Techno-economic Analysis 51
4.1.1. Need for conducting Techno-economic analyses 51
4.1.2. Review of methodology for conducting techno-economic analyses 52
4.2. Consumer Impacts Analysis 53
4.2.1. Life cycle cost analysis 53
4.2.2. Payback period analysis 53
4.3. Methodology 54
4.3.1. Techno-economic Analysis for super-efficiency in Indian refrigerators 54
4.4. Consumer Impacts Analysis 57
4.4.1. LCC of super-efficiency in Indian refrigerators 57
4.1.2. Payback period analysis for super efficient refrigerators 58
4.5. Results 58
4.5.1. Technological options for super efficiency in Indian refrigerators 58
4.5.2. Cost-efficiency relationship 61
4.5.3. LCC and Payback period analysis 68

List of Figures

Figure 1: Projected power consumption by kitchen appliances in India (2006-2031) 12
Figure 2: Population of refrigerators in India (2006-2031) 12
Figure 3: International comparison: Frost Free refrigerators in India 14
Figure 4: Approach to Techno-economic analyses of incremental costs of super-efficiency for Refrigerators in India 18
Figure 5:Sales volume for refrigeration appliances in India (1998-2015) 21
Figure 6: Sales Volume and Value category wise (1998-2005) 22
Figure 7: Storage Volume-wise sales Direct Cool refrigerators in India (2010-11) 23
Figure 8: Storage Volume-wise sales Frost Free refrigerators in India (2010-11) 23
Figure 9: Brand-wise market share in refrigeration appliances in India (2001-2010) 24
Figure 10: Sales volume of Star labeled refrigerators 25
Figure 11: Market share of star labelled frost free refrigerators in (a) 2009-10 and (b) 2010-11 26
Figure 12: Market share of star labelled Direct Cool refrigerators in (a) 2009-10 and (b) 2010-11 27
Figure 13: Rating plan January 2012 to December 2013 30
Figure 14: Rating plan January 2014 to December 2015 30
Figure 15: Rating plan January 2010 to December 2011 31
Figure 16: Typical single-stage vapour compression refrigeration 33
Figure 17: Working of reciprocating compressors 34
Figure 18: Expansion valve used in refrigeration systems 36
Figure 19: A refrigerator fitted with VIPs 43
Figure 20: Structure of a VIP 43
Figure 21: Vacuum Insulated Panels 43
Figure 22: Cost-efficiency Curve -without VIP (Case 1) for Direct Cool refrigerators 65
Figure 23: Cost efficiency curve - without VIP (Case 2) for Direct Cool refrigerator 66
Figure 24: Cost-efficiency Curve -without VIP (Case 1) for Frost free refrigerators 67
Figure 25: Cost efficiency curve - without VIP (Case 2) for Frost free refrigerators 67

List of Tables

Table 1: Annual verified savings in MW from BEE programs 10
Table 2: Highlights of BEE's standards and Labelling program for appliances and equipment 10
Table 5: Market share of Star labeled refrigerators (2007-2010) 25
Table 6: Production of star labelled frost free refrigerators 26
Table 7: Production of Star labelled Direct Cool Refrigerators 26
Table 8: Energy saving potential from different electrical products 28
Table 9: Demand Saving Potential (MW) from key electrical products 28
Table 10: Original Star rating plan announced by BEE 28
Table 11: Design options identified by US US DOE for energy improvements in domestic refrigerators 49
Table 12: Design options identified under EU Ecodesign Initiative for energy improvements in domestic refrigerators 50
Table 13: Compilation of design options for Indian refrigerators 56
Table 14: Design options under Case 1- Without VIPs for Direct Cool Refrigerators 63
Table 15: Design options under Case 2- With VIPs for Direct cool refrigerators 64
Table 16: Design options under Case 1- Without VIPs for Frost free Refrigerators 64
Table 17: Design options under Case 2- With VIPs for Frost free refrigerators 64
Table 18: Consumer Impacts Analysis of Design options: Case 1 for 180 L Direct Cool Refrigerators 69
Table 19: Consumer Impacts Analysis of Design options: Case 2 for 180 L Direct Cool Refrigerators 70
Table 20: Consumer Impacts Analysis of Design options: Case 1 for 230 L Frost free Refrigerators 71
Table 21: Consumer Impacts Analysis of Design options: Case 2 for 230 L Frost free Refrigerators 72

Executive Summary

Refrigerators have increasingly been finding way in the Indian homes. As per industry reports, the refrigerator market registered and annual growth of 15% for the year 2010-11. The total Indian market was at 8.4 million units in 2010-11, a 15% increase from 7.3 million units in 2009- 10. The contribution of frost-free category of refrigerators has been gradually increasing with approximately 24% share in 2011-10. The Bureau of Energy Efficiency (BEE) introduced mandatory star labelling for Frost free refrigerators in 2010 with a provision of tightening up of energy performance standards periodically i.e. subsequent revisions in the standards every two years. However, while revision of standards eliminates less efficient products from the market, by itself it does not provide an incentive to increase energy efficiency. On the other hand a technology push through the introduction of super-efficient appliances increases the average efficiency even without the imposition of energy efficiency standards. In the case of refrigerators there is still a gap between efficiency of a 5-star refrigerator and the best available technology globally; average energy consumption of currently available BEE 5-star models is 26% more than a frost free model of same capacity in the US.

Globally, super efficiency in home appliances like refrigerators is being explored in many developed countries. Energy agencies in nations like US, Europe, Japan and Australia continually evaluate technology trends in refrigerators market to understand energy efficiency improvements possible in existing refrigeration appliances from introduction of commercially available and economically feasible design modifications. These countries revise energy performance standards for refrigeration appliances based on these evaluations to decide standards that do not burden both manufacturers and consumers. The Super-Efficient Appliances Deployment Initiative (SEAD) has 16 member countries working together to "raise the efficiency floor by bolstering national or regional policies like Minimum Efficiency standards and labels and strengthening the foundations of efficiency programs by coordinating technical work to support these activities''.

Presently, achieving super efficiency is not on the agenda of Indian refrigerator manufacturers because of two main barriers. First, the uncertainty regarding market demand for Super-Efficient Products (SEPs) and, second theuncertainty about cost-effectives of manufacturing high-efficiency models. This study seeks to identify these barriers through a techno economic analysis of design options for improving efficiency of refrigerators in India. Such a study will be useful in indicating the maximum efficiency levels that can be achieved cost effectively using commercially available efficient technologies. This analysis will also help in designing incentive mechanisms for accelerating and commercializing super-efficient technologies so that high cost of the SEPs does not become a barrier. Also the introduction of these technologies will help the nation in moving on the path of low carbon development.

This present study explored the introduction of super-efficient or highly efficient refrigerators in the Indian market through a techno-economic evaluation of commercially available technology options for improving the energy efficiency of Indian refrigerators. Based on consultations with technical experts of leading refrigerator manufacturers in India, ICF compiled a list of design options most feasible for bringing about significant improvements in the energy performance of the baseline BEE 5-star labeled refrigerators. ICF, Shakti and CLASP had jointly agreed at project inception that stakeholder discussions would be limited to manufacturers accordingly ICF collected information on the percentage energy efficiency improvement potential, the approximate increase in manufacturing cost or incremental manufacturing cost and the subsequent increase in purchase cost of the product in Indian Rupees for a set of design options. These design options were combined to estimate their cumulative impact on energy efficiency for two cases. For Case I where vacuum insulated panels (VIPs) were not considered as a means for improving energy efficiency and in Case II where introduction of VIPs in the insulation component was considered. Both the cases comprised a set of design options that resulted in energy efficiency improvements when combined. These design options were common to both Direct Cool and Frost free 5-star labeled models. Based on the efficiency improvements and associated incremental manufacturing costs, Cost-efficiency curves were generated to understand cost-efficiency relationship. The impacts on consumer due to the increase in purchase price of more efficient or super-efficient product (both Frost free and Direct cool) was also evaluated through a Life cycle Costs (LCC) and Payback period analysis. It was observed that for few of the design options, the payback period is less than 5 years.

Findings from this study will be useful in indicating the maximum efficiency levels that can be achieved cost effectively using commercially available efficient technologies. This analysis will also help in designing incentive mechanisms for accelerating and commercializing super-efficient technologies so that high cost of the SEPs does not become a barrier. Also the introduction of these technologies will help India to move on the path of low carbon development.

1. Background, Scope and Methods

Shakti Sustainable Energy Foundation (Shakti) commissioned ICF International to undertake this techno-economic analysis of the incremental costs of super-efficiency for Indian refrigerators. The sub-sections below describe the background of this study, the scope and objectives, methodology and the organization of the remainder of this report

1.1. Energy efficiency in domestic appliances

Policies for promoting appliance energy efficiency

Energy efficiency is rapidly becoming a key policy tool all over the world to meet the substantial growth in energy demand. According to the International Energy Agency (IEA) 71% of the global emissions reductions would come from energy efficiency improvements in 2020 and 38% by 2050[1]. The mitigation potential of energy efficiency would be realized by policies that are designed to encourage the purchase of energy efficient appliances and equipment. Additionally policies will be needed to ensure optimized operation of these products to avoid the rebound effect[2]. By all accounts, programmes on energy efficiency are among the least cost options which provide positive returns to government, energy consumers and the environment.

Amongst all regulatory and policy instruments, energy performance standards for energy consuming products are the easiest to implement and have the highest potential to achieve energy savings targets in a short span of time. Globally, implementation of Minimum Energy Performance Standards (MEPS) that prescribe minimum efficiencies or maximum energy consumption that manufacturers must achieve in each and every product have helped bring about major improvements in the energy efficiency of home appliances like refrigerators. In all homes whether in the developed or developing world, a refrigerator runs for 365 days a year and almost the whole day. In the US, MEPS for residential refrigerators and freezers were first introduced in 1990 and subsequently revised in 1993 and 2001. A decline in energy consumption by 20% with each revision indicated that these efficiency gains were driven by MEPS. The average energy consumption of refrigerators and freezers in the US declined by 60% between 1980 and 2001; in UK, the energy consumption of refrigerators and freezers declined by 20-25% between 1989 and 2000 when energy label for refrigerators and freezers was introduced in 1995 and in Australia, energy consumption in the average refrigerator decreased by over 40% since 1993 while MEPS was introduced for refrigerators in Australia in 1999 (Ellis et al., 2007)

[1] IEA, 2011. Energy efficiency policy and carbon pricing: Information Paper

[2] Although use of energy efficient products reduces the demand for energy, consumers may undertake other energy intensive activities or use the energy efficient products for longer durations, thereby countering the potential savings of energy. This is called the **rebound effect**

In order to match growing energy demand with available energy efficiency technologies, governments need to develop and subsequently evolve both voluntary and mandatory Standards and Labeling (S&L) programs. These programs aim to remove inefficient products from the market and promote development of cost-effective energy efficient products through the implementation of energy performance standards and labels.

India's S&L program for equipment and appliances

India's Energy Conservation Act 2001 (EC Act) identifies S&L as a major program area for improving energy efficiency in the residential, commercial and public sectors. The S&L program comprises implementation of Minimum Energy Performance standards (MEPS) and 'Star' labeling of electrical equipment on a scale of 1 to 5 in increasing order of efficiency. The star label on products is aimed at helping consumers make energy efficient purchases. For household appliances labeling was first introduced in 2006 on a voluntary basis for both Frost Free and Direct Cool refrigerators. Observing the increasing market share of frost free refrigerators, BEE declared mandatory star labeling for this product class in January 2010 with tightening up of energy performance standards periodically i.e. subsequent revisions in the standards every two years.

Table 1: Annual verified savings in MW from BEE programs

2007-08	2008-09	2009-10	2010-11	2011-12*	Cumulative savings (MW)
623	1504	2868	2670	1602	9267

*till September 2011 (Source: BEE)

BEE's overall strategy is to begin labeling on a voluntary basis and then, as market receptivity increases, transition to a mandatory scheme. Twelve products are currently administered by the BEE under the voluntary labeling program. As per BEE, the verified savings related to all BEE programs have reached cumulative savings of more than 9,000 MW by September 2011 (Table 1). Table 2 shows the timeline for the S&L program since it began in 2006.

Table 2: Highlights of BEE's standards and Labelling program for appliances and equipment

Year	Action
2006	BEE announces voluntary star labelling scheme for **Frost Free refrigerators** and T-5 fluorescent lights in May 2006, followed by similar announcements for Direct Cool refrigerators, Electric Motors, ACs and Ceiling Fans in the same year
July 2009	BEE issues gazetted notification on Energy Consumption Standards and Manner of their Display on Labels for (a) Tubular Fluorescent Lamps b) Room Air Conditioners c) Distribution Transformer d) **Household Frost Free Refrigerators**
January 2010	BEE announces Mandatory star labelling for Tubular Fluorescent Lamps b) Room Air Conditioners c) Distribution Transformer d) **Household Frost Free Refrigerators**

Currently, the labelling program covers the following appliances:

Under mandatory scheme:

- Frost-free refrigerators
- Room air conditioners
- Fluorescent lamps
- Distribution transformers

Under voluntary scheme

- Direct cool refrigerators
- Ceiling fans
- General purpose industrial motors
- Agricultural pump sets
- Color televisions (CTVs)
- Washing machines
- Domestic gas stoves
- Stationary storage type water heaters (geysers)

The Indian program also combines comparative star labels with MEPS wherein products that pass the minimum energy requirements are awarded 1-star. The BEE star labels are based on comparative energy efficiency performance. Thus appliances like refrigerators are rated for their energy efficiency on a star rating scale of 1 to 5 with 5-star rating for the most energy-efficient appliance. The Indian program also includes a strategy to increase the stringency of both standard and labels every few years. This strategy was designed in order to quickly launch the program with relatively relaxed standards, but define regular intervals for improvement, after which efficiency requirements will become stringent. For refrigerators, updates in performance standards in 2012 and 2014 have been specified. In each step, MEPS and label levels are raised one step, corresponding to an approximately 20% increase in energy efficiency across every star label category.

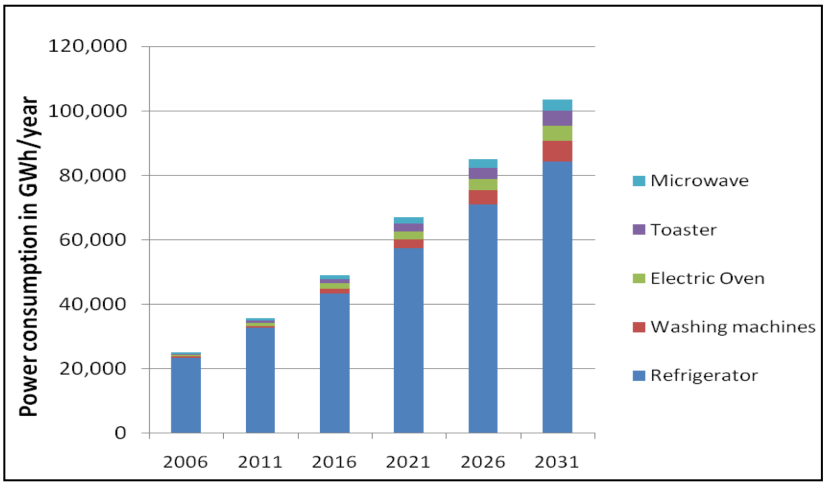
Energy demand by refrigeration appliances in India

Growing at a rate of 1.3% per annum[3]energy demand by India's residential sector is attributed to lighting appliances, cooling and heating appliances, kitchen appliances (e.g. refrigerators, microwave ovens, washing machines etc) and entertainment appliances. In another World Bank[4] supported study the data collected through National Sample Survey (NSS) on appliance ownership, household

[3]McKinsey Global Institute (2007) Curbing Energy demand and growth: the energy productivity opportunity. http://www.mckinsey.com/mgi/reports/pdfs/Curbing_Global_Energy/MGI_Curbing_Global_Energy_full_report.pdf
[4]World Bank, 2008. Background Paper India: Strategies for Low Carbon Growth

size and expenditure and electricity consumption showed that in kitchen appliances refrigerators had the largest share in the energy demand (93%) in 2006 (Figure 1).

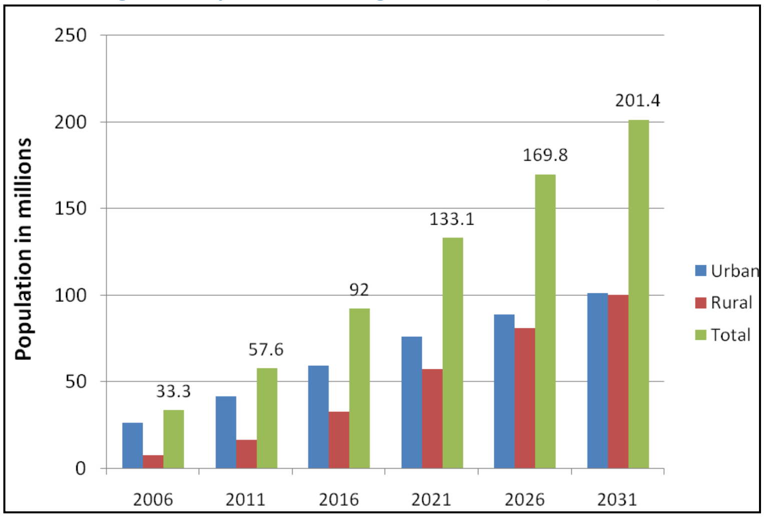
Figure 1: Projected power consumption by kitchen appliances in India (2006-2031)



(Source: World Bank, 2008)

If we look at Figure 2 showing the total power consumption by kitchen appliances, namely refrigerators, washing machines, microwave, electric oven and toasters, it can be observed that refrigerators have the largest share in electricity demand (93%) in this segment. The number of refrigerators is also projected to grow from 33.3 million units in 2006 to 133.1 million units in 2021. The total energy consumption of refrigerators was 23,490 GWh/year in 2006 and is likely to increase to 57,349 GWh/year in 2021. Corresponding to the total energy consumption from refrigerators in 2006, the total emissions of GHGs from refrigerators was 19.2 million tonnes of CO_2 and is projected to increase to 47 million tonnes of CO_2 in 2021.

Figure 2: Population of refrigerators in India (2006-2031)



(Source: World Bank, 2008)

The energy demand and number of refrigerators is also projected to reach 57,349 GWh/year and 133.1 million units in 2021 (Figure 2) respectively resulting in an increase in CO_2 emissions from 19.2

million tonnes in 2006 to 47 million tonnes in 2021(World Bank, 2008). Increased disposable income and low penetration in rural and semi-urban household are the chief drivers for rising demand for refrigerators in India.

Comparison of Energy performance standards for Indian refrigerators with global standards

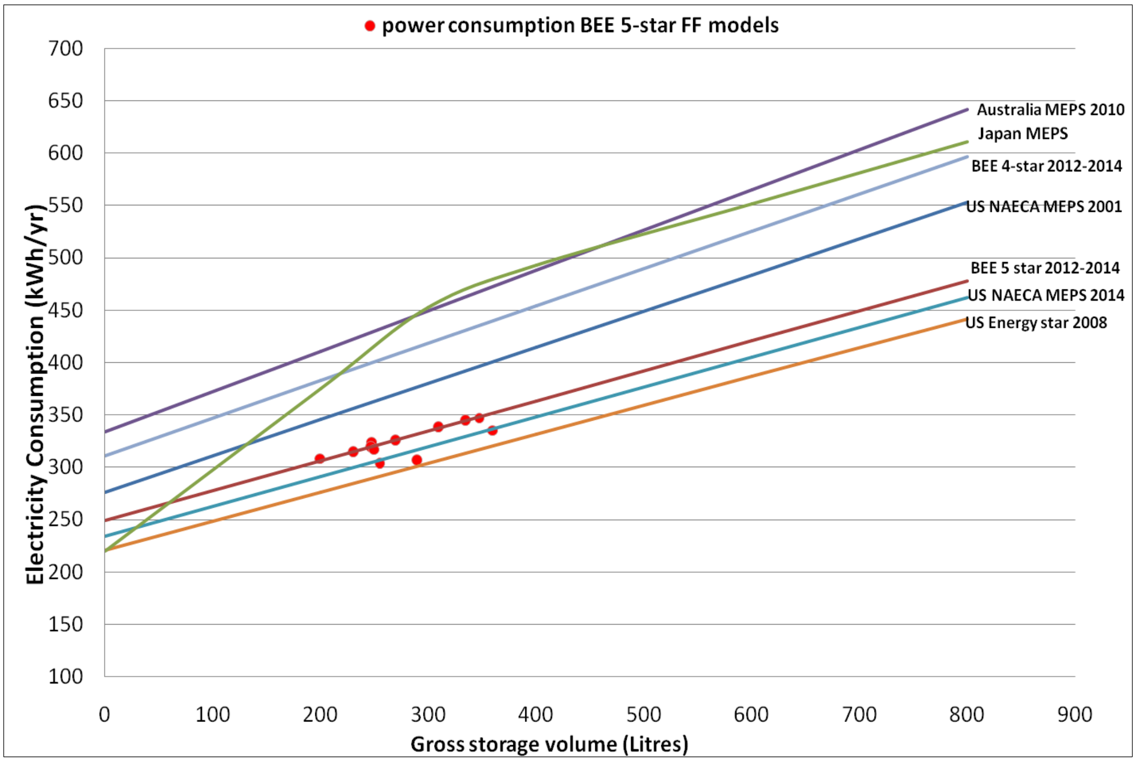
Refrigeration appliances are perhaps the most regulated products globally with respect to energy efficiency and yet, test procedures for these appliances are least harmonized with most complex and diverse range of national and regional test procedures used globally. This is also because energy consumption of refrigerators is affected by climatic and ambient temperature conditions in addition to lifestyle which vary considerably by the region. This makes international comparisons of energy performance of refrigerators challenging.

Many countries have programs for energy labelling and use different methods for determining energy efficiency standards for electrical equipment. The **MEPS** system is used in many countries like the US, Australia and India under which all efficiency levels of energy consuming products must not exceed certain standard value, which is the minimum efficiency. The second method is ***class-average standard value system,*** under which the average efficiency of all products covered in this system should exceed standard value. This system was used in Japan until 1999, when top runner standards were introduced. The Top Runner standards used a maximum standard value system which uses a base value of the product with the highest energy efficiency available in the market at the time of standard setting process and sets standard values by considering potential technological improvements added as efficiency improvements[5].

The US Department of Energy's (US DOE) Appliances and Commercial Equipment Standards Program is managed by the Office of Energy Efficiency and Renewable Energy (EERE), which develops and announces test procedures and prescribes mandatory MEPS for consumer appliances and commercial equipment required under the National Appliance Energy Conservation Act (NAECA, 1987). Under NAECA standards for residential refrigerators, refrigerator-freezers and freezer were first announced in 1989which were revised in 1997 and 2007. Besides, there is also the US Environment Protection Agency's (EPA) voluntary labelling program "Energy Star" under which energy star labels are given to energy consuming products that are at least 20% more efficient than the existing NAECA standard. Australia also has a standards and labeling program similar to India for nine categories of refrigeration appliances. In Japan, the Top Runner Program had resulted in an improvement of energy efficiency levels by 55.2% between 1998 and 2004.

[5]METI, 2010. Top Runner Program: Developing the world's most efficient appliances

Figure 3: International comparison: Frost Free refrigerators in India



It is useful to benchmark energy consumption of frost free refrigerators available currently in the Indian market against the energy performance standards of US, Japan and Australia. In order to compare energy performance standards of different countries it is necessary to convert energy consumption values under each test method to a common basis. Following were the equations used for plotting the graph for comparing the performance of BEE-5 star frost free refrigerators with MEPS in other countries.

US NAECA MEPS 2001	0.346*AV+ 276
US NAECA 2014	0.285AV+ 233.7
Energy star 200	0.276*AV+ 220.8
Australia MEPS	0.384*av + 334
Japan MEPS for upto 300 litre	0.302*AV+ 343
Japan MEPS for more than 300 litre	0.296AV+ 374

Figure 3 shows energy consumption of a sample of BEE 5-star labelled frost free refrigerators compared to MEPS in the US, Australia and Japan and latest Energy Star specifications. The idea behind this graph is to represent a comparison between MEPS of BEE 4 and 5 star categories with international standards on a broad level.

It can be observed that new energy performance standard prescribed by BEE for the 5-star Frost free category is comparable to the MEPS prescribed by US DOE under NAECA. However, the energy performance standard for the new BEE 5-star is superior to the MEPS in Australia for Frost free refrigerators.

The energy consumption of 200 litre BEE 5-star frost free refrigerator is 11% less than the same capacity refrigerator under present NAECA MEPS. But, Energy Star rated products in the US are on an average 25% more efficient than BEE 5-star refrigerators. As per BEE's roadmap for incresing the stringency level of energy consumption norms, the 5-star label refrigerator produced in 2014 will be 40% more efficient than those produced in 2012. Thus, the BEE-5 star of 2014 will be comparable to revised MEPS prescribed under NAECA in 2014.

Compared to MEPS prescibed for frost free refrigerators by the Agency of Natural Resources and Energy under the Ministry of Economy, Trade and Industry (METI) of Japan, BEE 4-star and 5-star frost free models are on an average 10% more efficient for volumes greater than 300 litres. Also, compared to the energy consumption prescribed under Australian MEPS for products of same storage volumes BEE 4 and 5-star labelled frost free refrigerators are 7% and 26% more efficient respectively.

1.2. Super-efficient Appliances

International and national efforts at promoting super- efficiency in appliances

One of the earliest examples of promoting super-efficiency in appliances was the Super-Efficient Refrigerator Program (SERP) in the US launched in 1992 which awarded $30 million to the refrigerator manufacturer that developed and commercialized a refrigerator that exceeded 1993 federal efficiency standards by at least 25%. The program was funded by 24 public and private utilities and was also called the *Golden Carrot Program*. In Sweden also, NUTEK (Swedish Agency for Economic and Regional Growth) developed a similar competition for super-efficient refrigerators. The program was based on a contest that would award an order for at least 500 energy efficient and environment friendly refrigerators and concluded with the production of a refrigerator with 30% lower energy consumption than the most efficient unit previously on the Swedish market.

At present, under EPA's Energy Star program appliances are given an Energy Star label if they are at least 20% more efficient than the existing MEPS prescribed under the NAECA. The market penetration of Energy Star products is promoted by means of various rebate schemes and other incentives under the Super-Efficient Home Appliances (SEHA) initiative. In China, the Sino-US CFC-Free Super-Efficient Refrigerator Project was initiated in 1997 to promote development of CFC-free refrigerators and at the same time increase energy efficiency of existing refrigerators.

In 2008, India launched National Mission on Enhanced Energy Efficiency (NMEEE) under the National Action Plan on Climate Change (NAPCC), which aims at accelerating market penetration of energy efficient appliances through various measures. The Super-Efficient Equipment Program (SEEP) is an initiative under NMEEE designed to promote super-efficient appliances SEAs that would save energy and enable in demand side management. The programme envisages a reduction in the cost of energy efficient appliances to accelerate market transformation and also encourage domestic manufacturing sector for sustaining the market. India is a also a member of the Super-efficient Equipment and Appliance Deployment (SEAD) initiative that seeks to transform the global market for efficient equipment and appliances by forging alliances between nations for promoting and transferring energy efficient technologies for appliances. This program aims to raise the energy efficiency standards in participating countries.

Super-efficient Appliances

Going by the programs implemented in US and Sweden to improve refrigerator efficiency and introduce superefficient refrigerators. A Super-Efficient Appliance (SEA) uses the best possible technology that is economically feasible to the extent to which efficiency could be improved through technology diffusion. Since markets and technologies change continually often in response to previous policies, setting performance standards or targets for voluntary and mandatory energy efficiency labeling for appliances involves analyses of technical, economic and market development trends for these appliances.

1.3. Techno-economic analysis of super efficiency in appliances

Refrigerators are among the most common household appliances in the world. To meet MEPS requirements in different countries major improvements have been brought about in the design of refrigerator systems. These include improvements in the cabinets such as advanced insulation, improved gaskets, improvements in refrigeration systems such as the use of efficient low GWP refrigerants, improved fan motors, high efficiency compressors and other design modifications such as improved heat exchangers, advanced defrost mechanisms.

In countries and regions like the US, Japan, Australia and the European Union, energy performance standards revisions are preceded by studies that economically evaluate technology options for appliances like refrigerators to achieve further improvements in the MEPS. Analysis done by Lawrence Berkeley National Laboratory (LBNL)[6] in 2005 found that efficiency improvements up to 45% in Indian refrigerators would be cost-effective for consumers. In the same study it was concluded that while BEE’s S&L program presents net benefits to consumers, there are opportunities for efficiency improvement that would optimize consumer benefits. Their analysis concluded that even through the market share of frost free units will increase overtime, the market will continue to be dominated by direct cool segment, where standards are relatively slack and there is a large scope for increasing the stringency of the standards.

A techno-economic analysis of design options for refrigerators will help in optimizing the impacts of policy actions by bringing about reductions in energy demand (due to improved efficiency), providing maximum benefits to energy consumers and also conform to the reality of the market and needs of supply chain players.

1.4. Objectives

The objective of this assignment was to conduct technical and economic analyses of design options for improving the energy efficiency of existing refrigerators in India. Following were the main objectives of the project:

[6]M.A.McNeil, M.Iyer, S.Meyers, V.E.Letschert, J.E.McMahon, Potential Benefits from Improved Energy Efficiency of Key Electrical Products: The Case of India, LBNL-58254, 2005.

- Identification of technological options/ design options available for improving energy efficiency of refrigerators in India
- Evaluation technical and economic feasibility of the design options with respect to incremental costs in manufacturing and retail price to consumer
- Life cycle costs analysis Payback period analysis to determining the time required to recover the additional investment made by the consumer in purchasing a super-efficient refrigerator model through lowered operating costs

1.5. Methodology

Figure 2 describes ICF's the approach for achieving the objectives under this study. The study was divided into three tasks:

Task 1: Market Assessment

This task comprises of an assessment of the India's refrigerator market based on category, brands and BEE star label. Market assessment also helped in understanding present and future trends in the demand of specific categories of refrigerators, drivers for this demand.

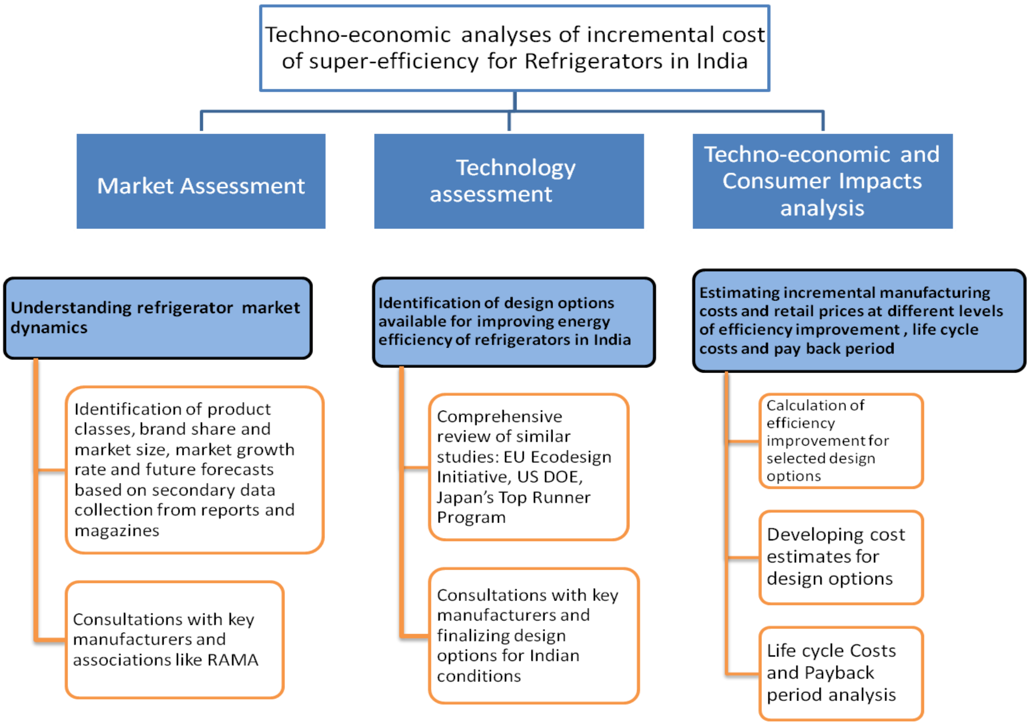
Task 2: Technology Assessment

An assessment of the technologies available for increasing refrigerator efficiency was discussed compiled from global studies evaluating design options.

Task 3: Techno-economic and Consumer Impacts Analysis

The list of design options was discussed with major manufacturers for their feedback on the efficiency levels achieved and costs associated with each option to the manufacturer and the consumer.

Figure 4: Approach to Techno-economic analyses of incremental costs of super-efficiency for Refrigerators in India



1.6. Organization of this report

Part 2 of this report is on market assessment of refrigerators in India and discusses the dynamics of the refrigerator market in India, the different categories of refrigerators available in the Indian market and their market share. This section also describes the market share of refrigerators based on storage volume and dominant brands. Market share of star labeled Frost free and Direct cool segments is also discussed in this section.

Part 3 discusses the various technology options available for improving energy efficiency of refrigerators in India. This section described basics of refrigeration technology and presents the findings of the review of global studies and reports on technology options available for improving efficiency of domestic refrigerators. ICF has studied two reports: US DOE's technical Support Document for revised NAECA standards for refrigerators and refrigerator- freezers and preparatory work done for the European Union's Ecodesign Initiative. At the end of this section, ICF has presented a list of design options that were summarized after review of studies in US and EU.

Part 4 discusses the techno-economic and consumer impacts analysis of selected design options for improving efficiency of refrigerators. It describes the findings from these analyses in the form of cost-efficiency curves and Life cycle costs and Payback period for design options for improving energy efficiency of Indian refrigerators.

2. Market Assessment

2.1. Product classes in refrigerators

Traditionally the household refrigerators have been free-standing or compact units as opposed to the built-in format where refrigerators are built into the kitchen cabinets. Some recent technological innovations, mainly to suit changing consumer needs have been introduction of **T**hrough-**T**he-**D**oor(TTD) ice dispensers, special refrigerators only for cooling wines (wine coolers)or Kimchi refrigerators that cater to specific markets in Europe and Korea (used for storing kimchi) etc. Generally, freestanding refrigeration appliances are categorized into four main categories based on their design:

- **Refrigerators**: 1-door manual defrost refrigerators that typically have one compartment suitable for storage of fresh food and in some cases, a small freezer compartment or an ice box (in case of even smaller capacities)
- **Refrigerator-freezers**: More than one door auto defrost refrigerators that have at least one compartment suitable for storage of fresh food and atleast one other for storage of frozen food or freezing food. These come in a variety of formats based on the number of doors they have (two door, three door and four door refrigerators) or the location of the freezer compartment (top mounted, bottom mounted, side by side)
- **Freezers**: These have one or more compartments suitable for freezing food from ambient temperatures and storing frozen food stuff

Based on the above three categories and different variations in these formats, US DOE defines energy performance standards for 18 product classes of refrigeration appliances. In Europe, energy performance standards for 10 product categories have been defined based on the temperatures maintained in different compartments. In Japan, refrigerators and refrigerator-freezers are classified into natural convection type (manual defrost) and forced circulation type (automatic defrost) which are further categorized based on their internal volumes (less than 300L and more than 300L). Energy performance standards for all these four categories of domestic refrigeration appliances have been prescribed in Japan.

2.2. Product classes in refrigerators defined by BEE

Despite presence of advanced refrigerator models found in international markets (TTD-refrigerators, side by side, French door, bottom mounted, multi-door) only two product categories: Manual defrost or Direct cool refrigerators and automatic defrost or Frost free refrigerators dominate the Indian market. BEE has prescribed mandatory and voluntary star labelling and energy performance standards for Frost free refrigerators and Direct cool refrigerators respectively. The latter occupies the largest market share while the sales volume of Frost free format has been increasing in recent years. These two product categories are defined below:

Direct Cool Refrigerators: Single door refrigerators where the upper portion of the unit houses the freezer, the middle portion is the refrigerator and the bottom portion is normally used for storing vegetables. In a Direct Cool refrigerator, cooling is obtained by natural convection only. Some models may have a fan to avoid internal condensation. These refrigerators require manual defrosting of the frost accumulated in the freezer. Storage capacities of Direct Cool refrigerators range from 50 litres to 300 litres. Direct cool models with storage volume ranging from 170 L to 200L have the maximum sale (Euromonitor, 2011).

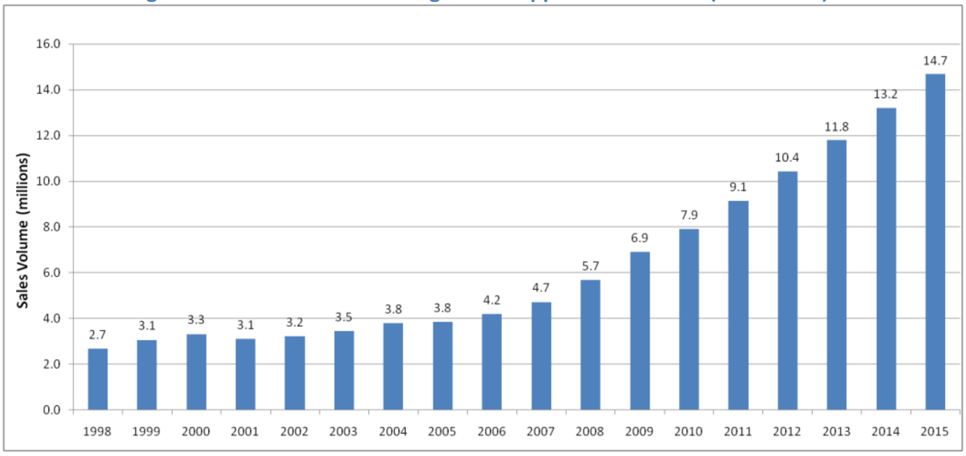
Frost Free Refrigerators: Frost Free refrigerators come with either two or three doors. Cooling in these refrigerators is by forced air circulation which leads automatic frosting and defrosting of the unit. Unfrozen food storage space may or may not be cooled by a frost free system but all storage spaces in the appliance whether frozen or unfrozen are automatically defrosted with automatic disposal of water. The gross volume of Frost Free models ranges from 200 litres to 600 litres. Frost free models with storage volume ranging from 220L to 300L are most popular and have highest sale (Euromonitor, 2011).

2.3. Refrigerator Market in India

In the present study, findings from Euromonitor's report on *Refrigeration Appliances in India* published in 2011 have been presented. The demand in India is primarily for freestanding refrigeration appliances and there is no significant presence of built-in appliances. However, the growing modular kitchen trend has prompted companies like Electrolux to launch built-in refrigeration appliances in the country, although demand and sales remained negligible in 2010.In the free-standing refrigeration appliances category, market for freezers and other categories like wine coolers/chillers is negligible. The concept of electric wine coolers is also very new and it has yet to gain popularity in India. Some industry experts also believe that this type of product is not suitable for Indian conditions and therefore the sale of electric wine coolers was negligible in 2010.

The growth forecast in sales volume and sales value for 2011-2015 has been based on CAGR of 15.6% for 2005-10. Figure 5 shows the change in total sales volume for refrigeration appliances from 1998 to 2009 and forecast for 2010-2015. Low household penetration rates, weather conditions, changing lifestyles and growing nuclear family trend will continue to drive the demand for refrigeration appliances in India. However, India being a price sensitive market, major increases in prices of refrigeration appliances can slow down growth in this segment. The Indian refrigeration market is predicted to reach the 15 million mark by 2015.

Figure 5:Sales volume for refrigeration appliances in India (1998-2015)



(Source: Euromonitor, 2011)

According to Euromonitor, dual colours, designs, metallic finishes and handle shapes are heavily influencing the purchasing decisions of consumers. The growth of large chained durable goods retailers has given an opportunity to companies to showcase their product ranges. Most people visit these outlets to gain product knowledge in order to make informed comparisons and choices.

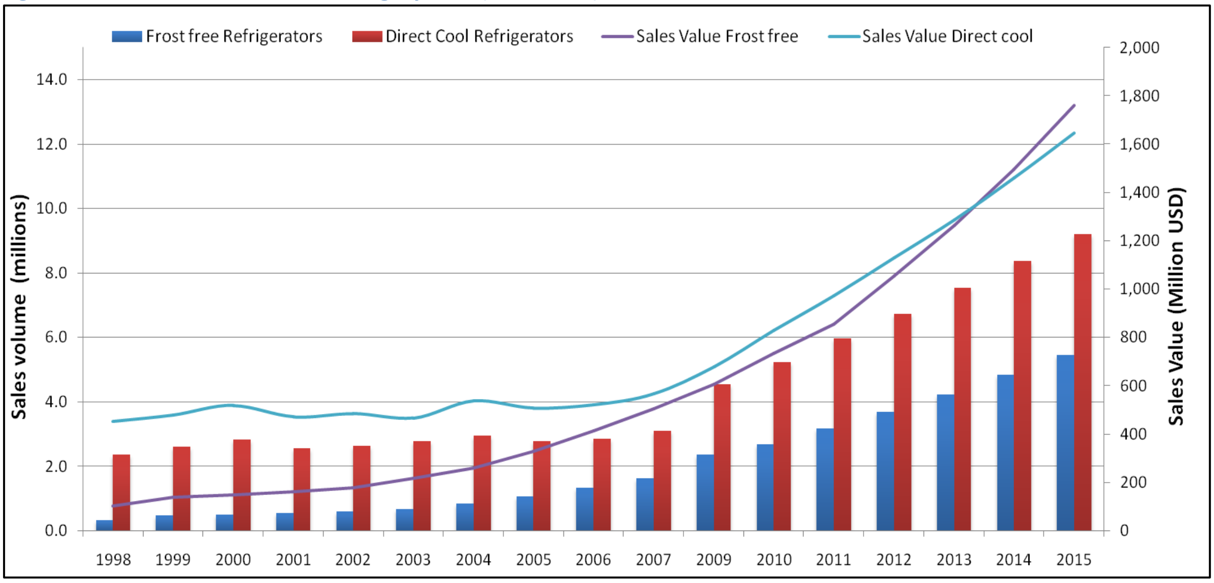
In general, the demand for refrigeration appliances is expected to grow in rural and semi-urban areas, where the household rate is very low. Importantly, a large proportion of the Indian population still resides in such areas. Thus, the prospects for refrigeration appliances are expected to be bright in the forecast period. Retail volume sales are projected to grow by 13%, driving the household penetration rate of fridges to 28% and fridge freezers to 13% in 2015.

2.3.1. Market share: By category

As mentioned in the previous sections, the two main categories if refrigerators in the Indian market are Direct Cool and Frost free refrigerators. Traditionally direct cool refrigerators have dominated the refrigerator market. The demand for Direct Cool refrigerators is primarily from semi-urban and rural areas, where low electricity supplies and the higher prices of frost-free products are major concerns. In 2010, five million Direct Cool refrigerators were sold and sales of direct cool units are predicted to record a 12% retail volume CAGR over 2010-2015. The expanding availability of fridges in smaller cities is expected to boost ownership of refrigerators to 28% in 2015, an increase of eight percentage points over 20% penetration in 2010 (Euromonitor, 2011).

In 2010, three million frost free refrigerators were sold as large numbers of consumers upgraded from manual defrost technology to auto defrost. Sales volume for frost free refrigerators is growing at a CAGR of 20.2% (2005-10) and is expected to reach 5.5 million units in 2015 (Figure 6). Market share of Frost free refrigerators has increased from 12% in 1998 to 34% in 2009. The market share of direct cool units has declined over time from 88% in 1998 to 66% in 2009. The sales value for the more expensive frost free refrigerators is also expected to touch 1800 million USD in 2015 while that for Direct cool refrigerators owing to a slower growth is expected to reach 1700 million USD in 2015.

Figure 6: Sales Volume and Value category wise (1998-2005)



(Source: Euromonitor, 2011)

Table 4 also shows the market share of different formats under Frost free segment. It can be observed that Top mounted freezer format is most popular under the frost free category, followed by top mounted models. Sales volumes of triple door frost free refrigerators like French door with or without TTD, vertical door with and without TTD and side by side formats are negligible

Table 3: Percentage market share of different categories in Frost Free segment

Frost Free format	Design	2005	2006	2007	2008	2009	2010
Double door	Bottom Mounted Freezer	-	1.2	1.8	2.5	2.4	2.5
	Top Mounted Freezer	35	33.9	37.1	40	44.5	47
Triple door	Side by side with TTD	-	1.6	1.9	2.1	2.1	2.2
	French door with TTD	-	0.8	0.9	0.9	1	1
	Vertical door with TTD	-	0.9	1	1.2	1.1	1.1
	Side by side without dispenser	-	1.5	1.7	1.7	1.9	2.1
	French door without dispenser	-	0.8	0.8	0.8	0.9	1
	Vertical door without dispenser	-	0.8	0.9	0.9	1	1.1

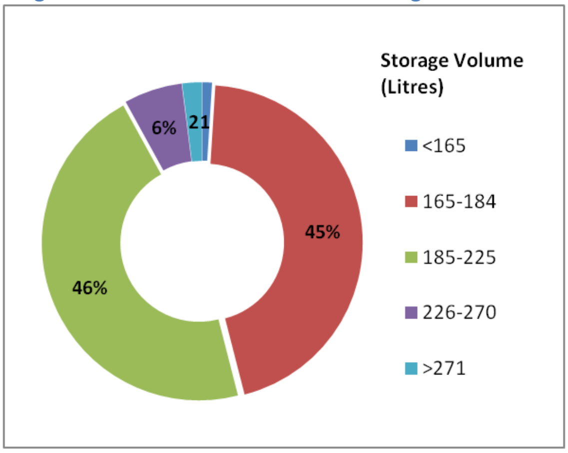
(Source: Euromonitor, 2011)

2.3.2. Market share: By storage volume

Figures 7 and 8 show the capacity wise sales of Direct Cool and Frost Free refrigerators respectively in 2010-11. It can be observed that In the Direct Cool segment models with capacities ranging from 185-225 litres are preferred, having a market share of 46%. However, lesser capacity models 165-184 litres are almost equally preferable by Indian consumers. In the Frost Free segment, models with storage capacities ranging from 226 to 270 litres recorded the largest sales percentage (61%) in

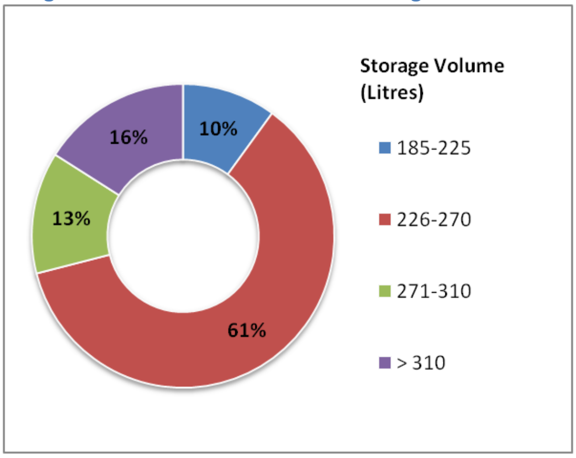
2010-11, while both lesser capacity models (185-225 litres) and higher capacity models (271-310 and greater than 310 litres) had modest market shares of 10%, 13% and 16% respectively.

Figure 7: Storage Volume-wise sales Direct Cool refrigerators in India (2010-11)



(Source: TV Veopar Journal, 2011)

Figure 8: Storage Volume-wise sales Frost Free refrigerators in India (2010-11)

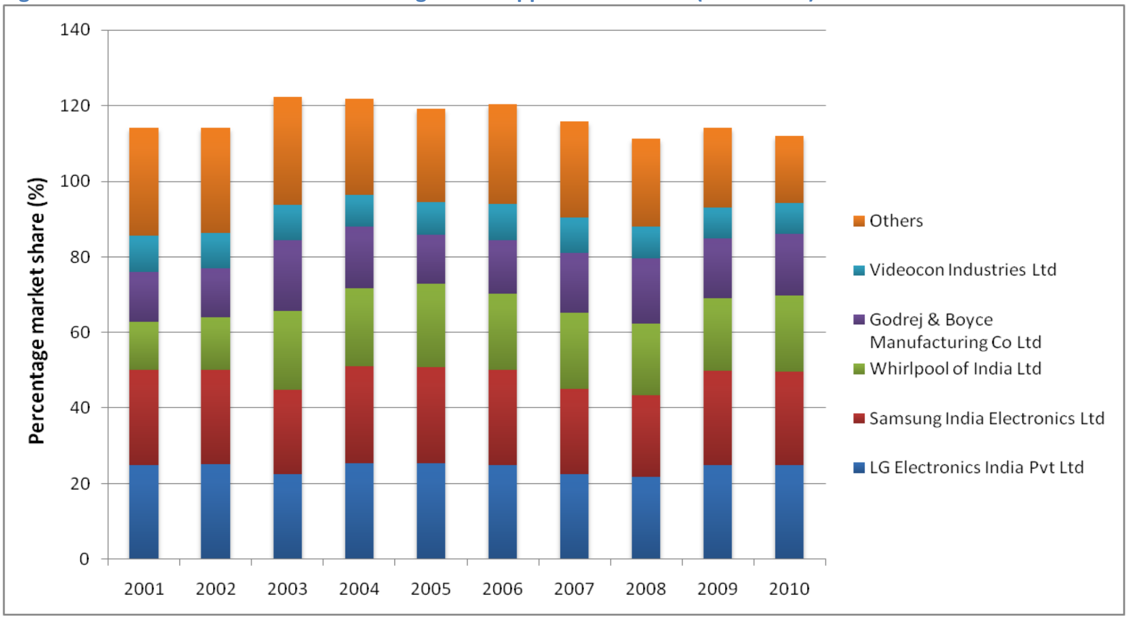


(Source: TV Veopar Journal, 2011)

2.3.3. Market share: By Brand

The competition between different manufactures in the Indian refrigerator market has changed over time with many players entering and leaving the market. Both LG and Samsung, multinational companies from Korea have managed to capture a combined 50% market share in refrigeration appliances in India. While LG has two refrigerator manufacturing units in India, Samsung has none and relies on imports to maintain its market share in India. Domestic manufacturers like Godrej and Videocon are also working on increasing their market shares; Godrej increased its market share marginally from 15.9% in 2009 to 16.2% in 2010. Whirlpool of India Ltd which has refrigerator manufacturing base in India has improved its presence in the market and increased its market share from 12.9% in 2001 to 20.2% in 2010 (Figure 9)

Figure 9: Brand-wise market share in refrigeration appliances in India (2001-2010)



(Source: Euromonitor, 2011)

Category wise market shares are different and given in Table 5. In 2010, in the Direct Cool segment LG and Samsung had 24.1% and 18% market share respectively while Whirlpool has a 18.1% and Godrej 17.8% market share. Other players like Videocon and Electrolux also had 10.3% and 10.5% market share respectively in the Direct cool category.

In the Frost free segment, Samsung had a 27% and LG a 26% market share while Whirlpool and Godrej had 24% and 13% market share respectively. Together these manufacturers had a 90% share in the Frost free market.

Table 4: Company market shares category wise (2005-2010)

	2006		2007		2008		2009		2010	
	DC	FF	DC	FF	DC	FF	DC	FF	DC	FF
LG Electronics India Pvt. Ltd	24	27.2	21	25.5	18	29.1	23.2	28	24.1	26
Samsung	11	21.3	14	20.1	18	21	17.2	23	18	27
Whirlpool	22	16.7	20	20.5	18	21	17.7	22	18.1	24
Godrej and Boyce	16	10.1	18	11.3	20	12	18.2	11.5	17.8	13
Videocon	10.2	8.7	10	8.1	10	5.5	10.1	4.4	10.3	4.2
Electrolux	11.8	4.4	12	4	11	4.1	11	3	10.5	3.1
Others	5	11.6	4.8	10.5	5.3	7.3	2.6	8.1	1.2	2.2

DC: Direct Cool FF: Frost Free (Source: Euromonitor, 2011)

2.3.4. Market share: By star label

When star labelling for refrigerators was first introduced in 2006 by BEE, no refrigerator model was a 1 star. Consequently, there has been zero market share of 1-star refrigerator models in India in both frost free and direct cool segments. It can be observed that the market share of 5-star labelled refrigerators has increased from 0.20% in 2007-08 to 58.09% in 2010-11 while that of 4-star labeled refrigerators has declined from 76.69% in 2007-08 to 20.63% in 2010-11 (Table 6)

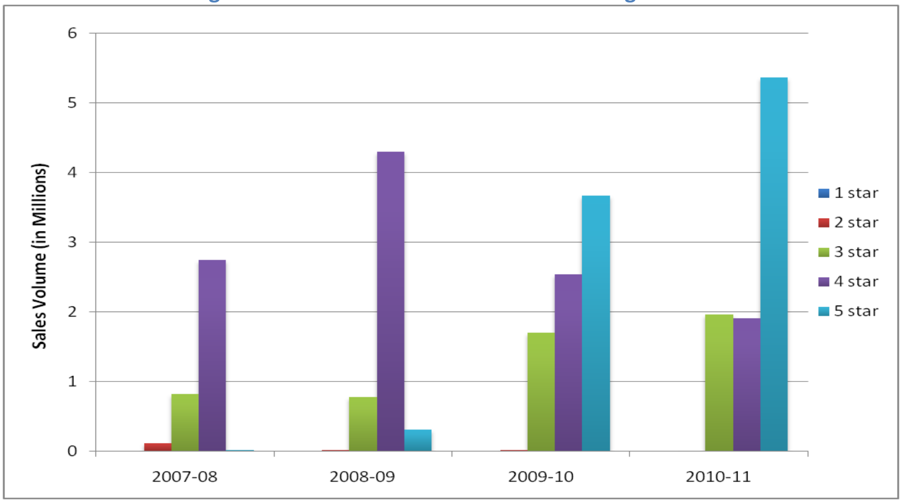
Table 5: Market share of Star labeled refrigerators (2007-2010)

Total Market share (%)	2007-08	2008-09	2009-10	2010-11
1 star	0.00	0.00	0.00	0.00
2 star	0.32	0.13	0.12	0.05
3 star	22.79	14.35	21.42	21.23
4 star	76.69	79.81	32.07	20.63
5 star	0.20	5.71	46.38	58.09

(Source: BEE)

This means that there has been a gradual market shift from less efficient refrigerator models to more efficient refrigerators. In 2010-11, the sale of 5-star labeled refrigerators reached 5.3 million units (Figure 10). Demand for 2-star labeled refrigerators has been negligible.

Figure 10: Sales volume of Star labeled refrigerators



(Source: BEE)

Market share of star labelled Frost Free Refrigerators

Table 7 shows the production of star labelled refrigerators in the frost free segment. The production data can be used as a proxy for sales data since star label wise sales data is rarely shared by manufacturers. A reasonable estimate of the market share of each star category can be determined by using the production data collected by BEE on an annual basis from the manufacturers. BEE had launched the star labelling program on a voluntary basis for frost free refrigerators in 2006 however labelling was made mandatory in January 2010. It can be observed that there were no products labelled as 1 or 2-star since 2007-08. Production of 5-star labelled refrigerators was very low till 2008-09, after which there was a huge surge in production in 2009-10 resulting in an almost 130% increase from 6,474 units in 2008-09 to 844,791 units in 2009-10. While production of 4-star labelled units registered a 36% decrease from 2009-10 to 2010-11. Production of 3-star refrigerators also increased between 2009-10 and 2010-11.

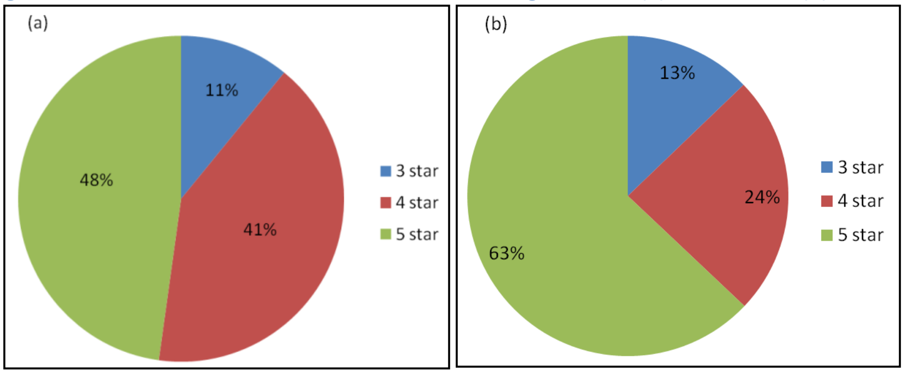
Table 6: Production of star labelled frost free refrigerators

Star Rating	Production			
	2007-08	2008-09	2009-10	2010-11
1	0	0	0	0
2	0	0	0	0
3	195,858	212,592	192,304	242,795
4	825,129	13,648,13	729,775	461,292
5	5,449	6,474	844,791	11,94,839
Total	**1026436**	**1,583,879**	**1,766,870**	**1,898,926**

(Source: BEE)

Figure 11shows the percentage market share of star labelled frost free refrigerators between 2009-10 and 2010-11. It can be observed that the percentage market share of 5-star labelled frost free refrigerators increased to 63% in 2010-11 from 48% in 2009-10 after mandatory labelling was introduced. Market share of 4-star frost free models declined between the same period from 41% to 24%, while that of 3-star models increased marginally from 11% to 13%.

Figure 11: Market share of star labelled frost free refrigerators in (a) 2009-10 and (b) 2010-11



(Source: BEE)

Market share of star labelled Direct Cool refrigerators

Table 7 shows the production of star labelled direct cool refrigerators from 2007-08 to 2010-11. Unlike frost free refrigerators, star labelling for direct cool segment is still voluntary. It can be observed that the production of 5-star labelled Direct Cool refrigerators has been increasing in recent years, an increase by 47% from 2009-10 to 2010-11. During the same time period, the production of 2-star labelled models declined by more than 50% between 2009-10 and 2010-11. The Direct Cool refrigerator market in 2010-11 was thus dominated by 5-star labelled models.

Table 7: Production of Star labelled Direct Cool Refrigerators

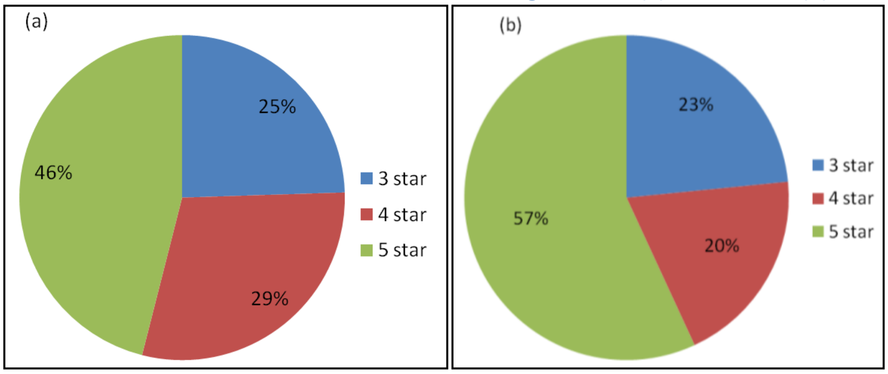
Star	Production			
	2007-08	2008-09	2009-10	2010-11
1	0	0	0	0

2	11,526	7,236	9,699	4,368
3	619,182	560,494	15,039,74	17,180,37
4	19,179,01	29,361,00	18,095,50	14,448,40
5	1,796	301,404	28,277,85	41,713,79
Total	**2,550,405**	**3,805,234**	**6,151,008**	**7,338,624**

(Source: BEE)

Percentage market share of 5-star labelled direct cool refrigerators has increased 46% in 2009-10 to 57% in 2010-11(Figure 6). Also, the market share of 3-star and 4-star labelled refrigerators was 23% and 20% respectively in 2010-11.

Figure 12: Market share of star labelled Direct Cool refrigerators in (a) 2009-10 and (b) 2010-11



(Source: BEE)

2.4. Standards and Labeling (S&L) Program in India for refrigerators

At the beginning of the S&L program BEE had identified products to be brought under the program based using the following criteria:

- The equipment/appliances were used commonly
- The energy intensity of the appliance/equipment was high
- Significant contribution of the appliance to power demand in that category (domestic, commercial, agricultural and industrial)
- Contribution of product to peak demand
- Energy savings potential in general and contribution to reduction in peak demand

In order to prioritize setting of energy performance standards for energy consuming products and identify products for mandatory star labelling, BEE conducted several studies to estimate the energy savings potential of key electrical equipments like Refrigerators (Frost Free and Direct Cool), Air Conditioners and Compact Fluorescent Lamps. Table 9shows the energy savings potential of these appliances from 2007 to 2020. It was found that amongst energy savings potential from refrigerators was the highest. It was also observed up till 2015 the energy savings potential from more efficient direct cool refrigerators was higher than that from more efficient frost free refrigerators, energy savings from energy efficient frost free refrigerators increased significantly after 2015. This was primarily due to the general shift in the refrigerator market from smaller direct cool models to larger frost free units in the future. Even the demand saving potential from frost free refrigerators was higher than that from direct cool single door refrigerators (Table 10). These factors prompted BEE to introduce mandatory star labelling for frost free refrigerators in 2010 while labelling for direct cool remained voluntary.

Table 8: Energy saving potential from different electrical products

Year	Refrigerators (Frost Free)	Refrigerators (Direct Cool)	Refrigerators (All)	ACs	CFL
2007	10	24	35	7	617
2011	138	232	370	98	950
2015	645	662	1307	424	1662
2020	1930	1671	3601	1776	2676

(Source: CLASP, 2007)

Table 9: Demand Saving Potential (MW) from key electrical products

Year	Refrigerators (Frost Free)	Refrigerators (Direct Cool)	Refrigerators (All)	ACs	CFL
2007	50	119	169	34	3016
2011	674	1136	1810	479	4644
2015	3153	3235	6388	2071	8122
2020	9436	8166	17602	8682	13081

(Source: CLASP, 2007)

In June 2005, BEE released draft MEPS for refrigerators. According to the Draft Standards document, the standards were designed not to be very tough and the star rating/labelling plan was planned to be upgraded every two years till an internationally benchmarked energy efficiency level could be achieved. BEE believed that this strategy will give manufacturers several years lead time to meet MEPS and develop production of higher star labeled products. Each star labelling category is 20% more efficient than the preceding one. BEE's original star labelling plan for Frost free refrigerators was as follows:

Table 10: Original Star rating plan announced by BEE

BEE Star category	June 2005	January 2010	January 2012
1 (*)	0.8716x+759	0.5578x+486	0.4463x+389
2 (**)	0.6973xx+607	0.4463x+389	0.357x+311
3 (***)	0.5578x+486	0.4463x+389	0.2856x+249
4 (****)	0.4463x+389	0.3570x+311	0.2285x+199
5 (*****)	0.3570x+311	0.2856x+249	0.1828x+159

(Source: McNiel, 2005)

Here x is adjusted volume, and the constant multiplied by X is the constant multiplier and is added to another constant which is the constant fixed allowance. For e.g. if 1-star in June 2005 was defined by the equation $0.8716X+759$, then 0.8716 is the constant multiplier and 759 is the constant fixed allowance while X is the adjusted volume. These terms are explained in the next section.

According to another study carried out by Lawrence Berkeley Laboratory (LBL) on the draft MEPS for frost free refrigerators, it was concluded that:

- MEPS and labeling levels for Frost free refrigerators were formulated in a manner that average efficiency of products in the market was 3-star and efficiency of the 5-star as 20% better than the best products in the market was an effective strategy in the long term. This strategy encourages improvement at high-efficiency end and provides a 5-star level that is both achievable and significant. However, there was no product in the market at that time which qualified as 1-star. Therefore setting the MEPS as 1-star level would have been a better strategy
- The standards for Direct cool refrigerators were found to be much less stringent than those for frost free since none of the models in the direct cool category would be labels less than 3-star with the 2005 levels and no models would be removed from the market with either 2005 or 2008 levels. Only in 2010 a few direct cool models would be removed by the standard.

The star labelling plan however remained the same and was not changed.

2.4.1. MEPS and star labelling for Refrigerators

The labelling scheme in India compares the energy consumption of different models on the basis of their storage volume. The star rating band (SRB) is based on the Total adjusted Volume of the refrigerator and two constants.

The Labeling scheme for refrigerators is as follows:

Star Rating Band (SRB)nf = $K_{nf} \times V_{adj}$_tot_nf + C_{nf}; where

- K_{nf} is Constant Multiplier (kWh/Litre/Year)
- V_{adj}_tot_nf dc is total adjusted storage volume for direct cool (litres)
- C_{nf} is Constant Fixed Allowance (kWh/Year)

BEE has defined the Knf and Cnf constants for Frost free and Direct cool refrigerators as a part of the rating plan. Calculation of the total Adjusted volume is based on the fresh food storage volume and freezer storage volume. It is calculated as follows:

For Frost free refrigerators

Total Adjusted Volume for a frost-free refrigerator (V_{adj}_tot_nf)

= Fresh Food Storage Volume + 1.62 x Freezer Storage Volume

For Direct cool refrigerators

Total Adjusted Volume for a frost-free refrigerator (V_{adj}_tot_nf)

= Fresh Food Storage Volume + 1.31 x Freezer Storage Volume

The CEC of the model is determined using BEE prescribed test procedure and is compared with the star rating bands. The star rating chosen for the model is based on the above comparison. The CEC of the tested product is compared to the lower and upper limits of the SRB and the star rating corresponding to the band whose lower rating is less than the CEC and upper limit is greater than or equal to CEC will be assigned to the model:

Lower Limit of SRB < CEC ≤ Upper Limit of SRB.

For both Direct cool and Frost free refrigerators with every revision the SRB becomes 20% more stringent than the previous band. This implies that a 5-star model in 2010 becomes a 4-star model in 2012 and so on resulting in a new 5-star for the year 2012 and removal of 1-star in 2010. Figures 13, 14 and 15 show the rating plan for Frost free refrigerators.

Figure 13: Rating plan January 2012 to December 2013

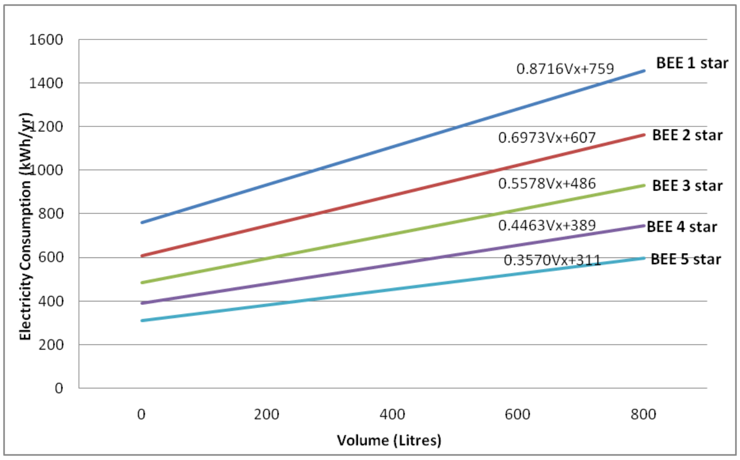


Figure 14: Rating plan January 2014 to December 2015

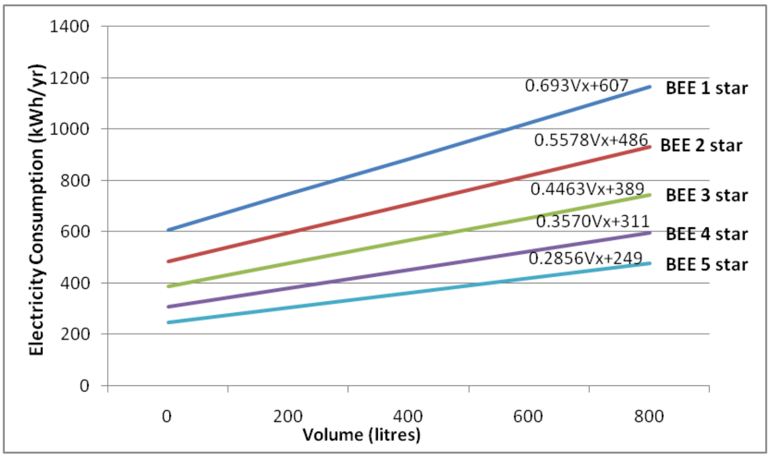
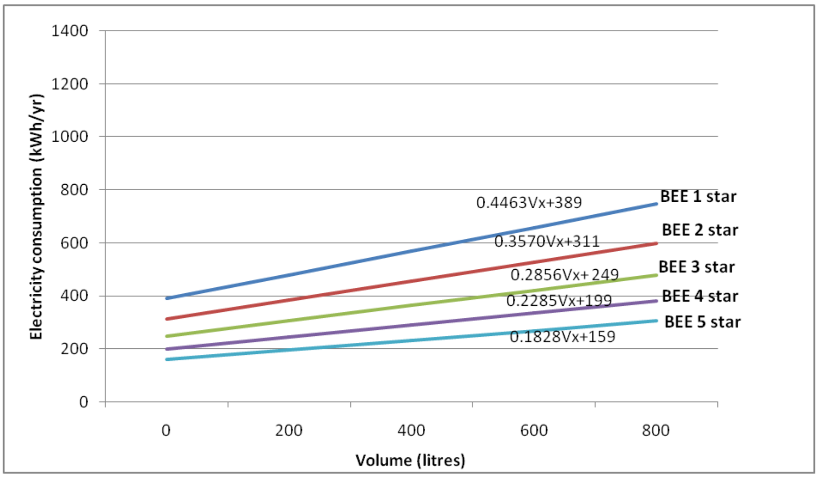


Figure 15: Rating plan January 2010 to December 2011



2.4.2. Test Procedure for Direct Cool and Frost Free refrigerators

A number of performance requirements must be met by Direct Cool and Frost Free refrigerators - freezers before being tested for energy consumption. These include:

- *Volume* – manufacturer declared values must be within defined tolerances of the measured compartment volumes.
- *Pull down test* – the unit is left off in an ambient temperature of 43°C with the doors open, the doors are then closed and the unit is switched on. The unit must reach certain internal temperatures within each compartment (as specified for its Group) after a period of 6 hours (including any compressor trips). This test is originally based on the US AHAM HRF-1 pull down test.
- *Temperature Operation Test* – the unit must be able to maintain acceptable internal temperatures in each compartment (as specified for its Group) under external ambient temperatures of 10°C, 32°C and 43°C. This test is identical to the ISO Temperature Operation Test.

Energy consumption is measured at specified internal compartment target temperatures (as specified for its Group) while operating at an ambient temperature of 32°C. During the energy consumption test, the freezer compartment does not contain test packages and any automatic defrost mechanism is allowed to operate. Energy consumption is measured over a whole number of defrost cycles and there are separate procedures for adaptive defrost systems (where time between defrosts exceeds 24 hours). There are no door openings in the test procedure. All tests are undertaken with a power supply at 230 Volts and 50 Hz.

Energy test procedures provide the foundation for all energy efficiency standards and energy efficiency labels. These test procedures provide a way to manufacturers, regulatory authorities and for consumers to compare and evaluate energy performance of appliances (Meier And Hill, 1997, Mahlia And Saidur, 2010). According to a few authors (Meir and Hill, 1997 and Weil and McMahon, 2005) the ideal test procedure meets the following criteria:

- Repeatability and accuracy of results
- Inexpensive to perform
- Accurate prediction of energy use under actual conditions
- Easy comparison of results with the results of other test procedures
- Reflection of relative performance of different design options for a given appliance performance of different design options for a given appliance

However time and again, energy test procedures particularly for refrigerators have been criticized for not accurately reflecting actual conditions. However refrigerators energy consumption is highly variable and sensitive to consumer behaviour and conditions in private homes.

More complex test procedures that capture real life conditions suffer the risk of not being repeatable or reproducible. Therefore, current energy test procedures may be perceived as a compromise keeping in mind the difficulty of any test procedure to reflect field conditions.

3. Technology Assessment

3. 1. Basic Refrigeration Technology

Refrigerators, refrigerator-freezers, and freezers are household appliances designed for the storage of food products. Refrigeration appliances are categorized into two main types based on their technology:

Vapor Compression-type: Refrigerators where refrigeration or cooling is done by means of a motor driven compressor

Absorption type: In these appliances, refrigeration is effected by an absorption process using heat as energy sources.

Most domestic refrigeration appliances uses vapour compression technology. In the next section working of a vapour-compression refrigerator is described.

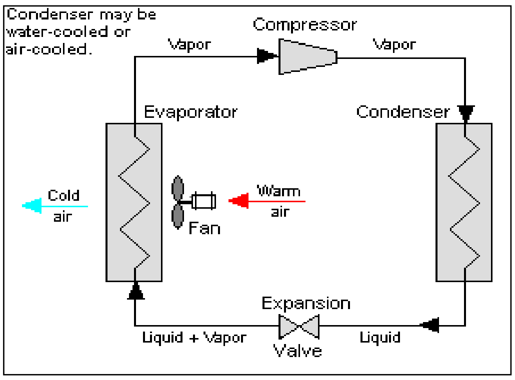
3.1.1. Working of a Vapor-compression type refrigerator

There are two major types of refrigerators based on their refrigeration cycle: ***vapour compression type*** and ***absorption*** type. Most household refrigerators and freezers use a vapour compression cycle. The typical operation of a refrigerator is described below:

Step1: the **refrigerant gas** enters the **compressor** as a low pressure-vapour and at slightly above the temperature of the interior of the refrigerator. The compressor compresses the refrigerant vapour which exits as a high-pressure superheated vapour.

Step2: The superheated vapour passes under pressure through the **condenser** coils/tubes which are cooled passively by exposure to air in the room. The condenser cools the refrigerant vapour which gets liquefied. The liquid refrigerant leaving the condenser is still under pressure but at a temperature slightly above the room temperature.

Figure 16: Typical single-stage vapour compression refrigeration



Step3: The liquid refrigerant is forced through the **expansion valve** which is a pin-hole sized constriction in the condenser tubing to an area of much lower pressure. This movement of the liquid refrigerant from an area of high pressure to that of low pressure results in evaporation of a portion of the liquid. The latent heat released in this process is absorbed to a large extent by the adjacent still-liquid refrigerant in a process called **auto-refrigeration**.

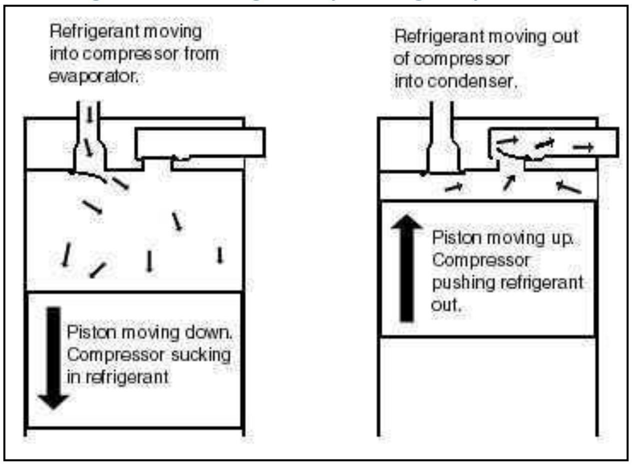
Step4: The cold and partially vaporized refrigerant moves through the **evaporator** coils/tubes. A **fan** blows air from the freezer compartment (box air) across the evaporator and the refrigerant now completely vaporizes, drawing latent heat from the box air. The cooled air is returned into the refrigerator and then to freezer compartment and so this keeps the box air cold. The cool air in the compartments is still warmer than the refrigerant in the evaporator. The slightly heated refrigerant vapour now leaves the evaporator and returns to the compressor inlet to continue the cycle.

3.1.2. Main components of a refrigerator

A typical domestic refrigerator comprises of certain internal parts that carry out the actual working of the refrigerator. Some of the internal components are located at the back of the refrigerator and some inside the main compartment of the refrigerator. Following are the key internal components of a refrigerator:

- **Compressor**: The compressor compresses the refrigerant and releases it at high pressure and temperature. The compressor is driven by an electric motor and is the major power consuming component of a refrigerator. Average compressor efficiency is a function of the cooling capacity or sizes i.e. smaller the compressor, lower the energy efficiency. Three types of compressors are available for use in refrigeration appliances: reciprocating, rotary and centrifugal compressors. Reciprocating compressors are the most common compressor technology used in domestic refrigeration appliances. Reciprocating compressors have a piston and cylinder arrangement. Functioning of a reciprocating compressor is described below:
    - The piston driven by the motor, moves down into the cylinder and compresses the refrigerant in the cylinder (increasing the volume of the cylinder), it sucks the refrigerant from the evaporator.

Figure 17: Working of reciprocating compressors



- The intake valve closes when the refrigerant pressure inside the cylinder becomes equal to that inside the evaporator.
- When the piston hits the point of maximum downward displacement it compresses the refrigerant on the upstroke. The refrigerant is pushed through the exhaust valve into the condenser.

Both the intake and exhaust valves are designed in a way that the refrigerant flows only in one direction through the system. Generally compressors are located at the bottom at the back of a refrigerator. Compressors are powered by motors and three types of motors are used in refrigerator compressors: resistance start/induction run (RSIR), capacitor start/induction run (CSIR), and resistance start/capacitor run (RSCR). Of the three motor types, the RSIR motor is the least efficient. The Coefficient of Performance or COP is often used to describe compressor efficiency. It is a dimension less quantity is the ratio of the output (in terms of cooling) to the input energy.

- **Condenser:** The condenser like an evaporator is a heat exchanger. Condenser removes heat released during the liquefaction of vaporized refrigerant. The three most prevalent condenser configurations are as follows:
    - *Forced-convection condensers or air-cooled condensers*: These use fans to move air through them to provide cooling. These condensers are located under the unit near the compressor. They can be fabricated of steel tubes with steel wire fins or copper tubes with aluminum fins. The tubes are arranged in a way to maximize the surface area and fans are used to increase air flow by forcing air over the surfaces
    - *Natural convection static condensers*: These don't use fans and are mounted at the back of the unit. They generally have steel tubes and steel wire fins
    - *Hot wall condensers*: These are integrated into the outer shell of the unit. Serpentine tubing is attached to the inside of the shell and provided with good thermal contact to the shell. These condensers are commonly used in freezers and compact/single door manual defrost units.
- **Expansion valve or the capillary:** The expansion valve or the capillary tube is a flow control device that controls the temperature and pressure of the liquid refrigerant as it enters the evaporator. The control devices are usually thermostatic i.e. they are responsive towards temperature changes of the refrigerant. There are two main types of capillary tubes-adiabatic and non-adiabatic; non-adiabatic type is more common

Figure 18: Expansion valve used in refrigeration systems

(

- **Evaporator:** the evaporator US DOEs the actual cooling in a refrigerator. An evaporator consists of finned tubes which absorbs heat from the air blown through a coil by a fan. Fins and tubes are made of metals of high thermal conductivity to maximize heat transfer. The refrigerant vaporizes from the heat it absorbs in the evaporator. Evaporators are also of three types:
    - *Forced convection evaporators*: these use fans to move air through them to provide cooling. They are made of aluminum or copper tubes and aluminum fins. They are generally located on the rear wall of the freezer compartment behind the panel. The evaporator fan circulates air through the evaporator and into both freezer and fresh food compartments. Because evaporator absorbs heat, the surrounding air becomes very cold and water vapors present in the inner chambers of refrigerator compartments freezes on the evaporator as frost. Most refrigerators using this type of configuration use automatic defrost. Thus forced convection evaporators are used in frost free refrigerators
    - *Roll bond evaporators*: These use natural convection cooling. These evaporators are fabricated from layers of aluminum sheet. As refrigerant passages are formed into evaporator walls, they are used in single door refrigerators. Manual defrosting is used for defrosting in refrigerators using these evaporators.
    - *Cold wall evaporators*: These are located within the walls of the freezer and are used in nearly all chest freezers and in many upright freezers. The evaporator consists of serpentines tube attached to the insulation side of the cabinet interior liner. These evaporators use natural convection for heat transfer

3.2. Factors affecting energy consumption in a refrigerator

In a recent study where energy consumption of refrigerators in Europe was analyzed under real life conditions[7]it was observed that the ambient temperature and the temperature variation have the greatest impact on a refrigerator's energy consumption. *Common consumer habit of placing the refrigerator in the kitchen adds heat load on the appliance and results in higher energy consumption*.

[7]Geppert, J. 2011. Modelling of domestic refrigerators' energy consumption under real life conditions in Europe, Volumes 2011-12, Shaker Publishers

In the European study, although the impact of door openings was found to be small, the impact increases with rising ambient temperatures as cold air inside the compartment is exchanged with warm and moist air from outside when door is opened. The other factors that affect refrigerator energy consumption are thermostat settings and heat load insertion when warm items are added to the unit. In another study done for refrigerators in residential homes in US, it was observed that energy consumption in frost free refrigerators responds significantly to door-open duration which is not seen in direct cool refrigerators that respond mainly to the number of door openings (Miller and Pratt, 1998).

In general, components of a refrigerator that consume electricity are the compressor (which is powered by an electric motor), the fans used in heat exchangers and in case of some refrigerator models, the anti-sweat heaters which use electricity to remove dew from the cabinet when ambient conditions are humid.

The thermal load or heat load on a refrigerator is contributed by three processes: (1) conduction through shell also called baseline load, (2) door-opening activity and associated food and air cooling and (3) defrosting.

- **Baseline load**: the heat transfer through the walls of the refrigerator shell is the major thermal load on the refrigerator. While baseline load will be determined by the ambient temperature, this load has no relationship with the number of occupants or their food usage patterns. It is related to the energy labelling which reflects refrigerator's ability to resist (with insulation) and remove (with the compressor) energy flowing through the shell. The baseline load of a refrigerator will therefore respond to factors such as refrigerator age, condition of shell and seals.
- **Occupant load**: this has little or no relation to the insulation in the refrigerator but is reflective of the usage characteristics and efficiency of the compressor i.e. how efficiently can the compressor remove associated food-compartment-door opening energy. This kind of load is directly associated to number of occupants and other usage characteristics
- **Defrosting:** Defrosting occurs in response to the baseline and occupant loads. Defrost system helps remove excess ice from evaporator surface. Manual defrosting is done using thermostat button in direct cool refrigerators while in frost free refrigerators, defrosting is automatic where defrost timer linked to compressor initiates defrost after a set interval of compressor operation by switching on the electric heater. The heater melts the frost. Defrost is triggered by compressor running time and so defrost load is linked to both baseline and occupant loads

3.3. Defrost system in Frost free refrigerators

Moisture enters refrigerator cabinet every time door is opened. Either through natural convection or forced air movement, the moisture condenses on coldest surface of cabinet which is the evaporator. As the evaporator is well below the freezing point therefore frost is formed on evaporator.

Why do Frost Free refrigerators consume more energy than Direct Cool refrigerators of same storage volume?

Automatic defrosting is the key feature that differentiates a Frost free unit from a direct cool one other than the presence of a separate freezer compartment in the frost free system. Frost forms when water vapour condenses on cold evaporator coils.

In automatic defrosting, three components of a frost free unit work in tandem:

- Defrost timer: a clock energized with compressor
- Heating coil/heater
- Temperature sensor

After a fixed time period, usually about 12 hours, the timer turns on the heater coils. The heater coils are located just beneath or on the side of the evaporator coil which is concealed behind a panel in the freezer compartment. The heater melts ice/frost when defrost timer turns it on. As the frost and ice melt, the resulting water drips into a drip pan which is connected to a tube that drains the water into a shallow pan at the bottom of refrigerator. Water is evaporated from the pan by a fan through the condenser. The defrosting process ends when defrost thermostat mounted on the evaporator coils senses that sufficiently high temperature has been attained. Heating the evaporator coils every 12 hours takes energy and leads to higher energy consumption in a frost free unit compared to manual defrosting direct cool refrigerator

Defrosting is linked to compressor run time since for most part; frost is formed on evaporator only when the compressor and fans are operating. So the longer the compressor runs, the more frost is formed and sooner the evaporator needs to be defrosted. A cumulative run timer operates only when compressor is switched on and based on the cumulative compressor running time of 8 hours it energizes the defrost heater to start defrosting process. The defrost thermostat uses a bimetal disc to sense temperature changes. The bimetal disc is made of two dissimilar metals that expand at different rates. The defrost timer allows a maximum defrost time of about 20 minutes. The actual length of defrosting depends on amount of frost in evaporator. When the bimetal senses that evaporator temperature has increased sufficiently, the defrost heater is switched off.

3.4. Refrigerator storage volume

Refrigerator storage volume in India (and most European countries) is measured and defined in Litres. In US, storage volume is defined in cubic feet (ft^3). Manufacturers are required to calculate the storage volume by measuring the length, width and height of every part and fresh food and freezer compartment of the refrigerator. The gross storage volume takes into account also the space taken up by shelves, hardware etc. Following are the types of volume associated with a refrigerator

- **Total Gross Volume** is the sum of gross volumes for all compartments in a refrigerating appliance.
- **Gross Volume** - Measured volume enclosed within a compartment. While determining gross volume, internal fittings like shelves, removable partitions, containers, evaporator, thermostat & internal light housings are believed as not in place. Volume occupied by the barrier air ducts is not considered.

- **Total Storage Volume** – the sum of the storage volumes for all compartments in a refrigerating appliance.
- **Storage Volume** – gross volume of a compartment minus the volumes of components and spaces recognized as being unusable for food storage. When the storage volume is determined, internal fittings like shelves, removable partitions, containers, evaporator, thermostat & internal housings are believed to be in place.

In energy test procedures, both gross volume and storage volumes are not used to calculate the energy consumption of a refrigerator. A refrigerator's annual energy use is based on its **Adjusted Volume or AV.** The AV is adjusted to account for the increased energy use of a unit's freezer compartment relative to the fresh food compartment. The AV is the sum of the volumes of different compartments weighted by the difference in temperatures between the interior of the compartment and the ambient temperature (Mahlia and Saidur, 2010). The AV is the sum of the fresh food storage volume and the product of the freezer storage volume and an AV factor:

Adjusted Volume= Fresh food storage volume+ AV factor × Freezer storage volume

Under different standards, the value of the AV factor differs because of difference in the test procedure prescribed target temperatures for fresh food compartment and freezer compartment. For instance in India the energy test procedures prescribed for Frost Free refrigerators used an AV factor of 1.62 and an AV factor of 1.31 for Direct Cool refrigerators.

3.5. Technologies for improving refrigerator efficiency: Review of global studies

A refrigerator consumes energy because of two of its key functions: cooling the food item contained in its compartments and retaining this cooling within the compartments. The first function is performed by components like compressor and heat exchangers (including fan motors). The second function is more challenging and is generally taken care of by the insulation. It is more challenging since any change or improvement in the insulation has a direct bearing on the physical features of the refrigerator. Most manufacturers shy away from changing this external component for improving energy efficiency, because of compromises on the aesthetics or storage volume of the refrigerator. However recent advancements in insulation technology have provided valuable insights into achieving better energy performance without any compromises on the outer feature or utility. Over the years, refrigeration technology has evolved and refrigerators are becoming more energy efficient. The current design of refrigerator insulation comprising ploy-urethane (PU) foam has evolved from the use of fibre glass as insulation until mid-eighties in India. The use of foam insulation allowed refrigerator manufacturers to increase storage volume while maintaining same external dimensions. However, chlorofluorocarbons (CFC) were used in the PU insulation which added the potential environment hazard component to use of such insulation materials. After the global ban on the use of CFCs, manufacturers migrated to the use of hydro fluorocarbons (HFC) based refrigerant and foam blowing compounds. There is a recent shift globally towards using hydrocarbon based compounds in refrigerators such as iso-butane and cyclo-pentane. Further, the technological developments have led to identification of superior insulation material and products namely vacuum insulated panel (VIP) in order to meet both energy efficiency improvements while maintaining the thin wall in larger refrigerators. Centrifugal compressors have been phased out and have been replaced with reciprocating compressors that provide better miscibility with synthetic and mineral oil (Reference: Tiwari, 2011, IJEST). Today compressors are located at the bottom of the refrigerator. Capillary tube is used as an expansion device. Even more doors have been added to a refrigerator to increase the number of compartments in the unit. Consumers have become increasingly aware of energy savings associated with usage of their appliances and manufacturers are also seeing this increasing consumer interest as an opportunity for introducing intelligent controls in their products. These intelligent controls while maximizing consumer benefit and convenience also try to optimize energy consumption from refrigerators. Refrigerators using microprocessor sensors have led to introductions like (1) adaptive defrost sensor, (2) automatic control of anti-condensation heaters, (3) door open alarm sensor (4) sensor to control temperatures under different operating conditions for energy savings and (5) smart grid interoperability (Bansal et al. 2011).

In US, the Department of Energy (US US DOE), as a part of the revision of energy performance standards with time, prepares a Technical Support Document that describes the results of its technology assessment which is based on an analysis of design options available for improving the energy efficiency of domestic refrigeration appliances. US DOE typically uses information about existing technology options based on technologies commercially available in (global) market and prototype designs and concepts as inputs in identifying technologies that manufacturers of those products could use to attain higher efficiency levels. In Europe, various studies like GEA in 1993, COLD-II study in 2000 and 2005 and the most recent preparatory studies for the *EU Ecodesign Initiative* have provided technical basis for both energy labelling and energy efficiency requirements by providing a techno-economic analysis of design options for improving refrigerator efficiency. The *Top Runner Program* in Japan also briefly evaluated technological options for improving appliance energy efficiency before prescribing further improvements in energy standards that although may burden manufacturers initially but benefit consumers through energy and monetary savings

Based on the review of the above mentioned studies, it can be concluded that typically, options for improving energy efficiency of refrigerators focus on changes in the following components:

- Insulation
- Gasket and Door design
- Compressor
- Heat exchangers (Evaporator and Condenser)
- Fan and Fan motor
- Defrost system

In some studies modifications in other components like expansion valve, anti-sweat heaters and changes in the refrigeration cycle, refrigeration system and refrigerants have also been found to lead to minor improvements in the energy efficiency. In the next section, we describe of some of the design options considered in appliance standards revision exercises done by the US DOE[8] and

[8] Technical Support Document for NAECA standards coming into effect in 2014

European Union[9]. These studies are fairly comprehensive and detailed and therefore provide a good understanding of global knowledge on energy improving technologies for domestic refrigeration appliances. We have decided to use these studies for compiling the list of design options for improving the energy efficiency of refrigerators in India leading to introduction of super-efficient refrigerators in India.

It must be noted that we have considered only those design options that were applicable only to product categories equivalent to Direct Cool and Frost Free refrigerators available in the Indian market. In the US, the product **Category 3** of Refrigerator-freezers with automatic defrosts and top mounted freezer without an automatic icemaker is most similar to the Frost Free refrigerators of India. However refrigerators in this category are typically of much higher storage capacities (more than 300 litres). Similarly, the product category 1 that included refrigerators and refrigerator-freezers with manual defrost is equivalent to the direct cool category of refrigerators available in the Indian market. In the European markets the domestic refrigeration appliances are categorized mainly on the basis of the temperatures maintained in different compartments. The product category 7 was found closest to Indian top mounted frost free and product category 3 is similar to Indian direct cool refrigerators. In the next section we have discussed the efficiency improving design options compiled from studies in US[10] and Europe.

3.5.1. Insulation

The energy consumption of a refrigerator is directly related to the cabinet internal load and the external thermal load. With time, the insulation performance declines and air leakages across the edges of the cabinet and door gasket results in higher energy consumption for providing the same cooling effect. Energy measurement standards have traditionally ignored cabinet heat load where a well-insulated cabinet with a less efficient refrigeration system may rank the same in an energy test as the one with less insulation but more efficient refrigeration system (Bansal et al., 2011).

Reducing cabinet heat load will decrease energy input to the compressor by an amount proportional to the reduction (Bansal et al., 2011). Improvements in the insulation for reducing the heat load on comprise the following design changes:

- Increase in insulation thickness
- Improved in thermal resistivity of insulation
- Use of Vacuum Insulated Panels (VIPs)
- Use of gas filled panels

Increase in insulation thickness: PU foam is an established insulation material for cold appliances that replaced the traditional glass wool some decades ago. PU foam insulation provides structural strength to the cabinet. Through the 1980s, CFC-11 a choloroflorocarbon was being used as a blowing agent in almost all PU foam insulation. However under the Montreal Protocol, all CFCs were banned from use by the mid-1990s due to their high ozone depletion potential (ODP). The use of non CFC based blowing agent reduces the thermal conductivity of the insulation. Alternatives to

[9] preparatory studies for the EU Ecodesign initiative
[10] Technical Support Document for NAECA standards coming into effect in 2014

non-CFC blowing agents are Hydro fluorocarbons.HFCs have good refrigerant properties. However the Global Warming Potential (GWP) of HFCs is high. For instance HFC-134a which is used as a (refrigerant and blowing agent) has a GWP of 1430 (put one example each). On account of high GWP, there has been a recent shift globally towards using hydrocarbon based compounds in refrigerators such as iso-butane and cyclo-pentane which have a GWP of less than 5.Increasing the insulation thickness will reduce the thermal load to the cabinet but also leads to reductions in the storage volume of the appliance due to an increase in its external dimensions. This also leads to changes in the manufacturing line and increases overall costs of the product.

At present the blowing agent used in European refrigerators is Cyclo-pentane while in the US, because of dangers of the flammability of hydrocarbons like Cyclo-pentane, HFC-245fa is used since it has a zero ODP but has a superior thermal performance compared to HFC 134a and cyclo-pentane. However, HFC-245fa has a GWP of 3410 and HFC-134a has a GWP of 3730

In Europe, based on various experiments with insulation thickness it was found that if external volume was kept a constant, an insulation thickness was allowed to increase, an economic optimum occurs for a 15mm increase in thickness that US DOEs not lead to a decline in internal volume. Such an intervention was found to lead to energy efficiency improvement up to 10%

In the US, increasing insulation thickness as a means to improve energy improvement for frost free refrigerators was rejected through consultations with manufacturers. However for compact refrigerators (direct cool refrigerators) and freezers that do not have an insulation thickness of more than an inch, the US DOE considered increases upto 3/4th inch of these products leading to a 20% increase in efficiency of manual defrost refrigerators (4ft^3 volume). The baseline insulation thickness of refrigerator-freezers was 1.5 to 2.75 inches in the doors, 1.5 to 3 inches in the cabinet walls.

Improved resistivity of PU foam insulation*:* Improved resistivity of PU foam insulation through the use of additives in the foam was reported in the Technical Support Document (TSD) for the rule making by US DOE. The addition of carbon black additives provided a means to improve the thermal insulation of PU foam when combined with HCFC 1441b or cyclo-pentane resulted in lowered thermal conductivity of insulation. However US DOE ruled out the option based on manufacturer consultations when it was reported that there are no available options for improvement in PU foam insulation performance. In Europe this option was not considered as a possible design intervention because of limited evidence to support energy savings associated with the option.

Vacuum Insulated Panels (VIPs): Vacuum-insulated panel (VIPs) technology is based on the reduction in conductivity which occurs in a vacuum, the same concept which is used to reduce heat leakage in thermos bottles. The basic VIP consists of a core insulating material (made up of polystyrene, open cell PU, silica powder or glass fiber), an airtight envelope and an absorber to prevent the panel from collapsing.

Figure 19: A refrigerator fitted with VIPs

Figure 20: Structure of a VIP

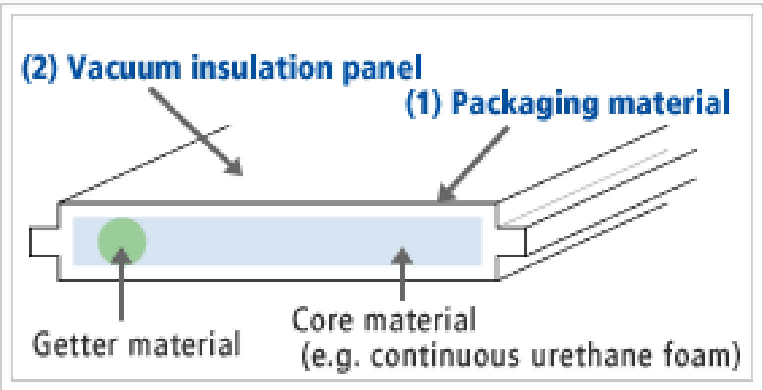
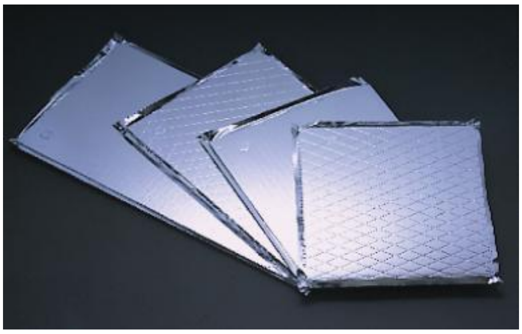


Figure 21: Vacuum Insulated Panels



The US DOE considered the addition of ½-inch thick VIPs to the walls and doors of the cabinet for all refrigerator product classes, and the remainder of the insulation thickness was filled with PU foam. Because the material costs of VIPs are high, US DOE used an 11.7% addition for frost free refrigerators and a 19.6% addition for direct cool refrigerators to achieve efficiency increases ranging from 25-30% and 60% respectively. Also the added VIPs were placed in different locations in the tested models.

In Europe, in 2005, VIPs were used in very few models to reach specific high efficiency levels, however the costs were high. The Ecodesign requirements recommended the use of VIPs in the front door or cabinet wall assuming a panel thickness of 50% of PU Foam insulation. A 6-12% improvement in energy efficiency was reported to be possible from the introduction of VIPs in baseline models.

3.5.2. Gasket and Door design

A significant portion of the thermal load on refrigerator occurs around the edges of the doors and through the gaskets on the door edges also called 'edge loads' and contributed according to some estimates by US DOE to 28% of total heat load into the cabinet. Improvement in the door gasket design for reducing the heat load comprises primarily the following design changes:

- Improved gaskets
- Double door gaskets

Improved gaskets: Design of door gaskets is a balance between improving the thermal-efficiency performance of the gasket and ensuring that the door is not difficult to open. If the gasket magnet force is too strong, it becomes difficult to open the door (US DOE, 2011). However, gasket design has improved several times in the past few decades and therefore it is uncertain how further can gaskets be improved.

Most manufacturers interviewed opined that limited additional improvement potential exists for door frame/gasket area of refrigerators and although properly designed and installed gasket systems provide a tight seal, there isn't any further reduction in air leakage that can be achieved with further improvements.

Similarly in the European study, it was found that it is impossible to fix a value for the gain associated with a good gasket design and the percentage of energy savings is too small and has already been applied to the market.

Double door gaskets: A double door gasket is an additional inner door seal gasket that is added to the gasket design. In all studies, the introduction of double door gaskets was not seen as a favourable alternative because of performance problems with such gaskets. According to US DOE, ice could form between gaskets drastically reducing their effectiveness. In addition, these gaskets are visually unattractive and make it difficult to open cabinet doors.

3.5.3. Heat Exchanger Improvements

As discussed above, the Evaporator and the Condenser are the two heat exchangers within the refrigerator. Published studies have indicated that an improvement in the performance of the heat exchangers can result in major energy efficiency improvements. Since both evaporators and condensers have fans for increasing the heat transfer, improvements in fan motorwill result in energy efficiency improvements. Improvements in the heat exchangers are categorized into the following:

- Increase in area of heat exchangers
- Improved heat exchangers
- Improved fans and fan motors

Increase in area of heat exchangers: Increasing the heat exchanger surface area can be achieved by increasing the face area of the evaporator or adding more tube rows. However there is trade-off between increasing the volume occupied by heat exchanger and reducing the interior volume of the refrigerator.

US DOE considered an increase in evaporator surface area for all products analyzed. In some cases (compact refrigerators) the size increase was limited by available space. In general, it was found that an increase in evaporator size 14% by area led to a 5% improvement in energy efficiency. Similarly for condensers, an increase in surface area by 100% led to a 10% improvement in energy efficiency

In the European study it was reported that practical constraints limited the increase in surface area of evaporator to 20% or less for majority of the base case models considered and led to a 3% improvement in the energy efficiency of baseline refrigerator model. Also, increasing the surface area of evaporator by 5-10% led to a 1% improvement in the energy performance of baseline refrigerator.

Improved heat exchangers: Improving heat exchanger performance can be achieved through the use of enhanced fins and/or tubes. Some of the technologies for improving heat exchanger performance are micro-channel heat exchangers, electro-hydro-dynamic enhancement, and the adoption of phase-change materials.

US DOE did not consider the improvement in performance of heat exchangers through use of enhanced fins/tube as a design option for improving energy efficiency in refrigerators because of significantly less work done by manufacturers in developing this technology. For electro-hydro-dynamic enhancement that uses high-voltage fields to improve heat exchange, safety issues involved in using such high voltages discouraged use of this option as a potential intervention.

In Europe where natural convection heat exchangers are used, potential for further improvements in efficiency was considered with the forced convection exchangers than with natural convection exchangers. The use of phase-change materials integrated into heat exchangers enables higher average evaporation temperatures to be achieved compared to conventional heat exchangers resulting in energy savings up to 3%.

Improved fans and fan motors: Fans are used to increase evaporator and condenser heat transfer. Because the evaporator fan and fan motor are located within the refrigerated cabinet the heat emanating from fan motor adds to the refrigeration load. More-efficient evaporator fan or evaporator fan motor designs contribute to efficiency improvements in two ways: (1) reducing the power consumption of the fan motor and (2) reducing the power consumption of the compressor due to decreased heat losses into the cabinet from the fan motor.

Fan design: Improvements in the typical axial design of the fan for a better airflow direction and improved efficiency were found to be not practical by US DOE. It was found that very little general data was available to quantify the energy benefit possible with improvement in fan blade design in the refrigeration products. In European study, further improvements in fan design were not considered

More efficient fan motors: The use of more efficient fan motors was explored in frost free refrigerators in Europe where 6-10W fans are already used in A class models. Low wattage brushless DC fans which led to improvements in energy efficiency by 9% of the unit were found to be a feasible option. Preparatory work for the EU Ecodesign requirements also evaluated the use of 1W 12V DC fans which are used in Japanese appliances and are also found in some European products; such fans are 75% more efficient than the traditional 8W evaporator fans used in most European products. However, such fans are not used in no-frost appliances in Europe.US DOE evaluated the use of 4W brushless DC fan motors for improving no-frost refrigerator efficiency by 5%. The same option was however not considered economically feasible for smaller capacity manual defrost refrigerators.

3.5.4. Compressor Improvements

The compressor is the primary energy-consuming component in a refrigerator, refrigerator-freezer, or freezer. Therefore, technologies that can advance compressor efficiency have a significant effect on overall product efficiency. In the US, refrigerator compressor capacities range from as low as 125 Btu/hr (for compact refrigerators) to as high as 2,000 Btu/hr for residential refrigerator-freezers. There three types of improvements in compressor technology are possible: (1) Improved compressor efficiency (2) Variable speed compressors and (3) Alternative compressors (e.g. linear compressors)

Improved Compressor efficiency: As described in section 3.1.2. two types of compressors are used in refrigeration products: reciprocating and rotary compressors. In most countries including India, reciprocating compressors are being used. The induction motor used for powering compressors most often is RSCR (Resistance-Start-Compressor-Run). Using high efficiency compressors is considered as a fairly straightforward for manufacturers as long as the appropriate compressors are present that match the refrigeration capacity (the compressor efficiency decreases when capacity decreases).

In US, efficiencies of compressors used in most common refrigerator-freezers ranged from and EER of 5.55 to6.25 with a COP of 1.65. A 10% improvement in energy efficiency was found to be economically possible by the increase in compressor EER from 5.55 to 6.1.

In Europe, single speed reciprocating compressors are the most common compressor technology used. In 2005, based on the findings of the COLD II study, iso-butane compressors were improved to reach a COP of 1.3 for A class appliances. For the Ecodesign requirement, improvement in COP to 1.5 for A+ model was considered economically and technically feasible, leading to 10% energy savings over the baseline.

Variable speed compressors: Variable Capacity Compressors (VCC), operate at low speed with a high percentage of on-time lowering the energy consumption by reducing off-cycle losses and by allowing heat exchangers to operate with lower mass flow. However, careful consideration must be given to how this technology is implemented since increased fan run times could negate compressor energy savings. VCCs use electronic controls to vary their speed

VCCs have been considered as a viable technology in most studies for improving energy efficiency of existing refrigerators. In the US, the implementation of VCCs combined with other interventions led to an improvement in energy efficiency by 5% while in Europe, multispeed variable speed compressors led to 15% energy savings.

Alternative compressors: Other types of compressors specifically Linear Compressors employ a different design than reciprocating or rotary compressors and are more efficient than either.

According to US DOE, while promising potential has been reported for linear compressors, there is very little information was available for commercialized linear compressors that could give an estimate of the performance and costs impacts of this technology. Therefore US DOE did not think this option was technically and economically feasible for the American refrigerator markets. Linear compressor technology has been patented by one manufacturers. In Europe also even though Linear Compressors are used in certain high efficiency models, its usage across different models was considered to be uneconomical

3.5.5. Defrost systems

Technologies associated with improvements in the defrost system are applicable only to those refrigeration appliances that use automatic defrost technology. Most auto-defrost units use electric heaters to remove frost from evaporator coils located in the freezer section of the frost free refrigerator. Energy associated with defrost included the energy input to the heater and also the cooling required in the cabinet for removing the defrost heat. There have been three types of technological improvements suggested for improving efficiency of the defrost system: (1) reduced energy for automatic defrost (2) adaptive defrost and (3) condenser hot gas

Reduced Energy for Automatic Defrost: In some cases, the defrost heat supplied is more than required. Thus, energy savings can be achieved by reducing the defrost heat by either using a smaller heater, reducing the heater on-time, reducing the frequency of defrost, or a combination of these. The US DOE found that since most manufacturers have already reduced the electric heat for auto-defrost in order to comply with energy efficiency standards that came into effect in 1993, it did not see it as a viable option for the next revision in the energy performance standards. In Europe also, the Ecodesign team did not find merit in introducing this technology because of lack of evidence supporting the energy savings that might be expected.

Adaptive Defrost: To reduce the energy used for defrost, adaptive defrost is a viable option. An adaptive defrost system controls both the defrost time and the amount of defrost heat. Such systems use controls to adjust the time between defrost cycles to the appropriate amount for the door opening frequency, ambient conditions, and other consumer usage patterns which affect the introduction of moisture into the cabinet. In US, the uses of adaptive defrost systems combined with other design options was seen as economically viable. In Europe, adaptive defrost systems with electronic temperature control and fuzzy logic was combined with the option of temperature control through electronic thermostats for achieving 2% energy savings.

Condenser Hot Gas: Another method of reducing the energy required for defrost is to eliminate the need for electric heaters by substituting condenser hot gas in their place. In a condenser hot gas defrost system, the compressor continues to run and a valve opens allowing hot compressed refrigerant to flow to the evaporator. Many frost-free refrigerator-freezers in the US in the 1960s and 1970s used a condenser hot gases defrost system. In 1995, US DOE decided to rule out this option because of absence of enough documented proof of the energy savings potential of this technology. In Europe, condenser hot gas systems with electronic controls were found to be applicable to freezer compartments for high humidity ambient conditions but the extra costs associated were considered too high compared to the benefits

3.5.6. Other technological options

Following were the other technological options considered that could lead to small improvements in the energy demand from domestic refrigeration appliances:

Alternative refrigerants: The use of alternative refrigerants is more with respect to meeting the requirements under the Montreal protocol under which HCFCs were banned for use as refrigerants. In the US, R134a is used as a refrigerant because of its zero ODP. US DOE eliminated the use of alternative refrigerants as a design option for most product classes because available alternatives are either banned or have lower thermo-dynamic efficiencies or are hydrocarbons (e.g. isobutane) which have problems with safety. In Europe it was observed that it was difficult to quantify the energy gains associated with alternative refrigerants. At present hydrocarbons are used as refrigerants in European refrigerators.

Component Location: US DOE evaluated alternate locations for some of the components such as locating compressor at the top of the refrigerator, locating evaporator fan motor outside the cabinet to reduce internal loads from heat loss of the motor. However it was observed that these changes would increase structural requirements for the refrigerator cabinet reduced design flexibility, and the fact that reduction of motor losses (by using more efficient fan motors) may be a more effective approach to reducing the impact of the fan motor power input. Therefore, US DOE eliminated this option for further economic analysis

Alternative Refrigeration Cycles: Alternative refrigeration cycles may have the potential to improve system efficiency. US DOE evaluated several alternative refrigeration cycles for refrigerator-freezers like *Lorenz-Meutzner Cycle, Dual-Loop System, Two-Stage System, Control Valve System, Ejector Refrigerator and Tandem System*. However limited research on these alternative refrigeration cycles, their practical feasibility and compatibility with existing refrigerants prevented these design options to be further analyses economically by US DOE.

Alternative Refrigeration Systems: Alternative refrigeration systems US DOEs not use vapor compression to provide refrigeration. Three alternative refrigeration systems were considered by US DOE: the Stirling cycle, thermoelectric cooling, and thermo-acoustic cooling. The US DOE did not find these options feasible because of technical difficulties, limited efficiency improvements and lack of research and development in investigating technologies like thermo-acoustic refrigeration systems. In Europe, the Ecodesign team found no clear advantage in favour of these technologies for domestic refrigerators and observed that COPs obtained were in the same range as those using vapour compressions technologies. Also these refrigeration cycles require redesigning of heat exchangers to be able to transfer cooling capacity into refrigerator or freezer compartments

Improved Expansion Valve: Residential refrigeration products exclusively use capillary tubes for refrigerant flow metering. Solenoid valves were studied by the US DOE however it was observed that solenoid valves increase the required starting torque of the compressor motor and negatively affected system reliability. US DOE did not find any merit in use of improved expansion valves as it was unclear about what these improvements would be and their potential to lead to energy savings. However in Europe, the use of bi-stable solenoid valves was found to lead to 2% energy savings in domestic refrigerators.

Control System: Improvements in the control system chiefly pertain to those controlling the temperature and air-distribution within the refrigeration product. US DOE did not identify any relevant information showing the energy benefit of electronic temperature control or air distribution systems. In Europe, electronic temperature control was combined with adaptive defrost or bi-stable solenoid valve to achieve2% energy savings in the appliance.

3.6. Summary of technologically feasible options from global studies

Tables 10 and 11 summarize the design options discussed above that were further subjected to cost-effectiveness analysis in the studies done by US DOE and EU Ecodesign Initiative.

Table 11: Design options identified by US US DOE for energy improvements in domestic refrigerators

Insulation	Increased insulation thickness
	Vacuum-Insulated panels
Anti-sweat Heaters	Variable anti-sweat heating
Compressor	Improved compressor efficiency
	Variable-speed compressors
Evaporator	Increased evaporator surface area
Condenser	Increased condenser surface area
	Forced convection condenser (for upright freezers)
Fans and Fan Motor	Evaporator fan motor improvements(Brushless DC motors
	Condenser fan motor improvements (Brushless DC motors
Defrost system	Adaptive defrost

Table 12: Design options identified under EU Ecodesign Initiative for energy improvements in domestic refrigerators

Insulation	Increase in thickness of the door insulation
	increase in thickness of wall insulation
	inclusion of VIPs in the door insulation
	inclusion of VIPs in wall insulation
Heat exchanger	increase in evaporator heat exchange area
	increase in condenser heat exchange area
Compressor	increase in the efficiency of reciprocating compressors
	Use of Variable speed compressors
Electronic controls	application of electronic controls
	application of low energy fans for the heat exchangers (brush less DC fan motors
Adaptive defrost	modified/adaptive defrost technology with electronic temperature controls
	Use of phase change materials integrated into heat exchanger+ compressor cycling optimization
	Bi-stable solenoid valve

4. Techno-economic and Consumer Impacts Analyses

4.1. Techno-economic Analysis

4.1.1. Need for conducting Techno-economic analyses

A techno-economic analysis is done to evaluate the impact of potential efficiency improvement through a technological intervention on the economics to the manufacturer and the consumer purchasing the new improved product. Revision of energy performance standards for products in many countries is preceded by a comprehensive review of progress in technologies available for improving the efficiency of the specific product. The cost-efficiency relationships derived from techno-economic analysis serves as a basis for cost-benefit calculations with respect to consumers, manufacturers and the country, from which a technically and economically feasible energy performance standard can be ultimately determined. Prior to revising the performance standards for residential refrigeration appliances, US DOE gathers information from manufacturers about new technological developments and design options available commercially for increasing the efficiency of existing refrigeration appliances. It prepares a Technical Support Document (TSD) that provides results of the engineering analyses of design options through cost efficiency relationships; TSD supports the rulemaking of standards for appliances.

In Europe too, under the Ecodesign initiative, similar assessments of commercially available technological options for improvements in energy performance of refrigeration appliances were undertaken. Under Japan's Top Runner Program, METI analyzed international markets for best available technology (BAT), discussed its feasibility with manufacturers and set the Top runner standards based on a pre-defined average efficiency that could be achieved using BAT. A techno-economic analysis is carried out to analyze potential efficiency improvement for consideration if new design that are already included in the existing appliance models or some combination of design that has higher efficiency than any existing models. A techno-economic analysis seeks to find answers to the following problem statements:

- *The best target efficiency level for standards*
  Considering that technologies for improving appliance efficiency are evolving continuously over the last few decades, there is a certain achievable limit to energy performance that can be reached. A techno-economic analysis helps in estimating the best target efficiency level through the introduction of the best available technology
- *How will the technology intervention(s) affect consumers and manufacturers financially?*
  It is a well-established fact that all new technological interventions in existing products have a cost associated with them. In general, it has been observed that more efficient products are more expensive than those that are relatively less efficient. By conducting a techno-economic analysis, the impact on the manufacturer as an increase in manufacturing cost and on the consumer through an increase in purchase cost can be determined.

- *Impacts on national energy consumption and GHG emissions*

When a more efficient product or super-efficient appliance will result in reduction in national energy consumption and consequently lead to a decline in net GHG emissions.

A potential drawback of techno-economic analysis is that the efficiency and cost of a project model may be subject to significant uncertainty since it has not been mass produced (Turiel et al. 1997). Projecting prices of models that are significantly more efficient than existing models is difficult and subject to uncertainties and variations (over time and for models of differing efficiencies) including the role of economies of scale and technological learning. Also typically manufacturers do not perform a rather theoretical techno-economic analysis for deriving at efficiency improvements. In most cases, manufacturers try out different combinations of options on the field, test the energy performance of the model and evaluate whether this meets prescribed standards and finally based on cost estimates mass produce the new improved model.

4.1.2. Review of methodology for conducting techno-economic analyses

According to Weil and McMahon (2005), a techno-economic analysis consists of the following steps:

• **Select Appliance class**: Most appliances are divided into different categories based on the service/utility provided by them. For example, in case of domestic refrigeration appliances, globally there are three main recognized categories:

  - Refrigerators: Those that have one compartment suitable for storage of fresh food
  - Refrigerator-freezers: at least one compartment is suitable for storage of fresh food and at least one another for freezing of fresh food and then storage of frozen food.
  - Freezers: having more than one or more compartments suitable for freezing food from ambient temperature or storing frozen food

In most developed countries, there are multiple product categories of refrigerators.

- **Select baseline units, representative of their class**: Selecting the baseline unit is the starting point for analyzing design options for improving energy efficiency. The baseline model should be representative of the class. It is recommended that the least efficient model is chosen as a baseline since this permits analysis of trial standards at all possible levels of efficiency starting from eliminating the least efficient models (Turiel et al, 1997). For products having an energy performance standard, a baseline model that has efficiency equal to the minimum or the average of the existing distribution of models can be selected.
- **Select design options that improve energy efficiency:** The list of potential design options can be prepared based on consultations with manufacturers, literature review and laboratory testing. It is also possible that not all options can be applied to base case models. Therefore, the initial option list will be focused on each base case model.
- **Efficiency Improvement from each design option:** Potential improvements in the energy efficiency of the appliance are calculated for each design option or component change.
- **Efficiency improvements from combined design options**: A combination of design options are applied to baseline models to derive cumulative impact on energy efficiency of the appliance. Combining design options and testing for their efficacy as a combination is difficult and will require testing of new model in test laboratories.

- **Cost estimates for each option**: Cost estimates for the manufacturer for producing improved product is estimated based on consultations with manufacturer. Additionally changes in consumer purchase costs of the new product over the baseline are also estimated. For this study, ICF used rough cost estimates (MRPs) provided by manufacturers
- **Cost-efficiency curves**: the final step of a techno-economic analysis is generating cost-efficiency curves which are determined by calculating life cycle cost of the appliance due to the efficiency improvement based on each design option.

4.2. Consumer Impacts Analysis

4.2.1. Life cycle cost analysis

To assess the impact of a new more efficient product on the cost to the consumer during the lifetime of the product, Life Cycle Cost is calculated. The US US DOE calculates LCC as the sum of the purchase cost and the annual operating costs discounted over the lifetime of the product and calculated based on the equation below:

$$LCC = PC + \sum_{1}^{N} \frac{OC}{(1-r)^{t}}$$

Where,
PC= Product Cost
OC= Annual operating cost of the product
r= discount rate
t= lifetime of the appliance

The annual operating cost of the product reflects the savings accruing to the consumer on account of the higher efficiency and is equal to the product of the Unit electricity Cost or tariff (Rs/kWh) and the energy consumption of the product. It is expected that the Life cycle cost of a more efficient product is likely to be lower than that of a less efficient product because of lowered operating costs associated with the former. The monetary savings to the consumer over the lifetime of the appliance have to also be discounted by using a constant discount factor r. Since consumers value immediate savings more than future savings, the time value of money is typically accounted for by discounting future savings using a discount rate (McNiel et al.)

4.2.2. Payback period analysis

The Payback period is an often used number when estimating the time period of returns from an initial investment in any product or service. As discussed in the previous sections, energy efficient appliances cost more than lesser efficient appliances. Similarly, introduction of a super-efficient refrigerator incorporating one design option or a combination of design operations has high initial investments associated with it. A payback period is the number of years after which cumulative operating cost savings exceed the incremental equipment cost. The incremental equipment cost is additional to the cost paid for by the consumer for a lesser efficient model:

Payback Period= ΔIC/ ΔOC

Where **ΔIC**is the purchase cost difference between a more efficient and less efficient product and

ΔOCis the difference in operating costs of a more efficient and less efficient product.

4.3. Methodology

4.3.1. Techno-economic Analysis for super-efficiency in Indian refrigerators

Based on the review of literature on methodology for conducting techno-economic analysis for higher efficiency in appliances, ICF used the following approach for conducting techno-economic analysis for super-efficiency/higher efficiency in Indian refrigerators.

Selection of Appliance class: In India, the refrigerator market is dominated by free-standing refrigerators or Direct Cool refrigerators which had a 79.4% market share in year 2010-11. The other category of Frost Free refrigerators is the fastest growing segment with sales increasing by a 15% retail volume CAGR (Euromonitor, 2011). For the present study, both direct cool and frost free refrigerators were considered for possible improvements in energy efficiency through introduction of changes in component design. ICF held discussions with Shakti regarding the selected appliance class for the analysis

Selection of baseline units: Baseline models for both categories of refrigerators have been selected based on market research report published by Euromonitor. In case of direct cool refrigerators, a 170 litre model was selected as baseline due to a higher market demand. For frost free refrigerators, a 240 litre model was selected. The selected baseline units are representative of their class owing to their higher market share compared to other volume categories.

List of design options for improving refrigerator efficiency: Based on a comprehensive review of similar studies done by agencies like US DOE, European Ecodesign Initiative and Japan's Top Runner Program, a list of design options for improving energy efficiency of both frost free and direct cool type of refrigerators was prepared. The different design modifications were listed under the following components of refrigerator design:

- Insulation
- Improvements in design of door gasket
- Anti-sweat heater
- Heat exchanger (condenser and evaporator)
- Fan and fan motors
- Compressor
- Expansion valve
- Defrost system
- Optimization of system controls
- Alternative refrigeration cycles

- Alternative refrigeration systems
- Other technologies (not mentioned under any of the above categories)

The list of options compiled and discussed with Indian manufacturers did not take into account global experience and evaluation of these options. This was because, Indian conditions are unique and while some options could have been rejected in other studies they might be feasible and implementable for Indian refrigerators. Therefore, a complete list of design options was taken to the manufacturers.

Consultations with manufacturers: The initial list of design options was prepared based on review of studies done globally on improving energy performance standards for refrigerators. ICF conducted meetings with four leading manufacturers for discussing these options. Two of these manufacturers are domestic and while the other two are international players that together comprise more than 50% of the market. All the consulted manufacturers have refrigerator manufacturing facilities in India.

For getting the desired inputs from manufacturers on the identified design options, ICF prepared a questionnaire for manufacturers in a spread sheet format, which is included in the annexures. The spread sheet comprised a list of the identified options and columns for requesting information from manufacturers under the following categories:

- *Feasibility or implement ability*: For each of the identified design option, the feasibility of implementing the option in India and the time period for bringing the technology to India was asked from consulting manufacturers
- *Applicability*: Applicability of the design option to Direct cool or/and frost free refrigerators was asked
- *Improvement in energy efficiency (%)*: The improvement in the energy efficiency of the baseline refrigerator models relative to the baseline BEE 5-star model was needed from manufacturers. Consulted experts were asked to provide an estimate of an improvement in energy efficiency with the introduction of each design option under each component category
- *Incremental manufacturing cost (INR)*: Each change in design of the component has a cost associated with it. This cost is reflective if the manufacturing cost (if the component is manufactured in India) or the import cost (if component is imported). The incremental cost to manufacture relative to baseline of 5-star was asked
- *Increase in consumer price (INR):* Manufacturers pass on any increase in the manufacturing cost to consumer. Therefore any change in the price of the product due to the introduction of a design option in the baseline model was captured through the questionnaire
- *Any other option:* Manufacturers were asked to provide information about any other option that was not included in the original list, which they felt could contribute to energy use reduction in a refrigerator

Table 13: Compilation of design options for Indian refrigerators

Component	Design Option
1. Insulation	Increased insulation thickness
	improved resistivity of insulation
	Increase in density of PU foam density
	improved thermal properties of insulation foam
	Vacuum-insulated panels in the model door
2. Design of door gasket	Double door gaskets
	improved door face frame
	gas filled panels
3. Anti sweat heater	Electronic control of hot gas discharge tube embedded around freezer door frame
	Optimal positioning and design of electric anti-sweat heaters of freezer doors
	Electric anti sweat heater sizing
	Variable anti-sweat heating
	Electric heater controls
4. Heat exchanger (Condenser and Evapoprator)	Improved heat exchange through use of enhanced fins/tubes of evaporator and condenser
	Increase in area of condenser
	Increase in area of evaporator
	Incorporating forced convection heat exchangers
5. Fan and fan motors	Use of more efficient fan motors like Brushless DC fan motors
	Use of phase-change materials integrated into heat exchanger to increase effective thermal capacity
	Phase-change materials+ optimization of the compressor on/off cycling
6. Compressor	Variable speed compressors/variable capacity compressors
	Linear compressors
	Alternative technologies to reciprocating compressors
7. Expansion Valve	Use of fluid control or solenoid valves
8. Defrost system	Reduced energy for automatic defrost
	Use of adaptive defrost system
	Condenser hot gas defrost system
9. System controls	Electronic temperature controls
	Air distribution control
	improved electric controls with VCCs
10. Alternative Refrigeration cycles	Lorenz Meutner cycle
	Dual loop system
	Two-stage system
11. Alternative Refrigeration systems	Stirling cycle,
	thermo-electric refrigeration
	thermo-acoustic
12. Other Technologies	Alternative refrigerants
	Change in component location

ICF encouraged consulted experts to share more information with respect to the challenges faced by manufacturers in improving energy performance for refrigerators in India and their general perception about how these challenges can be overcome was also discussed. It must be noted that estimates given by manufacturers on the incremental costs to producer and consumer *are indicative*. High estimates can often be provided for more efficient technology since the technology has not been imported or manufactured in India, in which case the estimates are subject to changes in exchange rates, global component/commodity prices and may change due to economies of scale.

Cost-efficiency curves
Based on the inputs from consulted manufacturers, ICF developed a cost-efficiency curve indicating the relationship between incremental manufacturing costs (INR) and the percentage efficiency improvements associated with each design option.

4.4. Consumer Impacts Analysis

4.4.1. LCC of super-efficiency in Indian refrigerators

ICF used the following inputs for calculating the Life Cycle Costs associated with each design option for improving energy efficiency in refrigerators (Direct Cool and Frost Free):

Product Cost (PC): Manufacturer consultations provided information about the change in product costs associated with specific design options. We assumed that these incremental values over the cost of the baseline of BEE 5-star was inclusive of the retail mark-up. ICF used present market data to estimate the average price of 180Litre 5-star Direct cool refrigerator and a 250Litre 5-star frost free refrigerator.

Appliance lifetime (t): The LCC analysis for introduced design options for improving refrigerator efficiency are based on certain assumptions about the lifetime of the appliance. According to Euromonitor (2011), the typical lifetime of a refrigerator is 10 years. However our experience conducting market research in North Delhi on refrigerator replacement cycle indicated that vintage of refrigerators owned range from 6 years to 20 years. In another study (McNiel et al. 2008) assumed a refrigerator lifetime of 15 years for Indian refrigerators. The feedback from manufacturers on refrigerator lifetime was also approximately 7 to 10 years. We have therefore used an average lifetime of 10 years for refrigerators for doing the LCC analysis.

Unit electricity cost (UEC): UEC used for LCC analysis was based on published tariffs from NPC report (2009-10), assuming that a domestic consumer using a refrigerator will fall in the tariff slab corresponding to 100kWh/month would give a national average rate of 4.5Rs/kWh (based on domestic sales). Using national average tariff rate from 2009-10 is a conservative assumption, since higher electricity prices at present and in the future will yield larger monetary savings to the consumer. To refine LCC estimates for the design options, ICF also used a year on year tariff escalation rate of 5% for determining the NPV of operational costs over the lifetime of the product. The escalation rate is based on average long term inflation rate.

Discounting factor (r): Calculating the discount factor for discounting operational energy savings to consumer overtime is challenging. Discounting factor used by McNiel et al (2008) for estimating potential energy savings from improved energy efficiency of refrigerators in India was 15% for domestic consumers. It was based on the rate used by utilities for their investment in Demand Side Management or efficiency programs. In India, very few utilities have guidelines for estimating cost-effectiveness of DSM interventions. Maharashtra Electricity Regulator Commission (MERC) has published Regulations for DSM measures and Program's Cost Effectiveness Assessment in 2010. In the present study we have used MERC's prescribed discounting factor for participants (consumers) in a DSM program, which is 13%.

Life cycle Cost for each design option was calculated as:

LCC= Product Cost + NPV of operational costs, discounted over lifetime of the product

4.1.2. Payback period analysis for super-efficient refrigerators

An estimate of the incremental price increase of the baseline product due to incorporation of the design option was obtained through manufacturer consultations. Baseline retail price was based on information available in public domain. The price of the new product due to each design option was calculated by summing the baseline retail price and the incremental price increase.

Baseline energy consumption for the two categories of refrigerators was obtained from BEE and national average tariff rate of Rs. 4.5/kWh) was used to calculate the operating costs of the baseline and new more efficient product.

4.5. Results

4.5.1. Technological options for super efficiency in Indian refrigerators

As described above, ICF approached four leading manufacturers with a list of design options studied globally for bringing about further energy improvements in existing domestic refrigeration appliances. Not all design options discussed with the manufacturers were found feasible for Indian conditions. The Indian scenario as described by one of the experts is different from rest of the world; it is characterized by diverse climatic conditions in different parts of the country, differing quality and reliability of supplied power and voltage fluctuations, differing ambient conditions (where in many domestic households refrigerators are kept in warm kitchens). These factors have prompted Indian manufacturers to over-design components used in Indian refrigerators to enhance their ability to withstand varied conditions.

Feedback on the design options for increasing efficiency of refrigerators keeping BEE 5-star as baseline is described below:

- ***Improvements in insulation***: All manufacturers agreed that refrigerator insulation is the most critical energy component of a refrigerator and the thickness of the PU foam determined the heat transfer through the walls of the cabinet. PU foam has replaced glass wool for long. Insulation around freezer was reported to be thicker than the remaining parts of refrigerator. The responses from the four manufacturers on different changes in the insulation properties have been tabulated below:

Design option	General observations	Specific comments
Blowing agent used in insulation	Blowing agents used by two of the consulted manufacturers is R141b; the other two manufacturers use cyclopentane as the blowing agent for PU foam insulation. Manufacturers using HCFC R141b have started working on the alternative blowing agent since as a part of commitment under the Montreal protocol, the Indian Ozone cell has called for a phase out of HCFC based compounds in cooling appliances.	
Increasing insulation thickness	Not viewed as a viable design option for increasing energy efficiency because of a trade-off with storage volume, physical dimensions of and aesthetics of the product. Any increase in insulation thickness beyond a certain threshold will lead to a redesigning of the product. This option will be considered as the last intervention when everything else has been implemented.	An increase in insulation thickness by 8-10 mm leads to approximately 10% energy savings.
improved thermal properties of insulation foam	Not considered very important by most manufacturers who purchase a fixed design of the insulation from insulation manufacturers.	
improved resistivity of insulation		
Increase in density of PU foam	Not considered very important by most manufacturers who purchase a fixed design of the insulation from insulation manufacturers.	This option was not a part of the original list of design options; it was recommended as a more feasible and viable option by one of the experts who suggested that both costs and time period required for introducing this design modification is less.
Vacuum Insulated Panels (VIPs)	This option is considered feasible however it is a very expensive intervention. VIPs are not available locally, they have to be imported. Also the logistics required for handling and transportaion of VIP fitted refrigerators is very different. Mishandling can even lead to breakage. Also thickness of VIPs can be vaired on different parts of the refrigerator to achieve efficiency levels	A 10% improvement in energy improvement is possible with VIPs. However the cost estimates range from Rs. 400 to 500/m2 of the panel. Consolidated estimates range from Rs.2000 to Rs. 4000 depending on size of refrigerator

- **Improvements in Door gasket design**

All consulted manufacturers believe that door gaskets used in Indian refrigerators have been considerably improved overtime to meet energy performance standards. As a design option, the knowledge amongst the consulted experts appeared limited indicating that further R&D needs to be done to understand energy savings potential of improved door gasket design. Only one manufacturer was aware of double door gaskets, which are used in European appliances. However, according to one expert, since India has internationally reputed gasket manufacturers, working on improved gaskets should not be a problem. Since information and cost estimates for this option was limited, this option was not considered for further analysis.

- **Anti-sweat heater**

According to all manufacturers anti-sweat heaters do not contribute much to energy consumption from refrigerator. These are chiefly used in models with side-by-side door, specifically the ones with a TTD. These are used to remove dew. Hence their usage is limited by geography and climate. Therefore design options associated with improvements in anti-sweat heater design like electronic control of hot gas discharge tube embedded around freezer door frame, optimal positioning and design of electric anti-sweat heaters of freezer doors, electric anti sweat heater sizing, variable anti-sweat heating and Electric heater controls were not considered feasible for application to commonly sold Direct cool and frost free refrigerator models in India

- **Heat exchanger improvements**

Improvements with respect to design of evaporators and condensers were discussed. In India, forced convection condensers are used. According to the consulted experts, any improvement in heat exchanger design needs to be combined with improvements in the fan motor that powers the component. Also, one industry expert suggested that improvements in the fan motor must not limit the voltage range it can work with. The responses from the four manufacturers on different changes in the heat exchanger have been tabulated below:

Design option	General observations	Specific comments
Increase in area of Evaporator and Condenser	According to one manufacturer, an increase in area of evaporator and condenser US DOEs not seem to be technically feasible; in increase in condenser area has reached saturation. However, most manufacturers believe that increasing the area of heat exchangers is feasible and implementable.	A 20% increase in heat exchanger area led to a 5-6% improvement in energy efficiency
Improved heat exchange through use of enhanced fins/tubes of evaporator and condenser	The improvements in heat exchange through use of enhanced fins/tubes of seemed viable but further studies needed to be done under Indian conditions to evaluate the impact on energy savings.	N.A
Incorporating forced convection heat exchangers	This was agreed by all consulted experts to be feasible alternative and something which was being studied and evaluated at present.	N.A.

- **Fan and Fan motor improvements**

All the experts consulted during the study, recommended only one feasible improvement in fan motor design: the introduction of Brushless DC (BLDC) fan motors which have an energy consumption of 2W compared to the conventional motors which consumer 6-10W. BLDC fan motors can be used only for frost free refrigerators. Introduction of BLDC fan motors needs to be made more cost-effective for companies that are importing it. One manufacturer has already introduced BLDC motors in BEE 5-star refrigerators launched to meet revised energy performance standards of 2012. Other design option like use of phase-change materials integrated into heat exchanger (to increase effective thermal capacity) was either unheard of or was stated to lead to no energy savings.

- **Compressor Improvements:**

Consulted manufacturers did not readily divulge information about their existing work on improving compressor energy efficiency. According to all manufacturers, the introduction of Variable Speed compressors (VSCs) was the next step in improving energy efficiency of domestic refrigerators which leads to a 15-20% improvement in energy efficiency. However the technology is expensive and may lead to a significant increase in cost of the product and since the Indian market is price-sensitive, the time period for introducing this technology ranges from 1.5 years to 4 years according to the experts. An alternative compressor technology like Linear Compressor is not feasible since one manufacturer has a patent on this technology and uses it for some of its premium refrigerator models. Other manufacturers are reluctant to introduce this technology in their products and believe that VSCs are better and more practical.

- **Improved Expansion valves:**

Improved expansion valves like fluid control or solenoid valves are not being currently used in India. One consulted expert stated that the technology will lead to a 5-10% improvement in energy efficiency but will take a long time to enter India.

- **Defrost system**

Improvements in the defrost system are applicable only to frost free refrigerators. According to one expert, reduction in the energy used for defrost can be achieved by reducing the wattage of the heater or its operating time or both. Adaptive defrost as an option is being used by one manufacturer while others perceived a time period of 5-6 months for such a technology to be implemented for Indian refrigerators and see an efficiency improvement by 3-5%.

- **Optimization of system controls**

The optimization of electronic temperature controls and air distribution controls in frost free refrigerators are largely perceived as minor changes where efficiency improvements (5-10%) are significant with relatively small investments in the cost. Most consulted experts feel that system controls are continuously being refined and improved to the level that in one case it has even reached saturation. Hence these changes have to be combined with other design options like adaptive defrost and VSCs to resulting further energy savings.

- **Other options**

ICF also discussed other options like alternative refrigeration systems and refrigeration cycles with manufacturers. However, most respondents remained either unaware of these options or cited lack of research on the relationship between these changes and a decline in energy consumption of domestic refrigerators. Therefore these options were not considered for further analysis.

4.5.2. Cost-efficiency relationship

Design options for efficiency improvements in Indian refrigerators

It must be understood, that complete data for all design options was difficult to obtain from the consulted experts. For e.g. for some options even if information with respect to feasibility, time period of implementation and efficiency improvements was available, the cost estimates were not provided by consulted experts. ICF observed that most technical experts in leading manufacturing companies do not willingly share data on cost estimates since this information is highly confidential.

Also, some of the experts consulted confessed to having limited knowledge about costs and efficiency estimates since no prior research has been conducted on these aspects by the Indian refrigerator manufacturing industry. According to one expert, during product development and designing, field technicians experiment with different combinations of design changes in a few components to meet the energy performance standard prescribed by BEE under the star label.

Hence, based on complete data on few but important design modifications in selected components, ICF tabulated a final list of design options and the energy efficiency improvements associated with these options and the time period required for their implementation or introduction in Indian refrigerator models in the table below:

Component	**Design Option**	**Energy efficiency improvement over BEE 5-star**	**Time period for implementation**	**Incremental Manufacturing Costs (INR)**
Insulation	*Increased insulation thickness (8 to 10 mm)*	10%	3-5 months	Rs.400/- approx
	Increase in density of PU foam	4 ~ 5%	1 month	Rs.250/-
	Vacuum-insulated panels in the model door	10 ~ 12%	3-5 months	Rs.400 ~ 500/-
Heat Exchanger Improvements	*Increase in area of condenser (20%)*	5-6%	2-3 months	Rs.150 ~ 180/-
	Increase in area of evaporator (by 20%)	5-6%	2-3 months	Rs.150 ~ 180/-
	Incorporating forced convection heat exchangers	5-6%	4-5 months	Rs.150 ~ 180/-
Fan Motors	*Brushless DC motors*	2-3%	4-5 months	Rs. 300
Compressor	*Variable speed compressors/variable capacity compressors*	25 to 30%	1- 1.5 years	Rs.2500 ~ 3000/-
Electronic Controls	*Electronic temperature controls,*	5 to 10%	6- 8 months	Rs.250 ~ 300/-
	air distribution control	5 to 10%	6- 8 months	Rs.250 ~ 300/-

Some options like Variable Speed Compressors have high initial investments associated with their introduction although the efficiency gains are significant (25-30%) while some options like better electronic controls of temperature and air distribution result in 5-10% energy savings at a much lower cost (Rs. 250-300). The time period required for most design options is less than 6 months which is a good indication since it implies that future improvements in energy efficiency of refrigerators will be able to meet BEE targets timely.

Combining options for energy efficiency improvements

As mentioned above, efficiency improvements in refrigerators while designing and development are brought about through a combination of changes in key components. ICF followed the same logic while arriving at different design options for improving efficiency of baseline BEE 5-star in both Direct cool and Frost free categories of refrigerators.

In the previous sections, alternative insulation technologies like VIPs were discussed. VIPs in the model door alone can lead to 10-12% improvement in the energy performance of BEE 5-star refrigerator. VIPs can also be used in combination with PU foam insulation wherein, VIPs can be fixed in certain critical parts of the refrigerator like the freezer door, near the compressor etc, where better insulation will result in significant reduction in energy consumption of the refrigerator. ICF therefore identified two cases for design improvements

- **Case 1: Without VIPs:** This combination of design options ruled out the introduction of VIPs in the model door and was focussed on achieving energy efficiency improvements through changes in the existing PU foam insulation, heat exchangers, compressor, fan motors and electronic controls
- **Case 2: With VIPs**: This combination of design options was based on the assumption that assuming that PU foam insulation cannot be used and VIPs replace PU foam insulation in all parts of the refrigerator.

For both the cases, with each successive improvement in % energy efficiency, options were combined and finally cumulative impact of combining options, one step at a time on the energy efficiency was estimated. The design options for direct cool and frost free refrigerators is described below.

Direct cool Refrigerators: The final list of design options and the associated energy efficiency improvements and incremental manufacturing costs for direct cool refrigerators is described in tables 15 and 16.

Table 14: Design options under Case 1- Without VIPs for Direct Cool Refrigerators

Design Number	Options	Efficiency Improvement (%)	Incremental Manufacturing Cost (INR)
1	increase in area of condenser by 20%	5%	170
2	1+ increase in area of evaporators by 20%	10%	340
3	2+increase in density of PU foam	15%	590
4	3+ incorporating forced convection heat exchangers	20%	760
5	4+ increase in insulation thickness	28%	1160
6	5+ variable speed compressors	53%	4160

It must be noted that the efficiency improvements associated with related options cannot be summed up. Therefore, and any impact on the energy efficiency cumulatively between related options needs to be discounted to account for any reductions that may occur when related options are combined. For e.g. although when individually implemented, increasing the thickness of PU foam and increasing the density of PU foam result in 10% and 5% energy efficiency improvement, when combined together, the resultant energy efficiency improvement will not be 10%+5% or 15%; in fact since both are related to insulation improvements, the efficiency improvement will be discounted by a small factor. Based on experts consulted, this discounting percentage ranged from 5% to 10%.

Table 15: Design options under Case 2- With VIPs for Direct cool refrigerators

Design Number	Options	Efficiency Improvement (%)	Incremental Manufacturing Cost (INR)
1	Vacuum-insulated panels in the model door	12%	500
2	1+ increase in area of condenser by 20%	18%	680
3	2+increase in area of evaporator by 20%	22%	860
4	3+ incorporating forced convection heat exchangers	26%	1020
5	3+ variable speed compressors	52%	3860

Frost free refrigerators: The final list of design options and the associated energy efficiency improvements and incremental manufacturing costs for direct cool refrigerators is described in tables 16 and 17

Table 16: Design options under Case 1- Without VIPs for Frost free Refrigerators

Design Number	Options	Efficiency Improvement (%)	Incremental Manufacturing Cost (INR)
1	increase in area of condenser by 20%	5%	170
2	1+ increase in area of evaporators by 20%	10%	340
3	2+increase in density of PU foam	15%	590
4	3+ incorporating forced convection heat exchangers	20%	760
5	4+ BLDC fan motors	23%	1060
6	5+electronic temperature controls	33%	1360
7	6+ air distribution controls	40%	1660
8	7+ increase in insulation thickness	47%	2060
9	8+ Variable speed compressors	70%	4660

Table 17: Design options under Case 2- With VIPs for Frost free refrigerators

Design Number	Options	Efficiency Improvement (%)	Incremental Manufacturing Cost (INR)
1	Vacuum-insulated panels in the model door	12%	500
2	1+BLDC fan motors	15%	800
3	2+increase in area of condenser by 20%	20%	970
4	3+ increase in area of evaporator by 20%	25%	1140
5	4+ incorporating forced convection heat exchangers	28%	1310
6	5+ electronic temperature controls	35%	1580
7	6+ air distribution controls	40%	1830
8	7+VSCs	60%	4830

Cost-efficiency curves

The cost efficiency curves in Figures 15 and 16 show the relationship between incremental manufacturing costs and corresponding efficiency improvement.

In Case 1, where VIPs have been ruled out as a means for improving energy efficiency, improvements in the existing PU foam insulation through various means like increasing insulation thickness and increasing density of PU foam have been considered. The range of efficiency improvements in this case ranges from 5% to 53% in case of Direct cool refrigerators (Figure 22) and upto 60% for frost free refrigerators (Figure 24). At each stage, cumulative improvements in energy efficiency and the incremental manufacturing cost are calculated. The introduction of Variable Speed Compressors (VSCs) leads to a 23% increase in energy efficiency improvement from 47% to 70% in frost free refrigerators.

It can be observed that in Case 2, through the introduction of VIPs, a 12% improvement in the energy efficiency is possible, this is the first option in this case for both direct cool and frost free refrigerators and has an incremental manufacturing cost of INR 500. There is a steep 60% increase in incremental manufacturing cost with design number 8 when VSCs are added to design number 7 and efficiency improves by 20% for frost free refrigerators (Figure 25)

Figure 22: Cost-efficiency Curve -without VIP (Case 1) for Direct Cool refrigerators

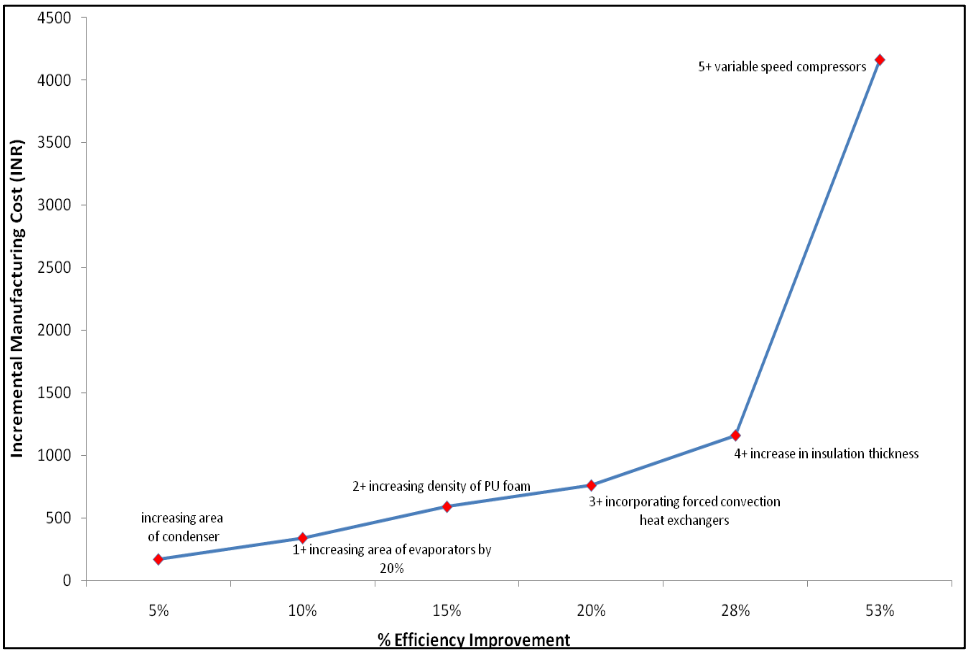


Figure 23: Cost efficiency curve - without VIP (Case 2) for Direct Cool refrigerator

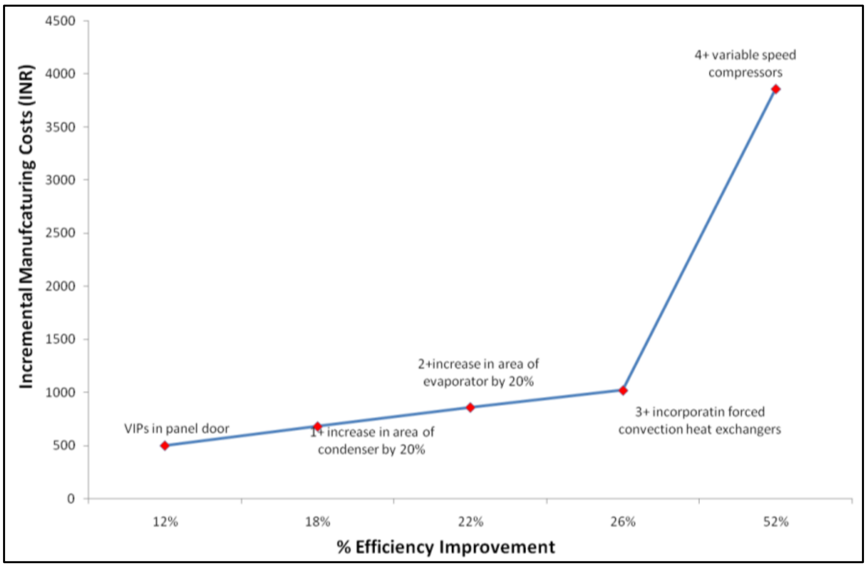


Figure 24: Cost-efficiency Curve -without VIP (Case 1) for Frost free refrigerators

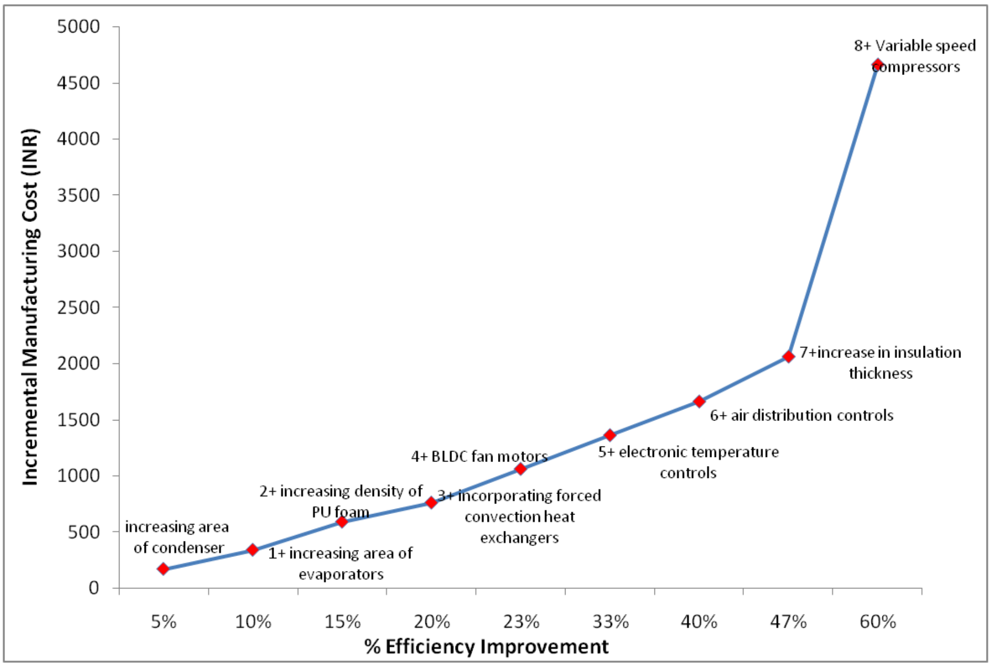
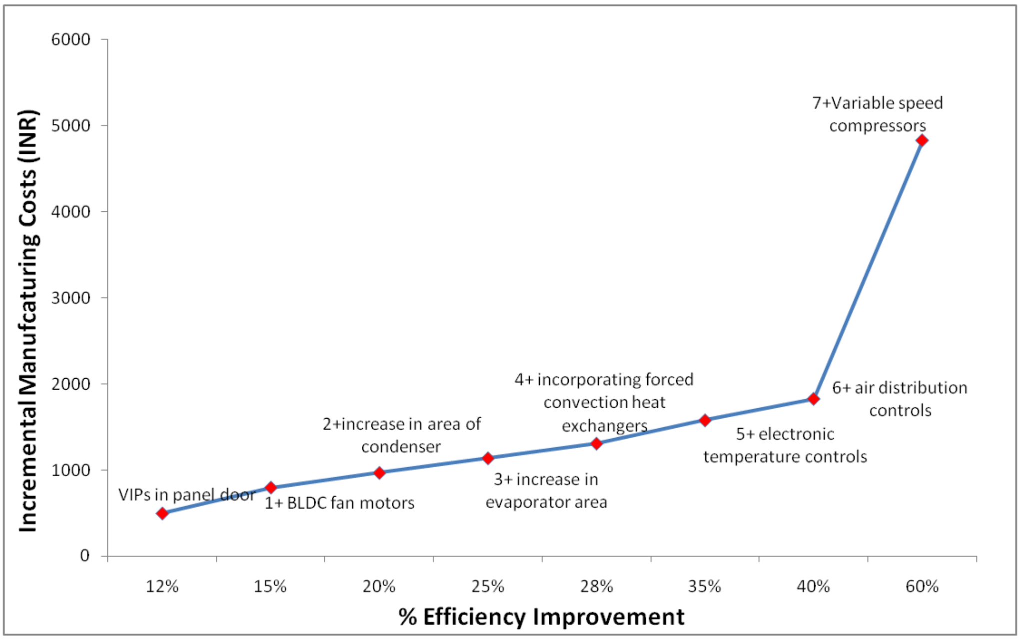


Figure 25: Cost efficiency curve - without VIP (Case 2) for Frost free refrigerators



4.5.3. LCC and Payback period analysis

The Life cycle costs for baseline and the design options under both case 1 and 2 were calculated assuming an appliance lifetime of 10 years and a year on year tariff escalation rate of 5%. These constants were used to calculate the NPV of operational costs of baseline product and improved products over the lifetime of the product discounted at 13%.

The simple payback period of improved product was calculated by dividing the difference in the retail cost of more efficient product and baseline 5-star and the monetary savings from the operation of more efficient product over the baseline. The LCC and Payback period was calculated for all design options and for both cases (case 1 and 2) for Direct cool and Frost free refrigerators.

Direct Cool Refrigerators

For Direct cool refrigerators, the LCC of the baseline was calculated to be INR 20,585 and the LCC of the option that led to maximum improvement in energy efficiency (design number 9 leading to 70% improvements in case 1) was INR 20,045. This was because the product cost of design number 9 was high. However, for all the other design options, with subsequent improvements in the energy efficiency, the LCC reduced since NPV of operational savings associated with improved product decreased over the lifetime of the product. Tables 18 and 19 show the LCC and Payback period associated with each combination of design option under case 1 and 2 respectively.

Under case 1, the payback period for two options: Design numbers 1,2 and 6 was less than 5 years. While for all the other options, the payback period ranged from 5.5 to 5.7 years. Under case 2, all but one (option 5) of the design options had a payback period of less than 5 years.

Frost free Refrigerators

For Frost free refrigerators, the LCC of the baseline was calculated to be INR 30,695 and the LCC of the option that led to maximum improvement in energy efficiency (design number 9 leading to 70% improvements in case 1) was marginally lower at INR 30,612. For all design options, with subsequent improvements in the energy efficiency, the LCC reduced since NPV of operational savings associated with improved product decreased over the lifetime of the product. Tables 20 and21 show the LCC and Payback period associated with each combination of design option under case 1 and 2 respectively.

For frost free refrigerators, under case 1, all design options except option 5 and 9 had a payback period less than 5 years. This implies, that design options for improving efficiency of baseline 5-star are cost-effective with small payback time periods. Even in case 2, all but two options had a payback period of less than 5 years.

Table 18: Consumer Impacts Analysis of Design options: Case 1 for 180 L Direct Cool Refrigerators

Design Number	Option	Efficiency improvement	Annual Energy Consumption (kWh/year)	Annual Operating Costs (INR) or Cost of Conserved Energy	Monetary savings (INR)	Retail cost of Product (INR)	% increase in retail product cost	Pay back period (Years)	Life cycle costs (INR)
0	Baseline	0	245	1103	0	12948	0	0.0	20585
1	increase in area of condenser by 20%	5%	233	1047	55	13220	2 %	4.9	20482
2	1+ increase in area of evaporators by 20%	10%	221	992	110	13492	4 %	4.9	20377
3	2+increase in density of PU foam	15%	208	937	165	13892	5 %	5.7	20383
4	3+ incorporating forced convection heat exchangers	20%	196	882	221	14164	5 %	5.5	20273
5	4+ increase in insulation thickness	28%	176	794	309	14644	5 %	5.5	20475
6	5+ variable speed compressors	53%	115	518	584	15124	7 %	3.7	20045

Table 19: Consumer Impacts Analysis of Design options: Case 2 for 180 L Direct Cool Refrigerators

Design number	Option	Efficiency improvement	Annual Energy Consumption (kWh/year)	Annual Operating Costs (INR) or Cost of Conserved Energy	Monetary savings (INR)	Retail cost of Product (INR)	% increase in retail product cost	Pay back period (Years)	Life cycle costs (INR)
0	**Baseline**	0	245	1103	0	12948	0	**0**	20,585
1	Vacuum-insulated panels in the model door	12%	216	970	132	13348	3	3.0	20,068
2	1+ increase in area of condenser by 20%	15%	208	937	165	13492	1	3.3	19,983
3	2+increase in area of evaporator by 20%	20%	196	882	221	13636	1	3.1	19,745
4	3+ incorporating forced convection heat exchangers	25%	184	827	276	13764	1	3.0	19,491
5	4+ variable speed compressors	28%	176	794	309	16036	17	10.0	21,534

Table 20: Consumer Impacts Analysis of Design options: Case 1 for 230 L Frost free Refrigerators

Design Number	Option	Efficiency improvement	Annual Energy Consumption (kWh/year)	Annual Operating Costs (INR). or Cost of Conserved Energy	Monetary savings (INR)	Retail cost of Product (INR)	% increase in retail product cost	Payback period (Years)	Life cycle costs (INR)
0	Baseline	0	315	1418	0	19,925	1	0.0	30,695
1	increase in area of condenser by 20%	5%	299	1347	71	20,197	1	3.8	30,428
2	1+ increase in area of evaporators by 20%	10%	284	1276	142	20,469	2	3.8	30,162
3	2+increase in density of PU foam	15%	268	1205	213	20,869	1	4.4	30,023
4	3+ incorporating forced convection heat exchangers	20%	252	1134	284	21,141	2	4.3	29,757
5	4+ BLDC fan motors	23%	243	1091	326	21,621	2	5.2	29,914
6	5+electronic temperature controls	33%	211	950	468	22,101	2	4.7	30,612
7	6+ air distribution controls	40%	189	851	567	22,581	3	4.7	29,043
8	7+ increase in insulation thickness	47%	167	751	666	23,221	1	4.9	28,929
9	8+ Variable speed compressors	70%	95	425	992	27,381	1	7.5	30,612

Table 21: Consumer Impacts Analysis of Design options: Case 2 for 230 L Frost free Refrigerators

Design Number	Option	Efficiency improvement	Annual Energy Consumption (kWh/year)	Annual Operating Costs (INR) or Cost of Conserved Energy	Monetary savings (INR)	Retail cost of Product (INR)	% increase in retail product cost	Pay back period (Years)	Life cycle costs (INR)
0	Baseline	**0**	315	1418	**0**	19,925	**0**	**0**	30,695
1	Vacuum-insulated panels in the model door	12%	277	1247	170	20,725	4	4.7	30,202
2	1+BLDC fan motors	15%	268	1205	213	21,205	2	6.0	30,359
3	2+increase in area of condenser by 20%	20%	252	1134	284	21,477	1	5.5	30,093
4	3+ increase in area of evaporator by 20%	25%	236	1063	354	21,749	1	5.1	29,826
5	4+ incorporating forced convection heat exchangers	28%	227	1021	397	22,021	1	5.3	29,775
6	5+ electronic temperature controls	35%	205	921	496	22,453	2	5.1	29,453
7	6+ air distribution controls	40%	189	851	567	22,853	2	5.2	29,315
8	7+VSCs	60%	126	567	851	27,653	21	9.1	31,009

Conclusions

The evaluation of efficiency improving design options for direct cool and frost free refrigerators is based completely on manufacturer inputs specifically on the costs of imported technologies and subsequent impact on the overall cost of the product as sold to the end consumer. Therefore, the increase in costs associated with increase in efficiency are strictly indicative and may not accurately represent true market conditions in the future, when these technologies will have to be deployed for meeting stricter energy performance standards (BEE has prescribed a 40% increase in efficiency over present baseline in the revisions that come into effect in 2014). Market dynamics will bring down the costs of these component design modifications in the future, substantially decreasing the pay back periods and costs borne by consumers. Also, ICF's consultations with manufacturers have indicated that some of the design options evaluated in the study have been introduced by some anufacturers for meeting the revised energy performance standards this year. As one manufacturer confirmed, BLDC fan motors have been used in its 5-star labelled frost free refrigerators launched this year. Advanced technologies like Linear compressors have been introduced in premium segment frost free refrigerator models of one brand.

There is therefore no doubt that both incremental manufacturing costs and retail prices will change when manufacturers bring about efficiency improvements using the studied design options in future as they would have the benefit of competitive pricing and economies of scale. The findings from this study will be useful in indicating maximum efficiency levels that can be achieved cost-effectively using commercially available component technologies.

References

1. Bansal, P., Vineyard, E. and Abdelaziz, O. 2011. Advances in household appliances - A review, Applied Thermal Engineering 31, 3748-3760
2. CLASP, 2007, India Labeling Program Impacts: Case study, available online at: http://www.clasponline.org/~/media/Files/SLDocuments/2006-2011/2007-05_IndiaLabelingProgramImpacts.pdf
3. Ellis, M., Jollands, N., Harrington, L. and Meier, A. 2007. Do energy efficient appliances cost more?, *ECEEE 2007 Summer Study*, 1127-1137
4. Euromonitor International, 2011. Refrigeration Appliances in India
5. Geppert, J. 2011. Modelling of domestic refrigerators' energy consumption under real life conditions in Europe, Volumes 2011-12, Shaker Publishers
6. Mahila, T.M.I and Saidur, R. 2010. A review on test procedure, energy efficiency standards and energy labels for room air conditioners and refrigerator–freezers, *Renewable and Sustainable Energy Reviews* 14, 1888-1900
7. Mc Neil, M.A., Iyer, M., Meyers, S., Letschert, V.E. and McMahon, J.E. 2008. Potential benefits from improved energy efficiency of key electrical products: The case of India, *Energy Policy* 36, 3467– 3476
8. McNeil, M. 2005. Comments on Indian Draft Standard Levels for Refrigerators , available online at: http://ies.lbl.gov/drupal.files/ies.lbl.gov.sandbox/LBNL%20India-Refrigerator-Final.pdf
9. Meir, A.K. and Hill, J.E. 1997. Energy test procedures for appliances, *Energy and Buildings,* 26**,** 23-33.
10. Miller, J.D. and Pratt, R.G. 1998. Estimates of Refrigerator Loads in Public Housing Based on Metered Consumption Data, Department of Energy
11. Turiel, I., Chap, T. And Mc Mahon, J.E. 1997. Theory and methodology of appliance standards, *Energy and Buildings* 26, 35-44
12. US US DOE, 2005, Technical Support Document: Analysis of Amended Energy Conservation Standards for Residential Refrigerator-Freezers, available online at: http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf
13. Weil, S. And Mc Mahon, J.E. 2005. *Energy efficiency standards and labels: a guidebook for appliances, equipment and lighting,* 2nd Edition*,* Washington DC, USA, Collaborative Labeling and Appliances Standards Program. http://www.clasponline.org/clasp.online.resource.php?sbo=289
14. Yanti, P.A.A. and Mahila, T.M.I. 2008. Methodology of Implementing Energy Efficiency Standards for Electric Motor, *European Journal of Scientific Research* 24(1), 134-147

Annexure 1: Format of Questionnaire given to experts for inputs on design options

Design intervention	**Feasibility/ implement ability in India** *(How difficult is it bringing technology to India, what is the expected time period for implementation))*	**Applicability** *(% of models already applied to at present)*	**% Improvement in efficiency** *(% improvement over a BEE- 5 star)*	**Incremental manufacturing cost** in UDS/INR/%(*This cost is relative to baseline BEE 5-star under market conditions)*	**Increase in consumer price** *(relative to price of BEE 5 star)*
1. Insulation					
Increased insulation thickness (mention thickness increase, corresponding increase in costs to manufacturers and consumers)					
improved resistivity of insulation (through addition of additives)					
Increase in density of PU foam					
improved thermal properties of insulation foam					
Vacuum-insulated panels in the model door					
2. Improvement of Door gasket design					
Double door gaskets					
Iimproved door face frame					
gas filled panels					
3. Anti-sweat heater					
Electronic control of hot gas discharge tube embedded around freezer door frame					
Optimal positioning and design of electric anti-sweat heaters of freezer doors					
Electric anti sweat heater sizing					

Variable anti-sweat heating electric heater control					
4. Condenser and Heat exchanger improvements					
Improved heat exchange through use of enhanced fins/tubes of evaporator and condenser					
Increase in area of condenser (mention a % increase in area of condenser and the corresponding increase in energy efficiency and costs to manufacturer and consumer)					
Increase in area of evaporator (mention a % increase in area of condenser and the corresponding increase in energy efficiency and costs to manufacturer and consumer)					
5. Improvements in fan motors					
Use of more efficient fan motors like Brushless DC fan motors					
Use of phase-change materials integrated into heat exchanger to increase effective thermal capacity					
Phase-change materials+ optimization of the compressor on/off cycling					
6. Compressor Improvements (improved compressor efficiency)					
Variable speed compressors/variable capacity compressors					
Linear compressors					
Alternative technologies to reciprocating compressors (mention if any and corresponding costs to manufacturer and consumer)					
7. Expansion Valve (Improved expansion valves)					
Use of fluid control or solenoid valves					
8. Defrost system (High efficiency defrost system and control for no-frost and forced air applications)					
Reduced energy for automatic defrost (the defrost heat can be reduced by either using a smaller heater, reducing the heater on-time, reducing the frequency of defrost, or a combination of these; mention with respect to these)					
Use of adaptive defrost system					
Condenser hot gas defrost system					
9. Optimization of system controls					
Electronic temperature controls					

Air distribution control					
improved electric controls with VCCs					
10. Alternative Refrigeration cycles					
Lorenz Meutner cycle					
Dual loop system					
Two-stage system					
11. Alternative Refrigeration systems					
Stirling cycle,					
thermo-electric refrigeration					
thermo-acoustic					
12. Other Technologies					
Alternative refrigerants					
Change in component location					
(Any other option not mentioned above)					

< This page is intentionally left blank>