SHAKTI
SUSTAINABLE ENERGY
FOUNDATION

The Celestial Earth

Optimal Cooling Pathways: An Implementation Framework for the India Cooling Action Plan

Final Report

Anindya Bhattacharya

July 2020

For Private Circulation Only

Suggested Citation: Bhattacharya, Anindya., Rauniyar, Avishek., Khanna, Yash.,Ghosh, Sankho.,Bhattacharya, Tania, (2020). *Optimal Cooling Pathways: An Implementation Framework for the Indian Cooling Action Plan*. The Celestial Earth. Gurugram, India

Disclaimer

The views/analysis expressed in this report/document do not necessarily reflect the views of Shakti Sustainable Energy Foundation. The Foundation also does not guarantee the accuracy of any data included in this publication nor does it accept any responsibility for the consequences of its use.

Acknowledgement

The Celestial Earth (TCE) would like to take this opportunity to recognize the invaluable contributions of various stakeholders in writing this report. They have supported TCE in reinforcing its modelling capabilities and intelligence and defining strategic next steps for developing the roadmap of successful implementation of the Indian Cooling Action Plan developed and published by the Govt. of India.

TCE expresses its sincere gratitude to Shakti Sustainable Energy Foundation (SSEF) for the project grant. Shakti Sustainable Energy Foundation seeks to facilitate India's transition to a sustainable energy future by aiding the design and implementation of policies in the following areas: clean power, energy efficiency, sustainable urban transport, climate change mitigation and clean energy finance.

The Celestial Earth conveys its thanks to Mr. Chinmaya Kumar Acharya, Mr. Subhashish Dey, Ms. Ritika Jain and all other colleagues for their time and effort in the project.

TCE is indebted to Alliance for Energy Efficient Economy (AEEE) especially to Dr. Satish Kumar and his team for their continuous support in terms of providing key inputs for developing the energy model for cooling and also evaluating the findings and results. TCE is also indebted to Greentech Knowledge Solutions Pvt. Ltd. (GKSP) for providing the key data and information related to national space cooling demand along with other key building architectural information which are used to build the foundation of this study. TCE is grateful to Mr. Sameer Maithel, Director, GKSP and Mr. Prashant Bhanware for their valuable time and effort to provide the required information for this study. TCE team also remains inspired and guided all the time by the group of experts from various institutions like EDS, CSC and TERI working in the sustainable cooling sector in India. Experts' contribution towards identifying the right data and information related to various cooling technologies has greatly strengthened the report.

TCE team remains inspired by the leadership of Dr. Amit Love, Jt. Director, Ozone Cell, MoEFCC, GoI, as the cell remain the apex body of the country in terms of determining the future cooling pathways of India. TCE in indebted to Dr. Love's erudite comments and overall guidance in terms of structuring the scope of work and its implementation.

TCE also expresses its profound thanks and gratitude to Shri Anil Jain, Secretary, Ministry of Coal, GoI for his leadership and inspiration to develop the Indian Cooling Energy Model to develop the pathways of implementing the ICAP in India.

Table of Contents

Acknowledgement 2

Tables 5

Figures 6

Abbreviation 8

Executive Summary 9

1.0 Introduction 12

1.1 Objectives of the study 12

1.2 Scope of work 12

2.0 Literature Review 13

3.0 Approach and Methodology 15

3.1 Methodology 16

3.2 Setting up the model 20

3.2.1 Cooling technology efficiency (efficiency input parameter) 21

3.2.2 Estimating cost of cooling technologies 23

3.2.3 Estimation of refrigerant demand 25

4.0 Space cooling requirement in India 25

4.1 Estimation of built-up area for cooling 26

4.2 Estimation of cooling requirement under various conditions 26

5.0 Implication of Cooling for All in India 31

5.1 Primary energy supply 31

5.2 Final energy consumption 32

5.3 Electricity Requirement for TCR 34

5.4 Overall GHG emissions impact due to cooling 37

5.5 Overall refrigerant demand for TCR 37

6.0 Developing scenarios of ICAP implementation 39

6.1 Contextualization of ICAP for Cooling for All 40

6.2 Setting up the ICAP Implementation Baseline for Space Cooling 41

6.3 Assessment of Baseline 42

6.4 ICAP Implementation scenarios 46

6.4.1 Description of the scenarios 46

6.4.2 Comfort Cooling Scenario ... 47

6.4.3 Sustainable cooling scenario ... 51

6.4.4 Smart Cooling Scenario-26C ... 58

6.4.5 Smart Cooling Scenario-28C ... 64

7.0 Summary and conclusions ... 70

8.0 Recommendations and Plan of Action ... 72

Reference ... 75

Tables

Table 1: Summary table for EE and OE 14
Table 2: Steps to calculate Room AC technology efficiency 22
Table 3: Investment cost estimation of room AC 23
Table 4: Physical parameters of cooling technologies 24
Table 5: Refrigerant charge rate 25
Table 6:Space cooling requirement in India for year 2017 29
Table 7:Basic assumptions for estimating OE 29
Table 8: ICAP Development Matrix 39
Table 9: Assumptions of ICAP Implementation Baseline 42
Table 10: Description of the scenario 46
Table 11: Summary of findings of all cooling scenarios 70
Table 12 Implementation plan of ICAP. 73

Figures

Figure 1: Scope of space cooling assessment ... 13
Figure 2: Comparison of cooling requirement assessment by different studies (Year 2017-18) ... 15
Figure 3: Approach of this study ... 16
Figure 4: Flow of Modelling Assessment ... 17
Figure 5:Steps to estimate the total cooling requirement ... 18
Figure 6:Determining the cooling technology parameters ... 19
Figure 7:MESSAGEix Modelling Framework and Output ... 20
Figure 8:Trend of cooling technology efficiency improvement ... 22
Figure 9:Improvements in EER for different cooling technologies ... 23
Figure 10: Investment cost of cooling technologies ... 24
Figure 11:Important variables used for floor space area estimation ... 26
Figure 12:Variables used for estimating space cooling requirement ... 27
Figure 13:Total space cooling requirement in India ... 28
Figure 14:Space cooling requirement for decent standard of living ... 30
Figure 15::Comparison of primary energy requirement under different cooling requirement ... 31
Figure 16:Comparison of final energy consumption under different cooling requirement scenario ... 32
Figure 17:Comparison of final energy consumption under different cooling requirement scenario ... 33
Figure 18:Comparison of total electricity consumption under different cooling requirement ... 34
Figure 19:Comparison of share of electricity use in residential & commercial sector ... 35
Figure 20: Comparison of share of electricity use by technologies ... 36
Figure 21: CO_2 emissions from space cooling ... 37
Figure 22: Refrigerant demand under different TCR scenarios ... 38
Figure 23: Development process of ICAP implementation scenarios ... 41
Figure 24:Cooling energy demand for BAU ... 42
Figure 25:CO_2 emissions under ICAP baseline ... 43
Figure 26: Cooling capacity addition requirement ... 44
Figure 27: Refrigerant demand for cooling in BAU ... 44
Figure 28: Cooling market size in ICAP Baseline ... 45
Figure 29:Baseline ICAP Indicators in 2037 ... 45
Figure 30: Comparison of total cooling requirement between BAU & CCS ... 47
Figure 31: Change in cooling energy demand under CCS ... 48
Figure 32: GHG Emissions comparison between BAU and CCS ... 48
Figure 33: Refrigerant demand comparison between BAU & CCS ... 49
Figure 34:Cooling Capacity addition in CCS ... 50

Figure 35:Cooling market in CCS scenario 50
Figure 36: ICAP indicators in CCS in 037 51
Figure 37: Reduction of total cooling requirement under Sustainable Cooling Scenario 52
Figure 38: change in cooling energy demand under Sustainable Cooling scenario 53
Figure 39: GHG Emissions comparison of Sustainable Cooling scenario 54
Figure 40:Refrigerant demand comparison of Sustainable Cooling Scenario 55
Figure 42: Cooling capacity addition in SCC 56
Figure 43: Cooling market size under SCS 57
Figure 44: ICAP indicators in CCS in 2037 57
Figure 45: Comparison of cooling energy demand between BAU & STS:26C 59
Figure 45: GHG Emissions comparison between BAU and STS:26C 60
Figure 46: Refrigerant demand comparison between BAU & STS:26C 61
Figure 48: Cooling capacity addition under STS:26C 62
Figure 49: Cooling market size in STS:26C 63
Figure 50:ICAP indicators under STS:26C in 2037 63
Figure 51:Comparison of total cooling requirement between BAU & STS:28C 64
Figure 52: Comparison of cooling energy demand between BAU & STS:28C 65
Figure 53: GHG Emissions comparison between BAU and STS:28C 66
Figure 54: Refrigerant demand comparison between BAU & STS:28C 67
Figure 55:Cooling capacity addition in STS:28C 68
Figure 56: Cooling market size in STS:28C Scenario 69
Figure 56:ICAP indicators under STS:28C in 2037 69

Abbreviation

AC	Air Conditioners
ATC	Adaptive Thermal Control
BAU	Business-as-Usual
CCS	Comfort Cooling Scenario
CEPT	Centre for Environment Planning and Technology
CFC	Chlorofluorocarbons
COP	Coefficient of Performance
$C0_2$	Carbon di-oxide
DCS	District Cooling System
DLS	Decent Living Standard
EE	Embodied Energy
EER	Energy Efficiency Ratio
ENS	Eco-Niwas Sahmita
FEC	Final Energy Consumption
GHG	Greenhouse Gas
GOI	Government of India
GJ	Giga Joule
GKSPL	Greentech Knowledge Solutions Pvt Ltd.
HCFC	Hydro-Chlorofluorocarbons
HVAC	Heating ventilation and air conditioning
ICAP	India Cooling Action Plan
IEA	Internal Energy Agency
IESS	India Energy Security Scenarios
IIASA	International Institute of Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LCE	Life Cycle Energy
NDC	Nationally Determined Contributions
NSSO	National Sample Survey Office
OE	Operational Energy
O&M	Operation and Maintenance
RAC	Refrigeration and air conditioning
RETV	Residential Envelope Transmittance Value
RE	Renewable Energy
SDG	Sustainable Development Goals
SCS	Sustainable Cooling Scenario
STS	Smart Cooling Scenario
TCR	Total Cooling Requirement
TCD	Total Cooling Demand
TDCD	Total Desired Cooing Demand
TERI	The Energy and Resource Institute
TR	Tonne Rate
VRF	Variable Refrigerant Flow

Executive Summary

The advent of global warming and climate change due to anthropologic activities has posed a major challenge on sustainable living conditions, specifically in the tropical countries. In that context, sustainable living refers to thermal comfort which accounts for a combination of factors such as comfortable temperature and humidity at the ambient. With the ever-increasing demand of active cooling systems such as air conditioners and chillers, there has been a greater challenge of ozone depletion due to the emissions of Chlorofluorocarbons (CFC) and Hydro-Chlorofluorocarbons (HCFC). Pertaining to the direct solution of utilization of active cooling systems could trigger a vicious cycle of increasing cooling demand, energy consumption and climate change. With the objective to mitigate the negative impacts of increasing cooling demand, the Ministry of Environment, Forest and Climate Change, Government of India (GOI), launched the India Cooling Action Plan (ICAP) in 2019. It provides policy guidance to help India to strategically develop long term plan to strike a balance between achieving the targets set under the Montreal Protocol, the Sustainable Development Goals (SDG), specifically SDG 3, 7, 9, 10 and 11 and also Nationally Determined Contributions (NDC) while achieving the overarching goals of Cooling for All.

Implementation of ICAP in India is a challenging task indeed. Given the goals of providing cooling and thermal comfort to more than a billion pollution is a daunting task. It is estimated that during 2017-18, only around 30% of total cooling requirement or demand is met with an estimated energy use of 120 Twh with a per capita cooling energy consumption is only around 100 unit per annum including the commercial space cooling. Global average of per capita cooling energy is around 1000 unit per annum. As a matter of fact, India is far behind the global average in terms of achieving the cooling demand for thermal comfort. However, ICAP aims to provide cooling comfort all across the country with the focus of sustainable development covering aspects of economics, environmental and socials developmental issues. The basic targets of the ICAP are as follows:

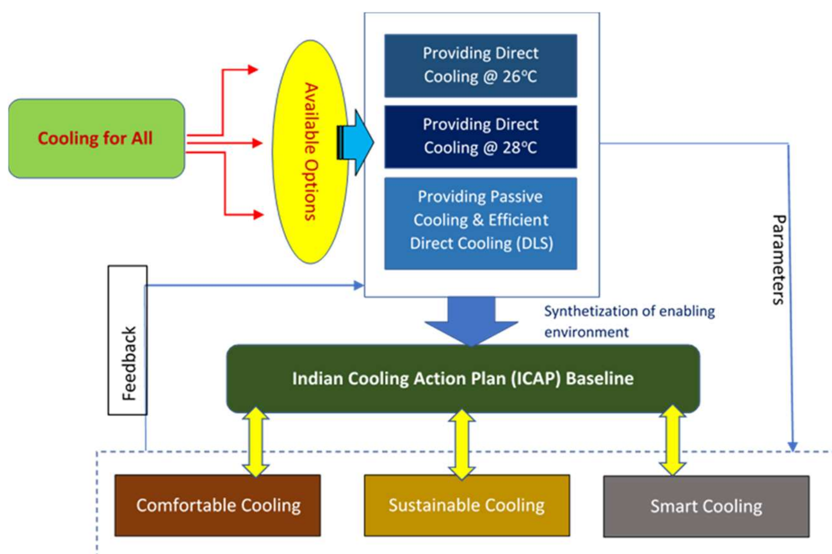
- ✓ Reduction of cooling demand up to 25% by year 2037-38
- ✓ Reduction of refrigerant demand up to 30% by year 2037-38
- ✓ Reduction of cooling energy requirements up to 40% by year 2037-38

In line with the goals and objectives of the ICAP on the tri level fronts of space cooling demand, refrigerant demand and the related energy demand and corresponding emissions, this study conducts a multi-scenario analysis to define the optimum technological pathways for Heating Ventilation and Air-Conditioning (HVAC) within the residential and the commercial sectors. The energy systems optimization was built using MESSAGEix, which is a one of the most advanced Integrated Assessment Modelling tool, developed by the International Institute of Applied Systems Analysis (IIASA). Henceforth the results of this study show a comprehensive energy balance, mapped from primary energy supply to the end-use energy demand, with special emphasis and constraints on the trends for cooling demand and technologies. In addition, various factors such as cooling technology efficiency, total space, the investment and operation and maintenance (O&M) cost of various cooling technologies have been used as pivotal parameters for the modelling assessment. However, the objectives of the study are as follows:

- ✓ Achieving the least cost pathway to achieve the ICAP targets of India and corresponding technology mix.

- ✓ Identifying alternative technology mix scenarios for cooling for a long-term planning and its impacts on energy supply mix, investments and emissions.
- ✓ Quantifying the optimal demand of refrigerants in the country and its alternative options.

While investigating the ICAP implementation in India, the study observes that there is an urgent requirement of a fixed baseline of cooling pathway in India which can be further used as the benchmark for other cooling scenarios. Considering the factors of technological development, scope of efficiency improvement, increasing cooling demand including population and economic development (in terms of rate of urbanization), the study set the baseline with 26°C set point temperature for cooling with an average efficiency improvement growth rate of 4% per annum between 2017 and 2037. It also considers to provide cooling to all possible corners of the country including urban and rural areas which is around 16 billion square meter areas of residential and commercial areas in 2017. It is estimated that the total cooling space could reach up to 50 billion square meters by 2037. It is estimated that during the period of ICAP first target years of 2037-38 the total electrical energy consumption of India for cooling would be 30% of total electricity consumed which is around 950 Twh. It is also estimated that to meet the cooling requirement of around 25EJ around 450 Million TR of total installed cooling capacity is required in the country which is closely around 6 times of current installed capacity in the country (aprox.70~80MTR). It is observed that cooling efficiency is an important parameter to keep the growth the cooling capacity addition under control. It is estimated that for every 1% drop in annual growth rate of efficiency improvement can cause 17% increase in cooling energy demand in India. For example, if the growth rate of annual RAC efficiency improvement drops from 4.5% to 3.5%, electricity consumption for RAC in 2037 increases from 500 Twh to 633 Twh. Therefore, cooling technology efficiency plays a pivotal role in ICAP implementation in India. Nevertheless, it is observed that increasing demand for cooling is outpacing the benefit of efficiency improvement in terms of curbing the demand growth for cooling energy and refrigerant. In this study the ICAP baseline is developed considering the facts and information adopted from the ICAP Report and other technical details from the three different options of achieving the Cooling for All goals. Finally, the ICAP implementation scenarios are built on technical parametric values directly adopted from the cooling options and ICAP baseline. Scenario building process iterated through the feedbacking and validation process of results and findings as shown in the figure below:



Major findings

ICAP space cooling baseline of India warrants for massive energy demand, emissions load and refrigerant demand. It also demands for significant amount of investment as well. However, the baseline cooling will still keep Indian per capita cooling energy demand (570 Kwh) by 2037 far below the world average of more than 1000 Kwh/ person.

Sustainable Cooling scenario (SCS) is found out to be the best possible solution for India not only to achieve the ICAP targets but also to get additional benefits of GHG emissions reduction and sustainable development for all. It is observed that only active strategies for cooling efficiency and energy consumption reduction is not sufficient to achieve the ICAP targets. Passive strategies are essential to implement indeed. Thus, SCS is a representation of the paradigm shift in building construction material use, designing and architype which can best fit India's climatic conditions and corresponding thermal comfort. Following the study of Mastrucci & Rao, 2019 the decent living standard for Indian people across varied climatic zones have been estimated based on cooling/heating energy required for sustainable living. Ranging between 40~50 Kwh/m^2 is estimated to be the cooling demand across the country which is around 40% lower than the national average of residential and commercial space cooling requirement. It is observed under the Sustainable Cooling scenario the cooling requirement reduces more than 60% by 2037 compared to Baseline and subsequently its cooling energy and refrigerant demands are also lower than Baseline to the level of 50~60%. This scenario clearly helps India to achieve its ICAP targets. However, it also warrants for policy level changes in terms of stricter implementation of ECBC, GRIHA, LEED etc. to improve the building energy efficiency and reduction in operational energy requirement. As a successful implementation strategy ICAP can thus adopt a mix pathway combining adoption of advance cooling technologies like DSC along with implementation of passive cooling techniques.

1.0 Introduction

The very first India Cooling Action Plan (ICAP) prepared by Ministry of Environment, Forest and Climate Change, GoI in 2019 determines the outlay of the upcoming cooling vision of India. With increasing cooling demand, the need of the hour is to understand the cooling requirement of the country and the corresponding energy need. While India is talking about the universal access to cooling facilities for comfortable living, future cooling requirement is an important factor for achieving the target. Moreover, sustainability and climate change being one of the main focuses of the country's Cooling Action Plan, it also important to measure the potential demand of refrigerants which are the sources of ODSs and GHGs. ICAP is a seminal document in this domain in India which provides the fundamental directions of the country's cooling future which is obviously directed towards sustainable pathway. The basic targets of the ICAP are as follows:

- ✓ Reduction of cooling demand up to 25% by year 2037-38
- ✓ Reduction of refrigerant demand up to 30% by year 2037-38
- ✓ Reduction of cooling energy requirements up to 40% by year 2037-38

With increasing cooling demand, the energy demand is going to increase with a potential increase in refrigerants (HCFs, others) requirement which needs to be addressed sustainably. Determining the best sustainable and low carbon pathway with optimal mix of efficient technologies and best approaches is going to be a key to achieving the proposed targets of ICAP i.e. reducing cooling demand with most optimal emission reductions.

1.1 Objectives of the study

The goal of this study is to assess the ICAP and its set targets in the context of an optimally determined integrated energy demand and supply framework which can develop an implementable road map of ICAP over the next three decades in the country (till 2047-48). The outcomes that will be rendered are as follows:

- ✓ Achieving the least cost pathway to achieve the ICAP targets of India and corresponding technology mix.
- ✓ Identifying alternative technology mix scenarios for cooling for a long-term planning and its impacts on energy supply mix, investments and emissions.
- ✓ Quantifying the optimal demand of refrigerants in the country and its alternative options.

1.2 Scope of work

Given the multidimensionality of the sectors related to national cooling requirement for comfortable living which encompasses sectors like residential and commercial spaces, transportation and vehicle movement and also the industrial use of cooling substances, the current study focuses only on space cooling issues. The space cooling comprises of 60% of total country's cooling energy demand and the expected total number of AC units could reach up to 170 million units by 2027 compared to 35 million units in 2017 (AEEE, 2018)1. While space cooling is the single most important sector for the country to be analysed, the study delved into the sector with an approach of dividing the space cooling into two stages:

- ✓ **Stage-1**: Dividing the space cooling requirement based on type occupancy: Residential & Commercial

- ✓ **Stage-2**: Dividing each type of occupancy into three categories of refrigerant types: Refrigerant based, Non-refrigerant based and Not-in-kind.

Figure 1 shows the categories of cooling technologies covered in this study.

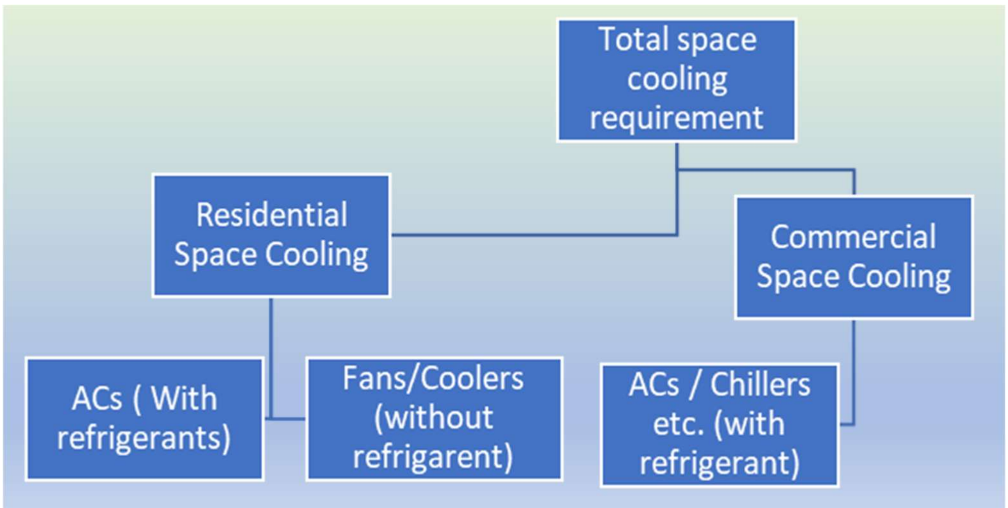


Figure 1: Scope of space cooling assessment

2.0 Literature Review

In India, space cooling is now a very debated area of analysis. The biggest deterrent for authentic estimation of the cooling requirement which are subject to the level of individual human comfort, the area of space to be cooled and the location of the space for cooling are hinged on reliable data and information. There is clear lack of unified single source data for estimation of space cooling requirement and subsequent energy demand. Nevertheless, there are certain studies and data sources available with referred and used to derive the key parameter values for the study. Around 300 million houses are required in the country under the housing for all scheme where currently (2018) the stock is around 230 million. There is an additional requirement of 60 million (20 million: Urban and 40 million rural) new houses. Around 40% new housing are required to be low cost affordable.

[1] Source: https://www.thehindubusinessline.com/economy/indias-cooling-energy-consumption-to-more-than-double-by-2027/article25135186.ece

There are several investigations pertaining to life cycle energy (LCE) of buildings. While a few studies partly focus on aspects of embodied energy in buildings, majority of the studies focus on operational energy, its attributes and measures of conservation. Table 1 summarizes the embodied energy and operational energy in buildings:

Table 1: Summary table for EE and OE

Reference	Building Characteristics	Embodied Energy ($GJ/m^2/Y$)	Operational Energy ($GJ/m^2/Y$)
(T. Ramesh 2010)	Residential buildings	0.025- 0.514	0.04- 1.19
	Office buildings	0.118- 0.50	0.784- 2.92
(K.I. Praseeda 2015)	Urban dwellings	1.01- 10.51	0.01-0.22
(B. V. Venkatarama Reddy 2017)	Rural dwellings	0.02-2.8	0.006- 0.053
(Rao 2018)	Single Family House (Rural)	0.079	0.098- 0.224
	Multi Family House (Urban)	0.08	0.092- 0.18
GKSPL Study	Residential buildings- Urban	-	0.57*

Note:

**Derived from RETV estimate which gives a quantitative measure of heat gains through the building envelope (excluding roof). Embodied energy is estimated using the energy consumed to produce the building material and used to construct the building. Operational energy is estimated in terms of energy use to make the space livable which includes cooling, heating and lighting energy together. Here only cooling energy part is considered.*

Literature review reveals a wide range of values for EE (0.02- 10.51 GJ/m2) and OE (0.006- 1.18GJ/m2) in residential buildings in India. While in one of the studies, GKSPL and CEPT University estimated the cooling requirement in terms of RETV (Residential Envelope Transmittance Value) is around 0.57 GJ/m2/y. This difference in EE and OE attributed to; variations in type of materials and building envelope. A few studies highlight that wood-based constructions and the use of soil based low energy materials lead to significant reduction in embodied energy. Also, some studies advocate optimum use of materials/resources to conserving embodied energy. With regard to operational energy assessment, there is no clear consensus regarding different energy components to be included. Some studies include energy consumption for heating, cooling, ventilation and lighting while others include energy consumption for hot water generation, household activities, water supply etc. in addition to lighting and air conditioning energy. Figure 2 below shows the comparison of different assessments of cooling requirement in India which are varying to the scale of 5X.

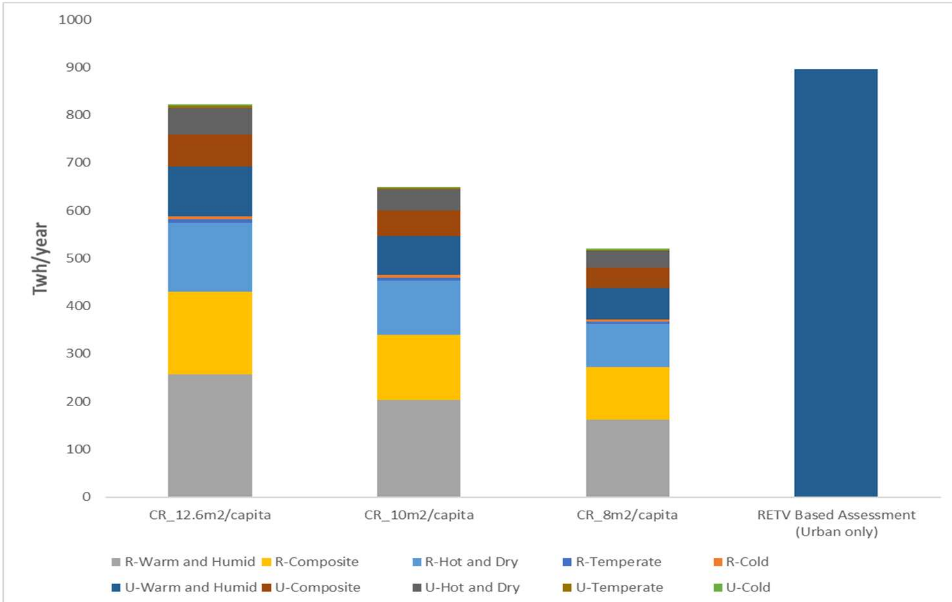


Figure 2: Comparison of cooling requirement assessment by different studies (Year 2017-18)

Nevertheless, the present study has not indulged into estimating the cooling requirement for thermal comfort of the country (with an estimated total floor space area to be cooled) rather focused on estimating the optimal allocation of cooling technologies to achieve the cooling requirement under different comfort levels (two different set point temperatures). In this context the study has referred to IETP 2020 Study as well as Decent Living Standard study of IIASA to obtain the Total Cooling Requirement of India.

3.0 Approach and Methodology

Considering the ICAP requirement and its successful implementation over the period of time (by 2037-38) , the study is focusing on assessing three important variables: **Total Cooling Requirement**: It is the total cooling energy required to make the total floor space area in the country occupied for residential or commercial purposes thermally comfortable with an indoor set point temperature.

A. **Total Cooling Demand**: It is the estimate of meeting the cooling requirement for thermal comfort for the total floor space area under certain set point temperature with the available cooling equipment and adjusted to *unmet cooling* [2]requirement occurred due to non-refrigerant cooling equipment like fans and evaporative coolers.
B. **Total Desired Cooling Demand**: It is the estimate of cooling demand adjusted to intervention of smart building technologies and envelope and passive cooling technologies to provide the thermal comfort in the given floor scape area under a certain set point temperature.

Figure 3 below shows the overall approach of estimating the TDCD in the context of TCR and TCD. TDCD is derived based on certain policy decisions in terms of use of highly efficient cooling

[2] Unmet cooling occurred due to use of non-refrigerant based cooling technologies like fan / air coolers to cool certain floor space area in stead of ACs. Due to

technologies, various smart cooling technologies and also various passive cooling technologies etc. Fundamentally the approach is to identify an optimal cooling pathway for India which could help implementing the ICAP target as well as can provide thermal comfort to all with certain cooling requirement.

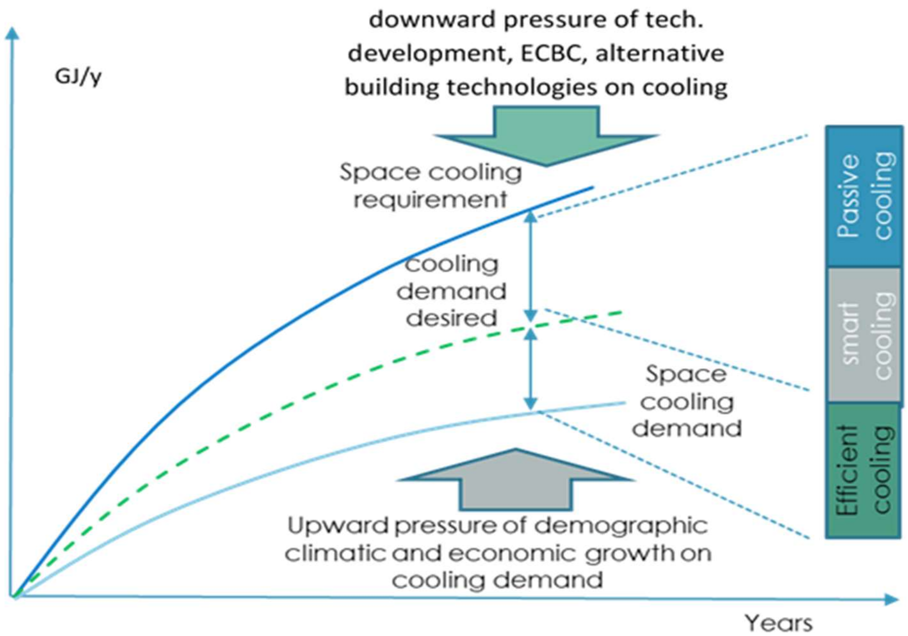


Figure 3: Approach of this study

3.1 Methodology

The study is using MESSAGEix one of the most advanced energy system optimization modelling platforms of the world, to conduct this assessment. MESSAGEix is developed by the International Institute for Applied Systems Analysis (IIASA) and is used by several international organizations like IPCC, IEA etc. The international publications that use this model are World Energy Outlook, Global Energy Assessment etc. Recently NITI Aayog, Govt. of India has also adopted this system modelling framework to develop India Energy System Model. This model optimizes the supply system based on the given set of energy demand for each type of consumers in the system. Model optimizes the energy supply mix to meet the set energy demand targets with the constraints of emissions, cost, technology availability etc. Demand sectors are assessed based on their useful energy demand pattern, which is otherwise the final energy adjusted with the equipment efficiency at each end-use level. Final energy is estimated based on the transmission and distribution efficiency of the system which are applied at the secondary energy level. Secondary energy is mainly the electrical energy produced through conversion of the primary energy sources like coal, oil, natural gas etc. Cooling technologies like ACs, chillers, VRFs etc. including fans and air coolers are all modelled in the energy system to provide the required cooling energy demand given to the system. Cooling requirement of residential and commercial sectors are separately given to the model as required cooling energy demand for thermal comfort for all. Through the process of using electrical energy to achieve the cooling demand the energy system identifies the least cost mix of technology use to achieve the required cooling demand.

MESSAGEix uses sets of mathematical equations for strategic planning and is a system (energy system) optimization tool. Using this model, the cooling demand from different sectors can be mapped to several cooling technologies. Each cooling technology has its own characteristics of up-taking a cooling demand with per-unit utilization of resources like energy, refrigerant and water. Those technologies are already mapped into the systems model, the model can be simulated to see the resource utilization by the cooling demand and accordingly optimize it based on several parameters to give minimum cost for the mix as depicted in the Figure 4 below:

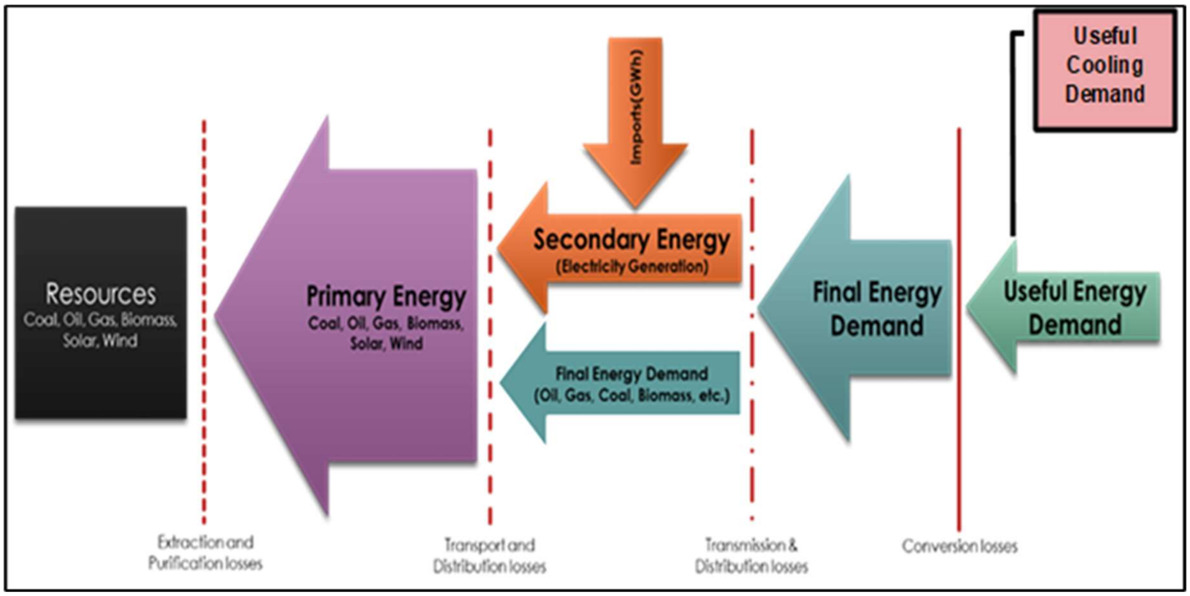


Figure 4: Flow of Modelling Assessment

Step-1: Estimating cooling requirement

This is the step required to first estimate the cooling energy demand for the entire energy system of the country. Based on IETP 2020 study and other necessary inputs 2017 base year total cooling requirement is estimated (see the next section for detail calculation). Cooling requirement is the equivalent amount of heat removal from the total space area to be cooled measured in ton of refrigeration (else in Gigajoule). Finally, projection of the cooling requirement until 2037 is conducted based on the information obtained from IESS 2047 Energy Calculator of NITI Aayog, Govt. of India. Figure 5 below shows the steps followed to derive the total cooling requirement for the model.

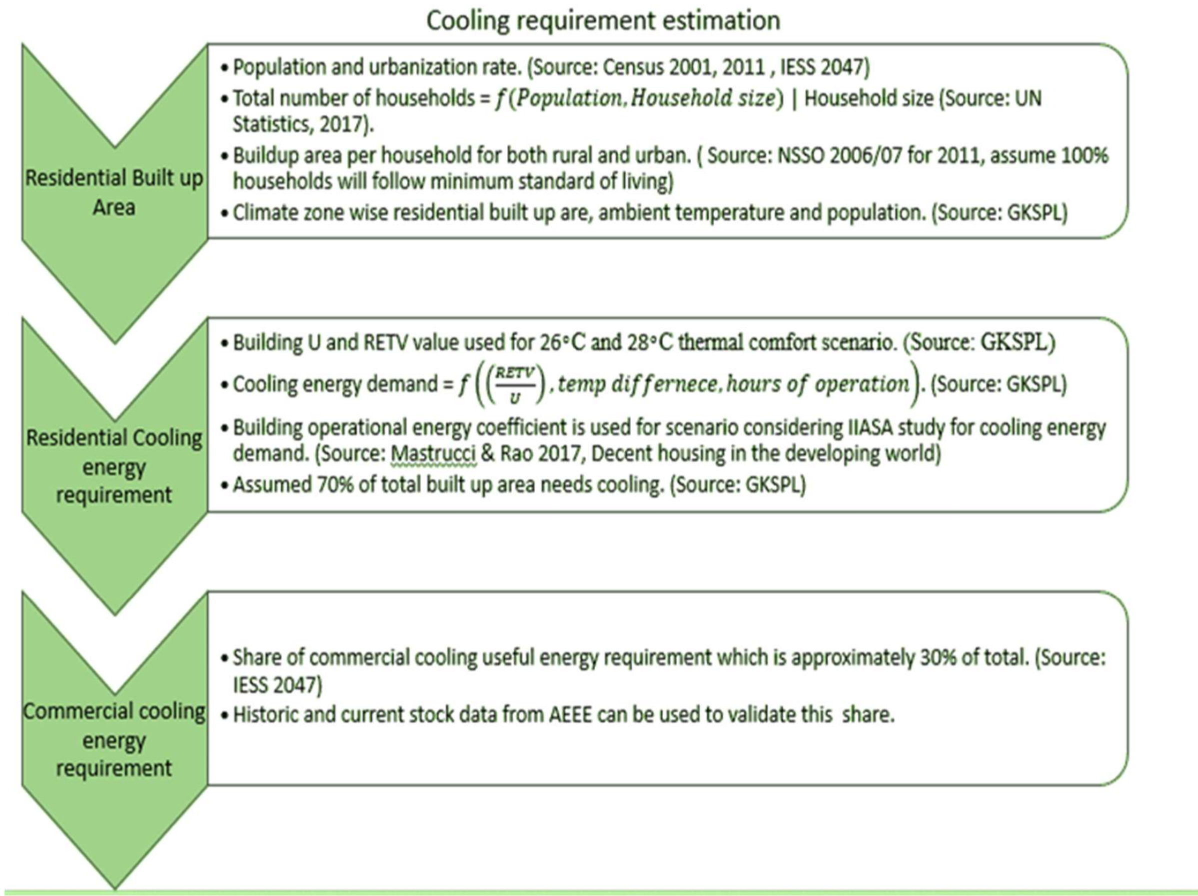


Figure 5:Steps to estimate the total cooling requirement

Step-2: Deriving cooling energy demand

In this stage, model determines the energy required to achieve the given cooling requirement. Cooling energy is mostly the electrical energy that is used to run the cooling equipment to achieve the cooling requirement. In this step the cooling technology wise different parameters are estimated based on the inputs from existing literatures. The cooling technologies like ACs, chillers, VRFs, Fans and Air Coolers are having different parametric values in terms of their efficiency of cooling. Cost is also an important parameter for each technology in the model which is also estimated in terms of providing unit cooling utility i.e INR/GJ of cooling. Figure 6 below shows the activities performed in this step-2.

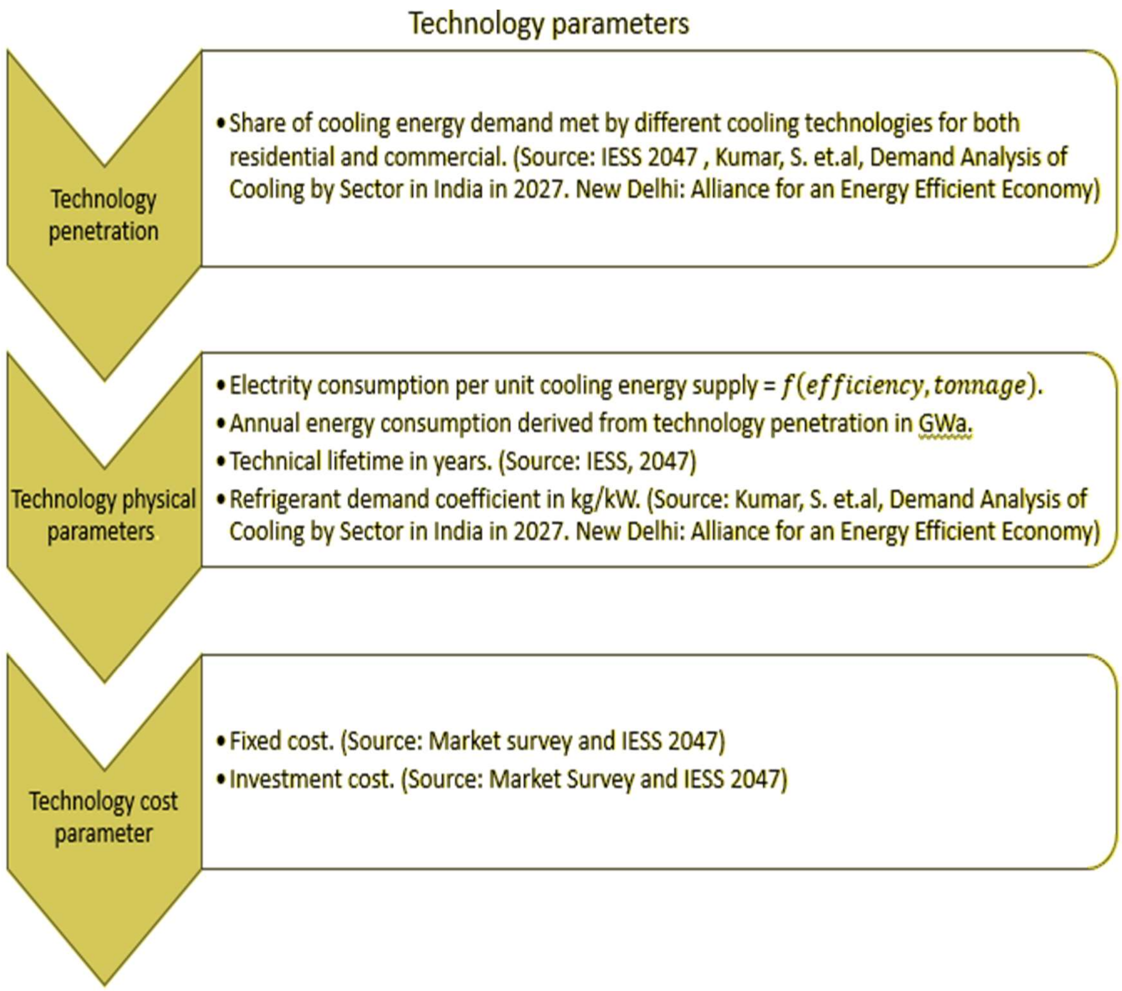


Figure 6:Determining the cooling technology parameters

Step-3: Optimizing energy systems with cooling requirement

With the input of overall cooling requirement (residential and commercial) over the period of time along with cooling technology mapping in the overall energy systems of the country, the MESSAGEix model optimizes the cooling energy demand (in terms of electricity) required by each type of cooling equipment (like ACs, chillers, VRF, Fans, Air Coolers etc.) to provide the required level of cooling requirement (Gigajoule) in a particular time period (year) in a least cost manner (INR). While determining the optimal mix of cooling energy requirement, model also considers several binding constraints given to the system like certain growth rate of technology penetration in the market (viz. AC market penetration rate of around 10% per annum average, Chiller market penetration rate of around 8% p.a etc.). Besides, the model also estimates the corresponding refrigerant demand in the system based on the refrigerant coefficient determined for each of the cooling technologies separately. Figure 7 below shows the model core mapping and the corresponding outputs for ease of understanding:

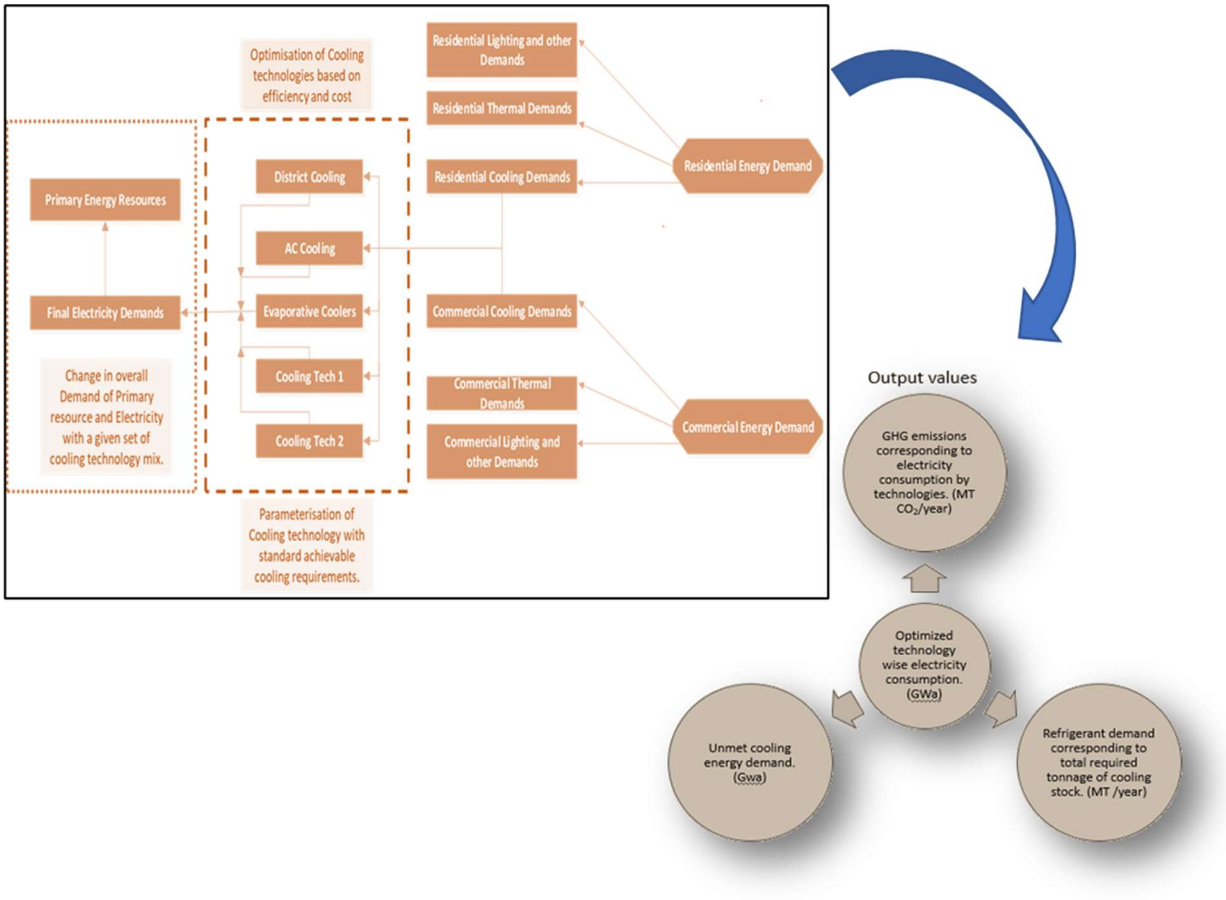


Figure 7:MESSAGEix Modelling Framework and Output

3.2 Setting up the model

The study primarily focuses on estimating the optimal mix of cooling technologies (with and without refrigerants) in India in order to meet the cooling requirement for all. While in the India Cooling Action Plan (ICAP) the focus was mainly on estimating the cooling technology landscape and corresponding cooling energy demand primarily projected in the basis of cooling equipment demand such as ACs, chillers, fans etc. in the market, the current study focuses on assessing the technology landscape in the context of "cooling for all" premise.

The term coined in this study "Total Cooling Requirement" or TCR is defined as the total space cooling requirement in the urban and rural areas put together in India to provide cooling (thermal) comfort. It is assumed in this study, that better the building envelope better the thermal performance in terms of lowering the heat gain inside the building. Lower the heat gain, lower the need of heat removal from inside and corresponding cooling energy requirement. In this study, TCR of India is not directly estimated rather adopted from another study conducted during the same time titled as "Developing cost-effective and low-carbon options to meet India's space cooling demand in urban residential buildings through 2050.(IETP Report 2020)" by Greentech Knowledge Solutions Pvt. Ltd. and others (2020). Using the bottom-up granular information at district level and with diversity of climatic zones for building types and construction material, the study estimated the TCR both for urban and rural India together. There are two thermal comfort set point temperatures 26C and 28C which provides a good amount of 2C comfort range which could provide a proxy range of adaptive comfort and human behavioral influences. More precisely, using the Residential Envelope Transmittance Value (RETV)3, building envelope thermal properties and U-value of roofs the study finally came up with the TCR. Couple of other major variables used in the estimation are population, household size and most importantly the dwelling area per household. Interestingly the study used the trend of change in dwelling area coverage per household in India using a reference of IEA study stating the global position of per capital residential area. IETP report considers the growth of per capita residential floor space is around 3% per annum between 2020 and 2050 and it increases from 10m2 / person in 2017 to 24.2m2/person by 2050.

Using this information of TCR of India between 2017 and 2050 the current study moves a step further to estimate the cooling energy demand to satisfy the TCR of India until 2050.In the process of doing so, all the major space cooling technologies (including non-refrigerant based technologies) were considered and classified into residential and commercial categories. In this context TCE is also split between residential and commercial using the parametric reference from India Energy Security Pathway Calculator 2015 and 2017 (upcoming) of NITI Aayog, Govt. of India.

Since the objective of this study is to estimate the optimal mix of cooling technology use to meet the TCR in the country thus it is essential to individually assess the cooling efficiency of each of the technologies. The study has used an energy systems optimization model with an objective to identify the least cost cooling technology mix for each of the year to meet the corresponding TCR. Here is the TCR measured in terms of Gigajoule. Thus, the efficiency of each cooling technologies like ACs, Chillers, VRF etc. has been measured in terms of unit of electricity consumed to remove certain amount of heat in GJ (unit: Kwh/GJ).

In the energy systems model, the technology mix is selected by the model endogenously based on two major parameters:

i) Technology efficiency in terms of delivering particular energy services and
ii) Levelized cost of the technology to provide the energy service over the life span.

3.2.1 Cooling technology efficiency (efficiency input parameter)

Here in this study, cooling technology efficiency is measured in terms of electricity consumed to remove 1 GJ of space heat. It is important to understand when the set point temperature is kept, cooling technology needs to remove more amount of heat (higher GJ amount) compared to high set point temperature. It is also assumed that for every degree centigrade change in set point temperature cooling efficiency changes by 4% (TERI, 2018). Therefore, in this study two set of efficiencies for each of the cooling technologies have been used. The cooling technology efficiency parameter perform the duty of estimating

[3] Residential envelope transmittance value (RETV) (W/m2) is the net heat gain rate (over the cooling period) through the building envelope (excluding roof) of the dwelling units divided by the area of the building envelope (excluding roof) of the dwelling units).

the electrical input energy required (in terms of Gwh) to supply the cooling demand of 1 GJ equivalent. Table 2 below shows the calculation for assessing the efficiency of a 1.5 TR air conditioning unit consuming 1.5 KW of energy:

Table 2: Steps to calculate Room AC technology efficiency

Technology: Room AC	Rating	Unit
Cooling	5275	Watt
Power	1580	Watt
Input Efficiency Parameter	0.01899	GJ/h
	8.3E-05	GWh/GJ
	9.4E-09	GWy/GJ

Note: GWy: Gigawatt year (i.e 8760 Gwh)

However, for the long-term assessment of the cooling technology efficiency, the study has referred to the projected EER (else COP) values of various cooling technologies mentioned in the report titled "Demand Analysis for Cooling by Sector in India in 2027" (AEEE, 2018). Based on the projected EER values the input efficiency parameters were further calculated for different cooling technologies as shown in the Figure 8 below.

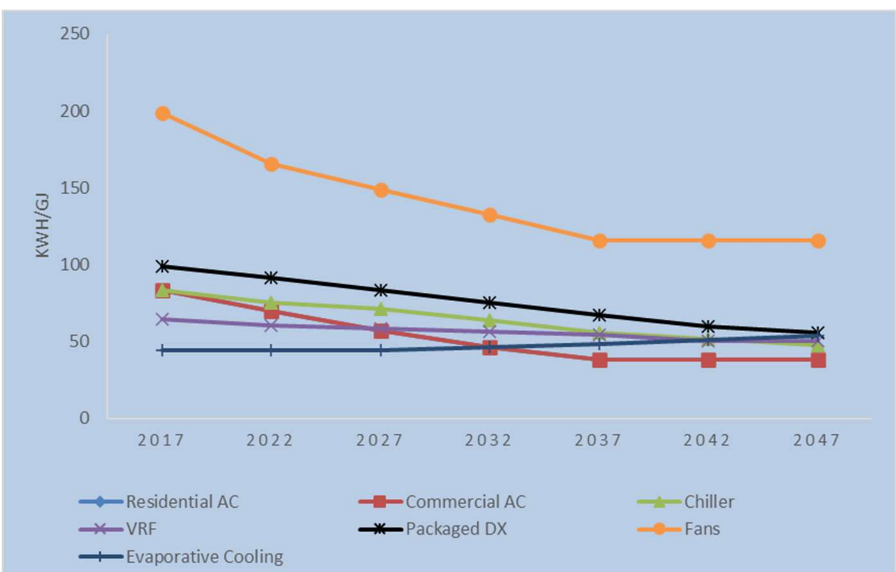


Figure 8:Trend of cooling technology efficiency improvement

It is observed that the Room AC efficiency is expected to increase 4% per annum basis until 2037 compared to 2% each for chiller and Packaged DX technologies. VRF is envisaged to be relatively more efficient. Calculation of input efficiency parameters for model for other technologies are given in the Annex at the end of the report. Figure 9 shows the corresponding EER improvement of different cooling technologies considered in the study.

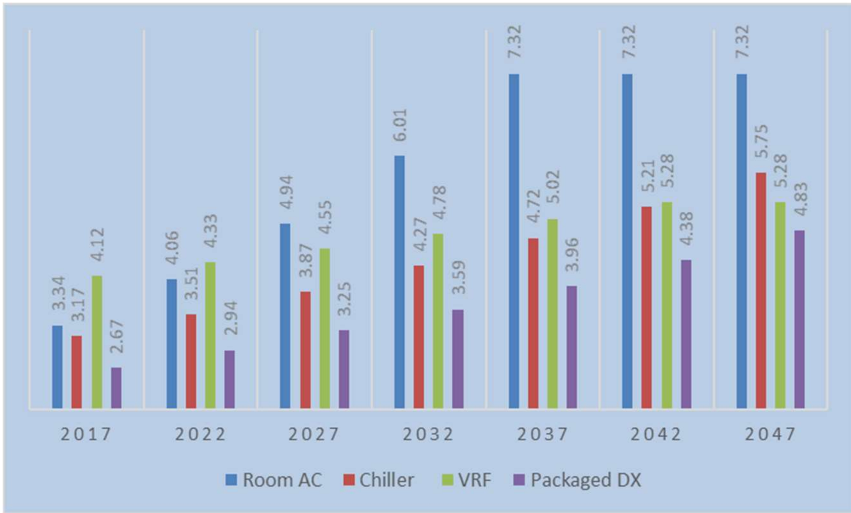


Figure 9:Improvements in EER for different cooling technologies

3.2.2 Estimating cost of cooling technologies

Cost of cooling technologies are estimated based on energy term of each of the technologies rather than unit price of the equipment in the market. The main reason of doing so is to allow the model to select the technology in terms of its cost of operation to deliver the required cooling by removal of heat. Therefore, coolers are appeared to be more expensive than room AC in terms of cost per unit of heat removal.

Table 3 below shows the cost calculation of the room AC cooling technology for the year 2017 considered in the baseline assessment. (See Annex for other technologies)

Table 3: Investment cost estimation of room AC

Technology: Room AC	Unit	Value
Rated Power	KW	1.5
Unit Cooling Capacity	TR	1.5
Hours of Operation /Year	Hours	1000
Energy Consumption /AC/Year	GWy/AC	2.05E-07
No. of ACs/GWy	No.	4,866,667
Unit Cost of AC	INR	30,000
Investment Cost	Billion INR/GWy	146

Figure 10 below shows the comparison of cooling technology costs in terms their unit of energy consumption to deliver the required cooling.

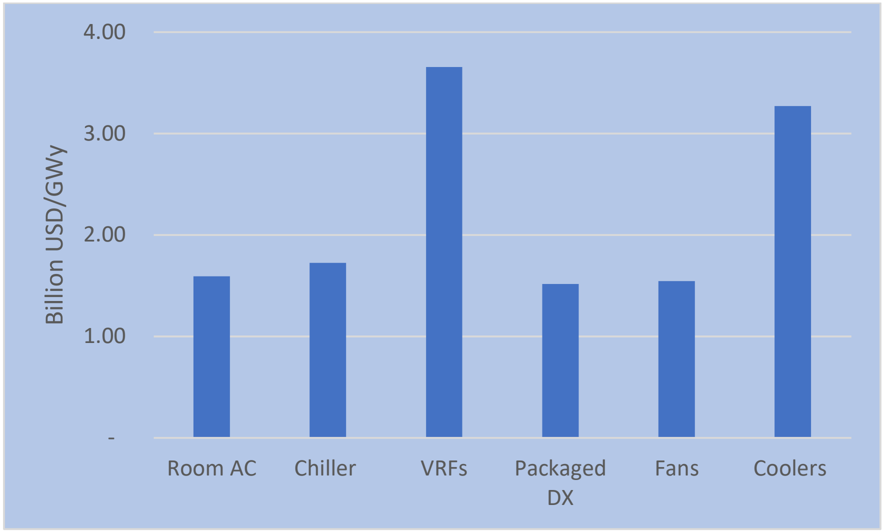


Figure 10: Investment cost of cooling technologies

Table 4 below summarizes the important technology input parameters for the model use.

Table 4: Physical parameters of cooling technologies

Technology	Life Span	Power rating (Watt/TR)	Unit capacity (TR)	Operating hours	Cost (INR /TR)
Room AC	10	1550	1.5	1500	30000
Chiller	20	1050	500	2500	30000
VRF	15	810	20	2500	60000
Packaged DX	15	1250	20	2500	50000
Fans	10	60		1200	1000/unit
Air cooler	5	250		1000	7000/unit

Note:

Room ACs: It is assumed that the majority of the ACs running in India (residential & commercial) are of 3 star rating in 2017-18. Average electricity consumption is 1.56 KW for 1.5 TR split capacity which consumes around 1.6 KW/h. Hours of operation are taken average here considering longer time running for commercial use of around 12 hours/day. Residential running hours of ACs are 8 hours / day for 5 months.

Chillers: Type of chillers considered here is water cooled screw type. The average capacity of the cooler is considered to be 500TR which is operational for 10 hours/day for 10 months in a year. The life span of the commercial chillers is considered to be 20 years minimum. Investment is very high for chiller which is around Rs.60,000/TR (Total cost could be between 2~3 Cr.). Power rating is adopted from AEEE Report on "Demand Analysis for Cooling by Sector in India in 2027" Table 2.4 Page-31.

VRF: Type of VRFs considered here are fitted with 42 KW of outdoor unit attached to 5.3 KW (1.5 TR) of 12 indoor cooling units. Estimated cooling capacity of 1 TR needs around 700~800 watts (http://www.ijste.org/articles/IJSTEV1I10045.pdf , Table 3.9). Power rating is adopted from AEEE Report on "Demand Analysis for Cooling by Sector in India in 2027" Table 2.6 Page-34.

Packaged DX: Power rating is adopted from AEEE Report on "Demand Analysis for Cooling by Sector in India in 2027" Table 2.8 Page-36. The minimum capacity of the unit is considered to be 20 TR.

3.2.3 Estimation of refrigerant demand

Estimation of refrigerant demand is critical and it depends on multiple factors of the operation and maintenance of the cooling equipment. It is estimated that the average rate of refrigerant charge ranges between 0.21~0.29 kg/KWc depending upon the type of cooling technologies (Kumar.S et.al., 2018) which equivalent to 0.73~1.02 Kg / TR unit. It is also assumed that there is a leakage of gas every year at the rate of 2-10% depending upon the technology and refrigerant type. Table 5 below shows the rate of charge for each technology used in this study at unit capacity of 1 TR (3.52 $KW_{thermal}$).

Table 5: Refrigerant charge rate

Technology	Value (Kg/ $KW_{thermal}$	Value (Kg/GJ)
Air conditioner	0.21	0.013
Chillers	0.29	0.011
VRF	0.23	0.011
Packaged DX	0.26	0.008

Source: Author estimated using information from AEEE, 2018

4.0 Space cooling requirement in India

In this study, the total space cooling requirement (TCR) is considered to be the target of achievement by the whole energy system of the country with possible options of energy supply mix. TCR is classified into two categories of cooling requirement in the system: Residential cooling and Commercial cooling. Using the residential and commercial cooling demand share in 2017 (IESS 2047 Ver. 2.0) the TCR is split into two components with 70:30 ratio.

In the IETP Study 2020, the space cooling requirement of India covering both rural and urban areas are considered for two different set point temperatures like 26 and 28 ^{o}C. The estimation of space cooling requirement is hinged on two main variables: i) residential built-up area and ii) cooling requirement for estimate built-up area.

4.1 Estimation of built-up area for cooling

Space built up area is estimated using projection of population and number of households in the country. Following the NSSO 2008 survey data on state-wide average built up area per household it is estimated that the residential floor space area could reach up to 50 billion square meter by 2050 from 16 billion square meter in 2017. It is envisaged that due to implementation of various national housing policies including Housing for All and Affordable Housing, the residential floor scape demand can increase by 4% per annum (IESS 2047). IETP study also benchmarked the residential space requirement in India in the global context of economic and social development. It is observed that by 2050 the projected floor space area could reach the Japanese standard of 25m2/capita (otherwise, around 130 m2/household). Figure 11 shows the variables used in estimating the space built-up area.

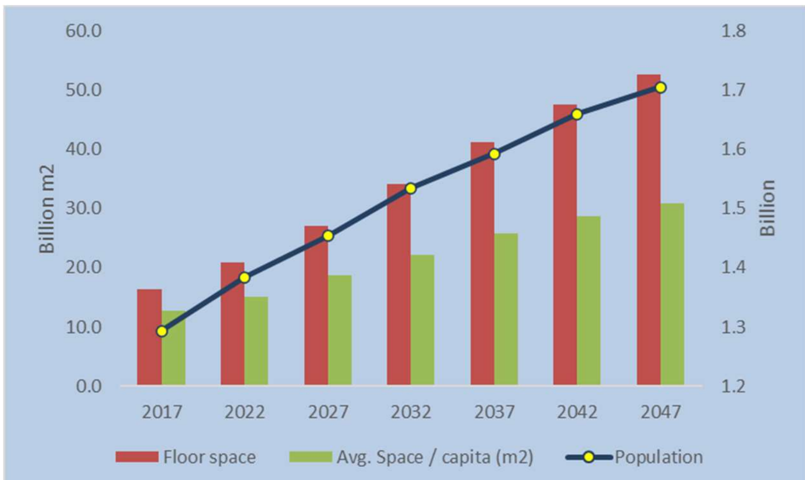


Figure 11:Important variables used for floor space area estimation

4.2 Estimation of cooling requirement under various conditions

In this study, the space cooling requirement is adopted from the IETP 2020 study. The overall methodology used for estimating the cooling requirement follows the Eco-Niwas Sahmita (ENS) approach. In summary the building blocks of this estimation approach are shown below in the Figure 12.

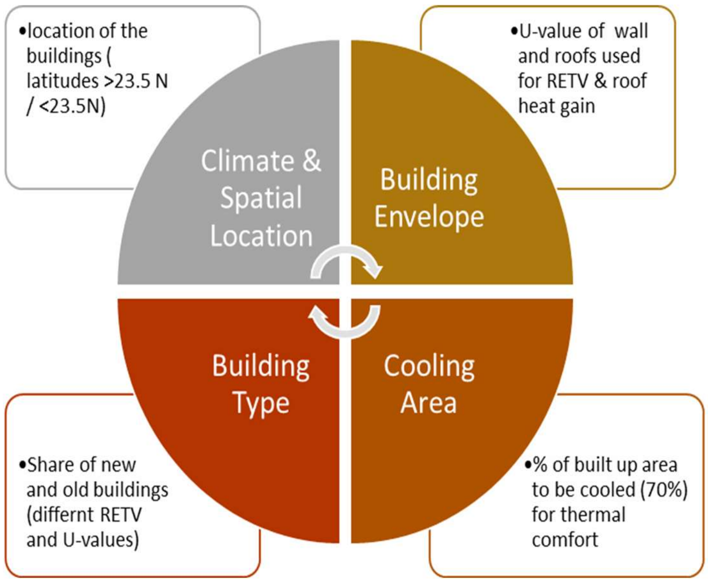
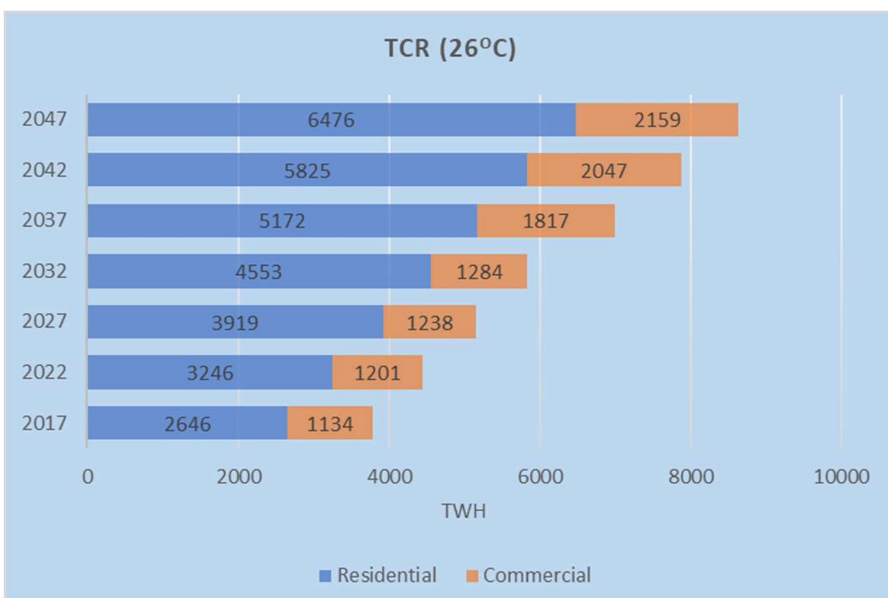


Figure 12:Variables used for estimating space cooling requirement

Based on above mentioned approach and methodology the Total Cooling Requirement has been estimated for residential and commercial together. Residential cooling is the combination of urban and rural space cooling while the commercial cooling is restricted to designated commercial establishment types mentioned in the IESS 2047 (NITI Aayog, 2015) (For further detail please see Annex-III). Figure 13 below shows the Total Cooling Requirement of India with 26 and 28°C set point temperature for thermal comfort. It is estimated that increasing the set point temperature by 2°C can save around 12% cooling requirement in the country and the subsequent demand for electricity and refrigerants.



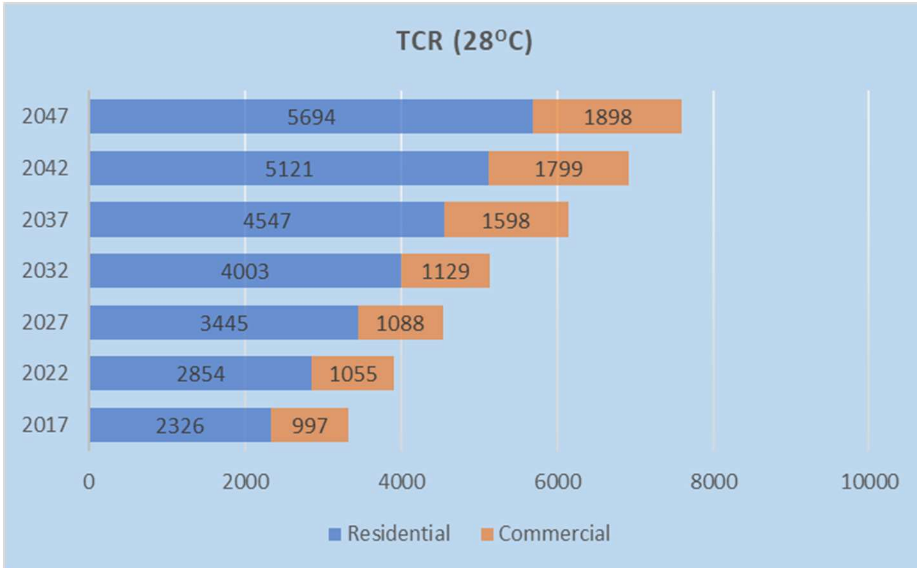


Figure 13:Total space cooling requirement in India

In addition to IETP 2020, the study also considered another set of assessment related to India's space cooling requirement which was conducted by Mastrucci and Rao in 2019. They have estimated the space cooling requirement in the context of building life cycle energy (LCE) which assesses the building embodied energy and building operational energy separately. Building operation energy further comprises of lighting, heating and cooling energy requirement to make the building operational and livable. Embodied energy was mainly determined based on the building materials used in construction. It is shown that the share of embodied energy in total LCE of a building also depends on the climatic condition where the building is located. In warm-humid climatic zone the EE has very less share in LCE compared to temperate and cold climatic zones. As a matter of fact, in terms of determining the space cooling requirement building operation energy has much significant role. More than 95% of the total operation energy is required for cooling. Based on different building archetype, climatic zones and per capita space required for decent living, the authors estimated the space cooling requirement in the country. Table 6 shows the summary of estimation of the space cooling requirement with an average per capita space of $10m^2$.

Table 6:Space cooling requirement in India for year 2017

Archetype	Climatic Zone	Operational Energy (GJ/m2/y)	Cooling Requirement (GJ/m2/y)	Population (Billion)	Cooling Space (Billion m2)	Cooling Requirement (Twh/year)
Rural Housing	Warm-Humid	0.224	0.224	0.31	3.2	203.1
	Composite	0.2	0.192	0.22	2.5	137.1
	Hot-Dry	0.179	0.177	0.21	2.2	113.2
	Temperate	0.098	0.098	0.02	2.1	5.8
	Cold	0.149	0.088	0.02	2.4	6.0
Urban Housing	Warm-Humid	0.179	0.179	0.16	1.6	81.7
	Composite	0.153	0.148	0.12	1.3	53.4
	Hot-Dry	0.137	0.137	0.11	1.2	44.1
	Temperate	0.092	0.092	0.01	0.1	2.8
	Cold	0.107	0.078	0.01	0.1	2.7
Total				**1.29**		**649.7**

source: Author estimates using data from Mastrucci & Rao, 2019.

The operation energy requirement is estimated based on certain basic assumptions of building utilization which are summarized below in the Table 7.

Table 7:Basic assumptions for estimating OE

Building Geometry		Building structure		Occupant's behaviour			Building envelope			
Dwelling size (m2)	Window size	Structural system	ventilation	Set point temp. (°C)	Relative Humidity	AC operational hours	Masonry material	Roof/ Floor material	wall insulation	Roof insulation
40	1/9 of the floor space	Masonry & RCC	0.5	26	60%	8	Fire clay bricks	Concrete slabs	not insulated	not insulated

Based on the 2017 estimate, the Total Space Cooling Requirement is further projected until 2047 using the same growth rate used in the IETP Study assuming same macroeconomic and socio-economic developmental factors. Figure 14 shows the projected space cooling requirement which is significantly lower than the IETP Study. Total Cooling Requirement (TCR) in the above-mentioned decent living standard scenario is estimated to be significantly lower than the IETP Study on both 26 °C and 28 °C set point temperature. Nevertheless, the TCR in 2017 is estimated to be 3.5 times more than the actual cooling energy consumed (around 100 Twh) in India on that year. So, it is obvious that space cooling is going to be a major energy consuming sector in India in the coming years.

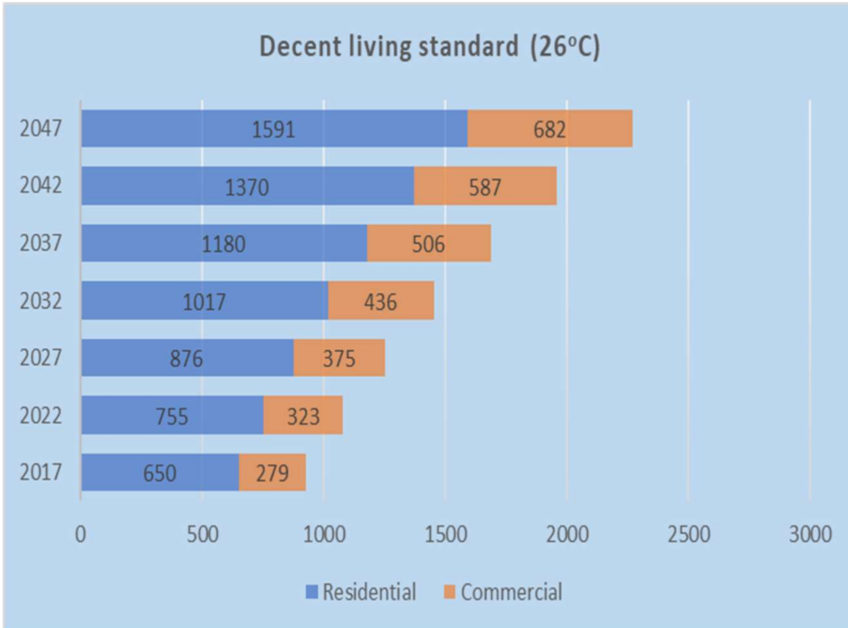


Figure 14:Space cooling requirement for decent standard of living

5.0 Implication of Cooling for All in India

In this section we have contextualized the total cooling requirement of India in the backdrop of national energy system. Energy system considers the entire flow of energy starting from its extraction to its final utilization by the consumers along with its losses and externalities like emissions, air pollutions and other resource consumptions. Given the complexity of Indian energy system in today's date where resource availability is constrained, pattern of energy use is rapidly changing due to socio-economic changes and above all while climate change is an imminent challenge for sustainable development, space cooling is a very important area to be analysed.

In this report, we have discussed the impact of burgeoning space cooling requirement in five major categories: i) impact of primary energy supply, ii) impact on final energy supply iii) Impact on electricity supply and iv) impact on GHG emissions and v) impact of refrigerant demand

5.1 Primary energy supply

The study estimates that to achieve the thermal comfort for all in India there will be an additional requirement of primary energy supply in the country. Figure 15 shows the comparison of primary energy supply required in India to provide cooling to all under different options. To achieve the cooling for all with 26 °C set point temperature, additional 40% of total primary energy supply would have required in 2017 which is around 300 MTOE. It is estimated that by 2037 India would be required around 360 MTOE of additional primary energy supply to meet the Total Cooling Requirement of the country. Further assessment shows that more than 80% of the additional requirement will be fulfilled by coal. However, if the set point temperature is increased to the level of 28°C, additional primary energy requirement could be reduced by 5~6% compared to 26 °C scenario. However, it is also estimated that under the decent living standard scenario there could be no additional primary energy requirement compared to BAU to provide thermal comfort (with 26°C).

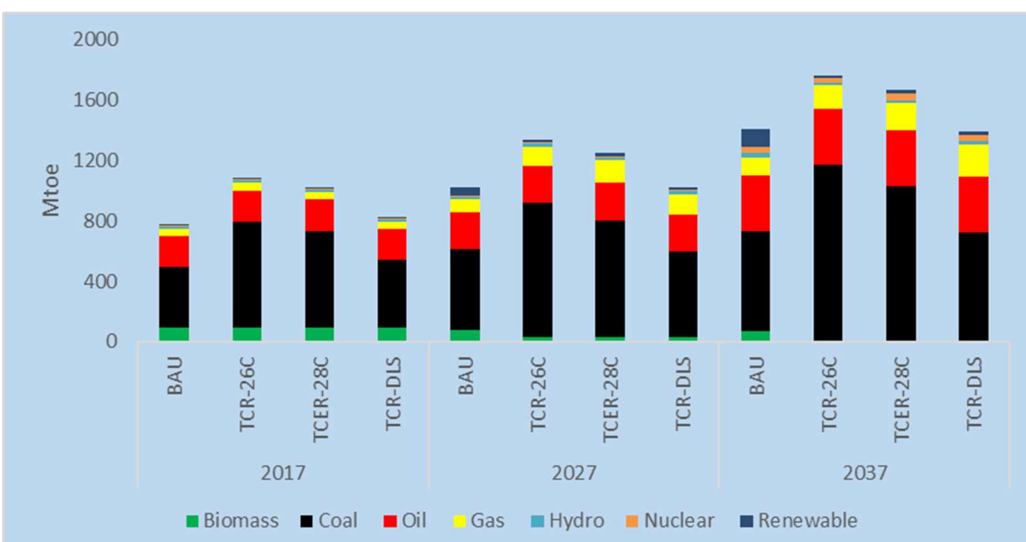


Figure 15::Comparison of primary energy requirement under different cooling requirement

5.2 Final energy consumption

The study also estimates that to achieve the thermal comfort for all in the country there is an additional requirement of energy in form of electricity in the residential and commercial sector to run the cooling systems (see Figure 16). These cooling machines could be either refrigerant based or could be without refrigerant base. It has been estimated that in 2022 there would 22% additional final energy requirement in India should the country aims to provide cooling comfort to all with a set point temperature of 26 °C. This additional requirement could be reduced by 4~5% if the set point temperature increases to 28 °C. Besides, if India follows the method of certain passive cooling along with decent living standard definitions (mentioned in the Table 9), the additional energy requirement could be further reduced to only 6% compared to the standard condition which is based on 26 °C. However, the additional energy requirement to meet the national cooling demand gradually declines over the period of time due to increasing efficiency of the cooling technologies, implementation of various passive cooling technologies in building construction etc.

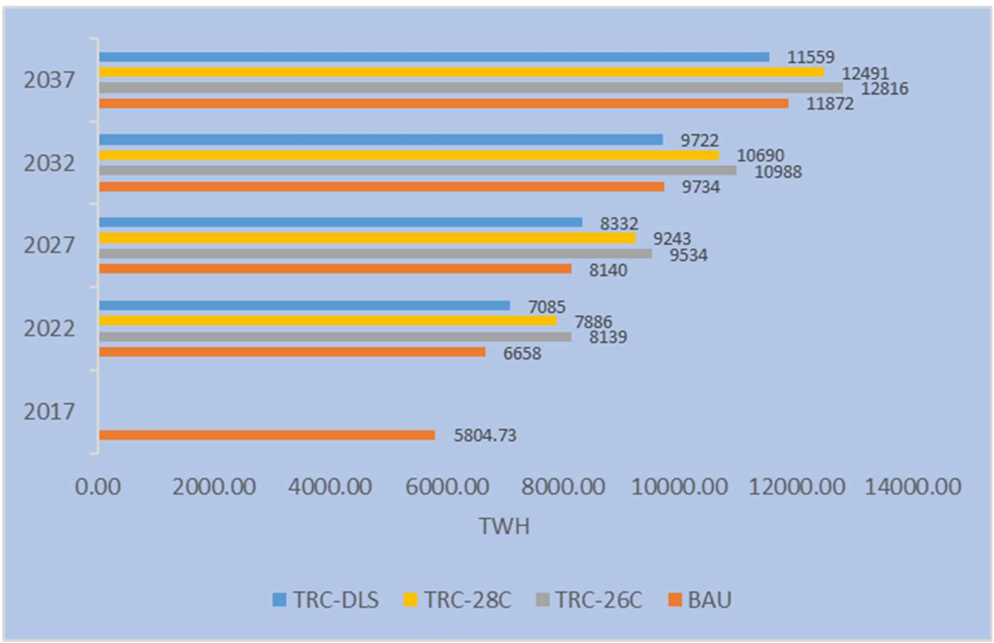
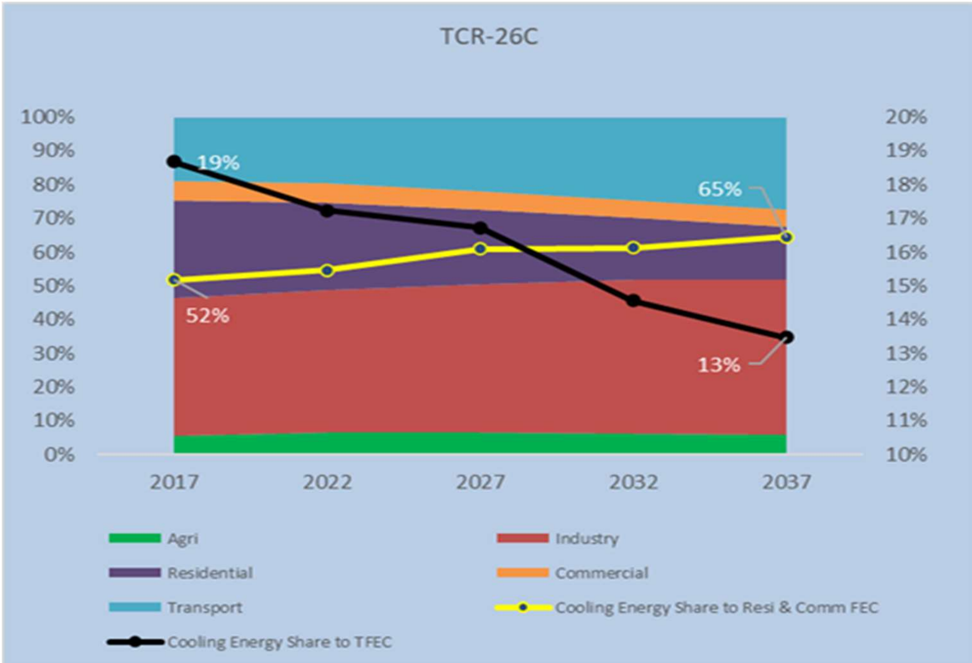


Figure 16:Comparison of final energy consumption under different cooling requirement scenario

It is also important to observe the share of cooling energy requirement over the total final energy demand in India over the period of time. In 2017 it is estimated that around 2.5 to 3% of total final energy consumption in India could be attributed towards cooling energy consumption. However, to achieve the thermal comfort for all the required share should be around 19% of total final energy consumption of the country (with 26 °C set point temp.). The required share reduces by 3% provided the set point temperature increases to 28 °C. Figure 17 below shows the comparison between different shares of cooling energy compared to total FEC and total residential and commercial energy consumption to achieve the thermal comfort for all under two set point temperatures. It is estimated that more than half of the energy required for residential and commercial sector would be used for cooling purposes in the coming years to provide thermal comfort.



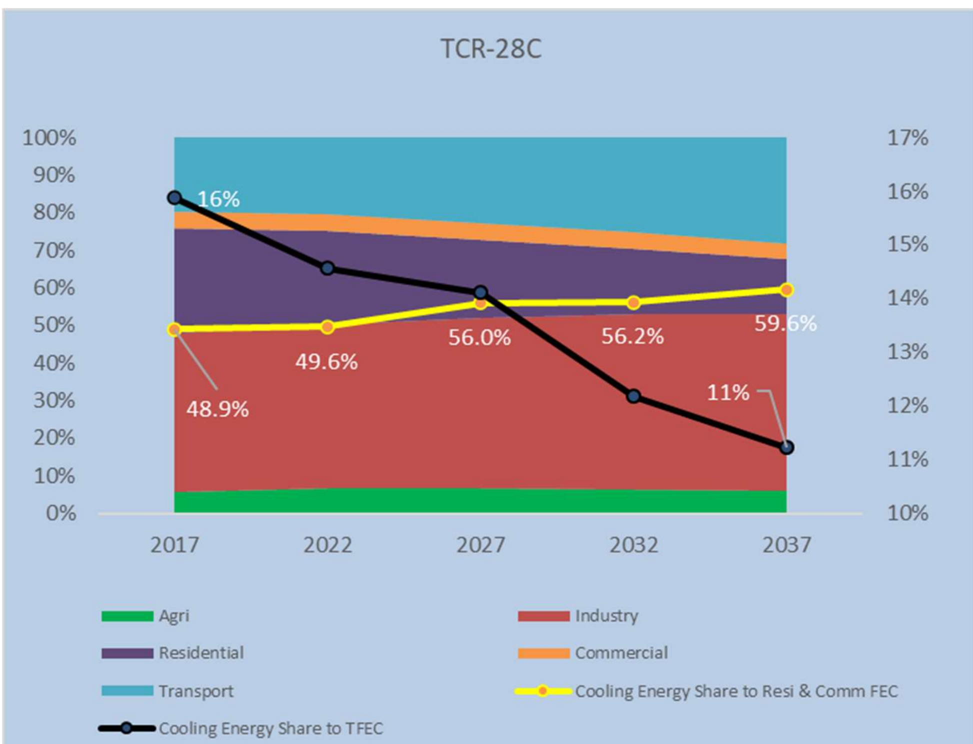


Figure 17:Comparison of final energy consumption under different cooling requirement scenario

5.3 Electricity Requirement for TCR

Due to increasing cooling energy requirement, country's power generation requirement also increases significantly compared to the national BAU. Under the TRC-26C condition power generation is expected to increase by 26% by 2037 compared to baseline scenario. Similarly, for TRC-28C condition the power generation is expected to increase by 15% by 2037. However, under the TRC-DLS condition the power generation is expected to be lower than baseline condition by around 16% in 2037. The main reason could be increasing level of building energy efficiency implementation (building envelope) along with increasing use of efficient cooling technologies. Figure 18 below shows the comparison of electricity consumption under different TCR conditions.

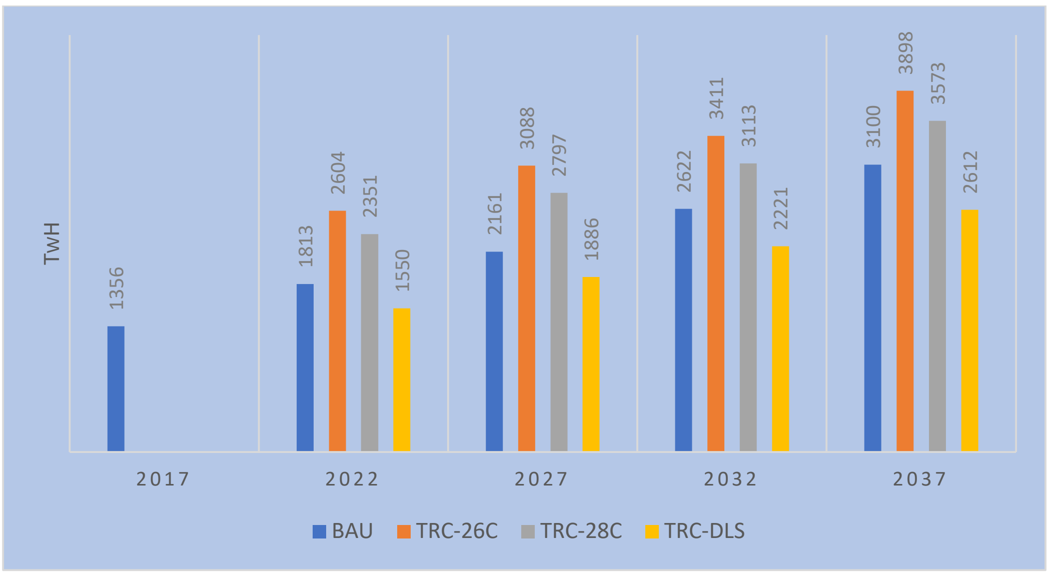


Figure 18:Comparison of total electricity consumption under different cooling requirement

It has been estimated that under the BAU scenario in 2017 base year around 26% and 11% electricity are consumed by the residential and commercial sectors respectively. While implementing thermal comfort for all in the country with 26 °C of set point temperature, the share of electricity consumption by the residential and commercial sectors went up to 40% and 16% respectively by 2037. It has been further estimated that if the set point temperature increases by 2 °C only (set at 28 °C), the share drops to 38% and 15% respectively for residential and commercial sectors in the country in 2037. However, it is observed that under the Decent Living Standard conditions in India, the share of electricity consumption in residential and commercial sectors in 2037 just fall below the BAU projection during the same time. Figure 19 below shows the comparison of share of electricity consumed by the residential and commercial sectors under different TCR conditions.

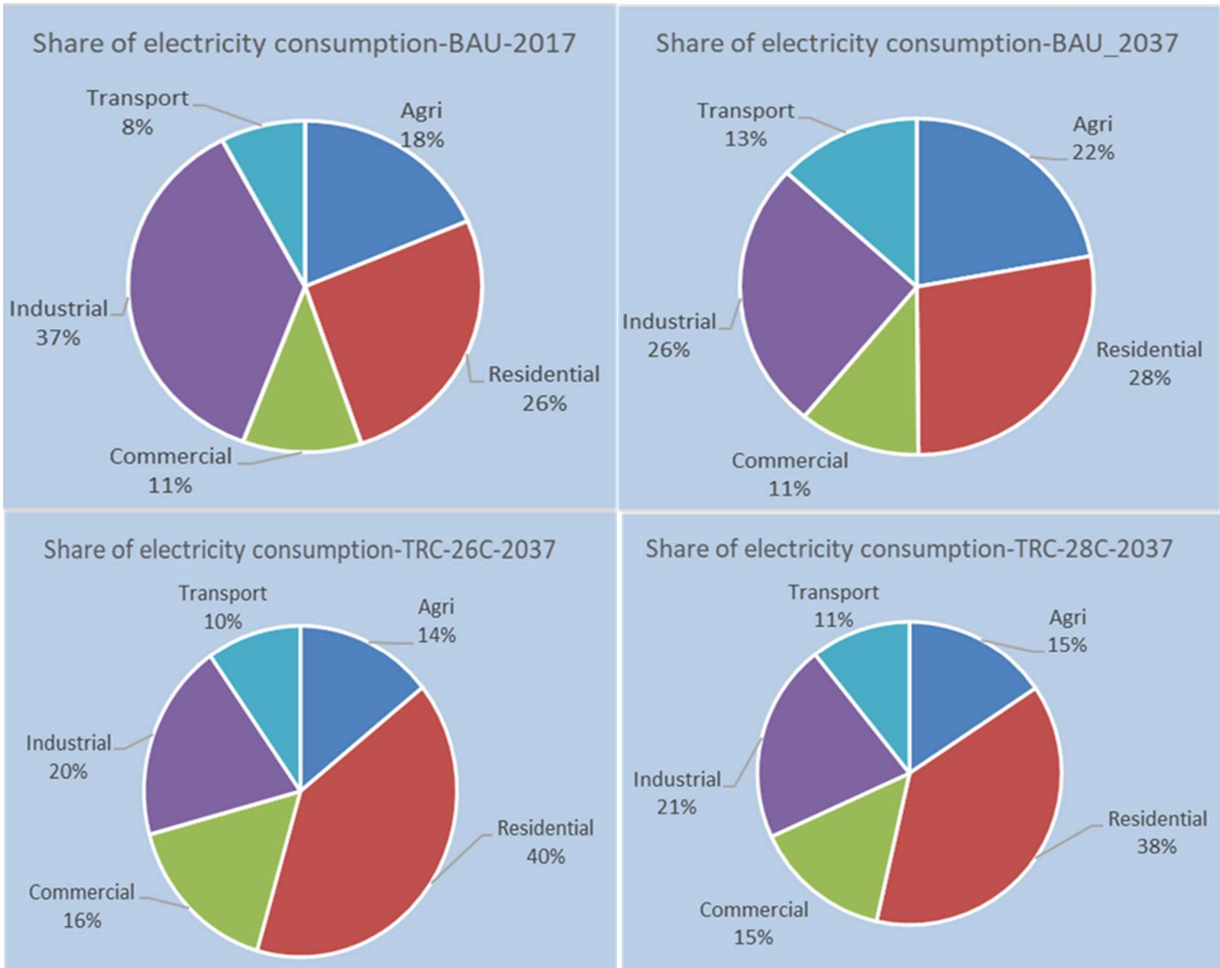
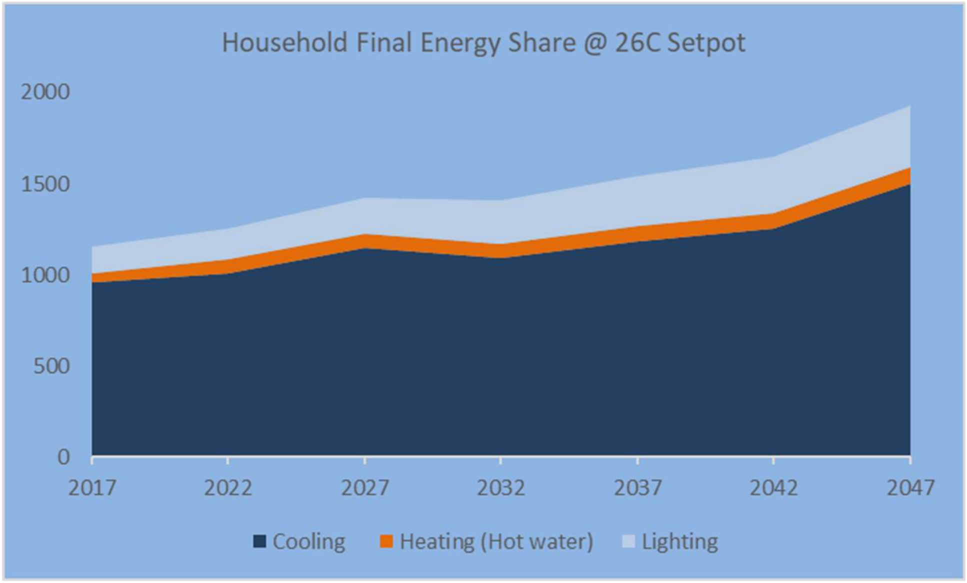


Figure 19:Comparison of share of electricity use in residential & commercial sector

It is further estimated that the cooling is the biggest source of electricity demand in the residential sector after the lighting. In 2017 the share of cooling demand within residential electricity consumption was around 83% which slightly reduces to 76% by 2037 under the TRC-26C scenario. In the case of TRC-28C the share of electricity consumption for cooling in residential sector is expected to be around 80% which further reduces to 72% by 2037 due to increasing efficiency in cooling technologies. Figure 16 below shows the share of electricity consumption in residential sector. In the TRC-28C scenario, the share of electricity within total electricity consumption in residential sector is expected to be around 80% I 2017 which further reduces to 72% in 2037. Figure 20 below shows the share of electricity consumption withing the residential sector in India.



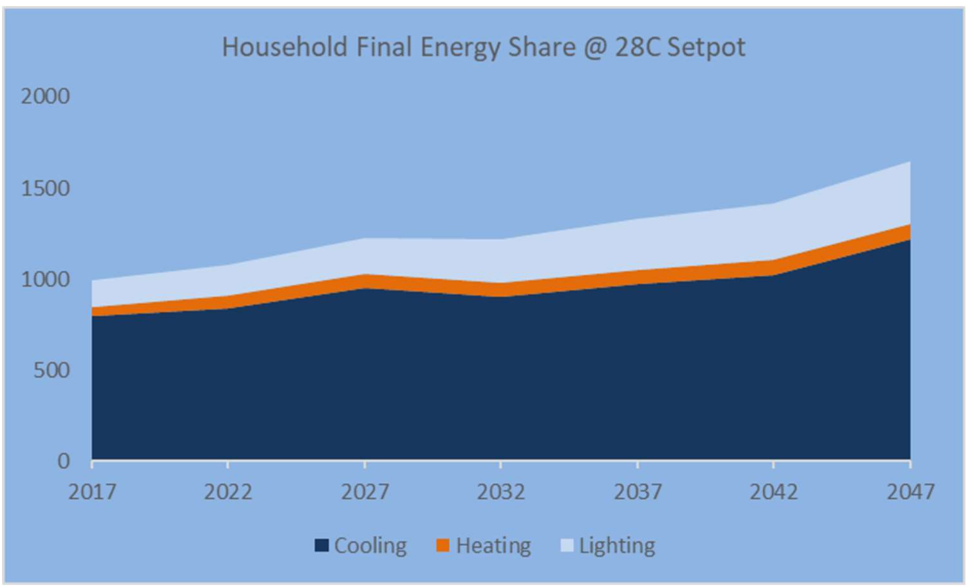


Figure 20: Comparison of share of electricity use by technologies

It has been estimated that electricity consumption for space cooling increases by around 400% in 2022 and around 220% in 2037 compared to the BAU scenario to provide cooling comfort to all with 26 °C set point. However, if the set point temperature increases to 28 °C the increase in power demand for space cooling could be limited to around 300% in 2022 and 160% in 2037. Under the Decent Living Standard condition (primarily a mix of passive cooling and efficiency cooling) it is observed that though the set point temperature is 26 °C, however due to introduction of better building envelope, smart and passive cooling technologies, cooling comfort can be provided to all with almost same amount of energy used in BAU level.

5.4 Overall GHG emissions impact due to cooling

It is estimated that the CO_2 emissions due to electrical energy consumption for space cooling is expected to be around 964 and 1219 $MtCO_2$ by 2037 if total TCR is achieved under the 28 °C and 26 °C set point temperatures respectively. However, under the projected BAU scenario the total CO_2 emissions due to cooling energy demand is expected to be around 740 Mt by 2037. Under the Decent Living Standard scenario, which comprises of improved building envelope, passive cooling etc. the CO_2 emissions is expected to be reduced to only 295 Mt by 2037. Figure 21below shows the trend in CO2 emissions from space cooling under the BAU and other TCR scenarios.

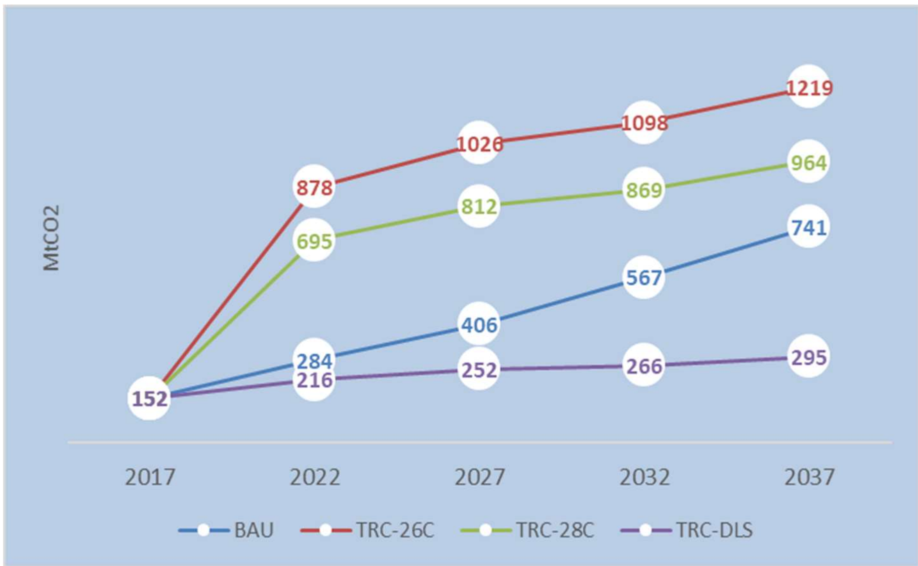


Figure 21: CO_2 emissions from space cooling

5.5 Overall refrigerant demand for TCR

It is estimated that under the optimal cooling technology pathway achieving the Total Cooling Requirement in India the refrigerant demand is expected to grow at the rate of 5% per annum. The total cumulative refrigerant demand for TCR achievement by 2037 could be around 335688 MT with the 26 °C set point temperature compared to 295103 MT for the same year for 28 °C set point temperature. Under the Decent Living Standard condition, the refrigerant demand could reach up to 81000 MT which significantly lower than the TCR-26C and TCR-28C conditions. Figure 22 shows the refrigerant demand under two different options of achieving the cooling target.

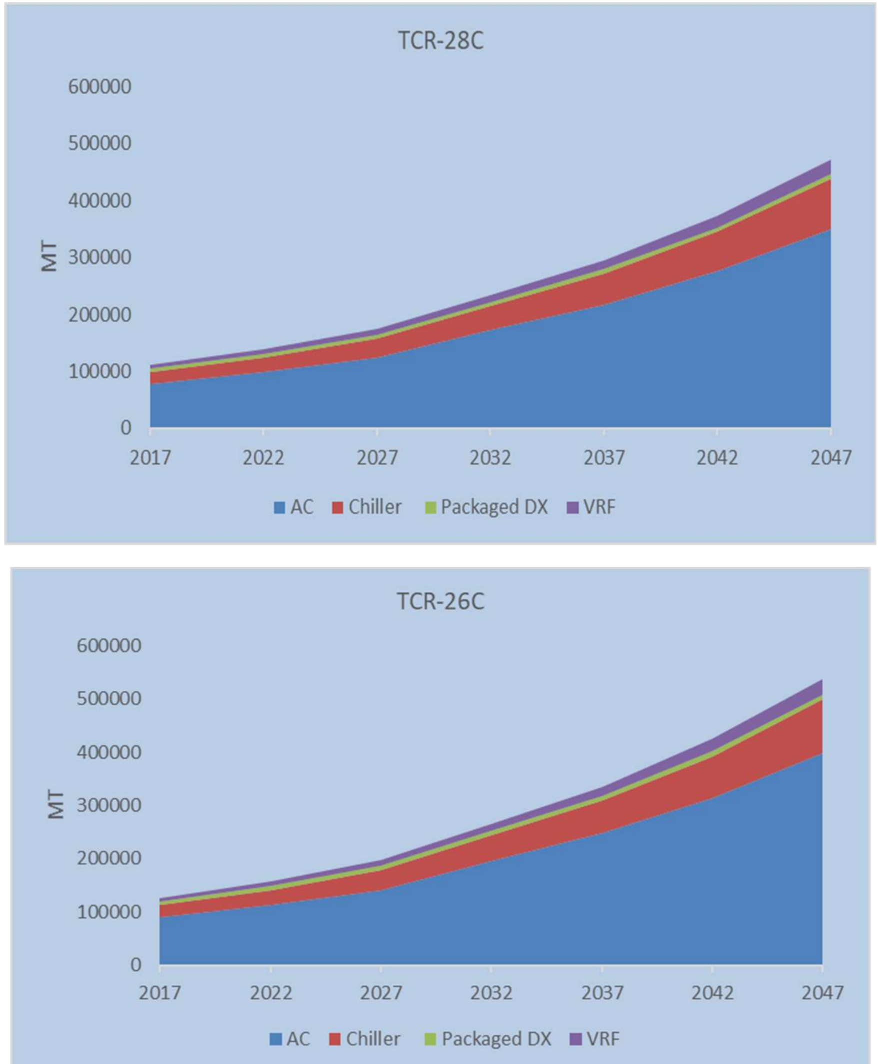


Figure 22: Refrigerant demand under different TCR scenarios

6.0 Developing scenarios of ICAP implementation

Considering the importance of the Indian Cooling Action Plan (ICAP) as a synergistic approach towards balancing the developmental objectives of India on three pillars of international commitments like Sustainable Development Goals, Paris Agreement and Montreal Protocol, the current study determines the baseline and other scenarios accordingly. It also considers India's domestic development policies as well while determining the scenarios. The following table (Table 8) shows the developmental matrix used to determine baseline and other space cooling scenarios.

Table 8: ICAP Development Matrix

International Commitments	Domestic Development Goals	Activity Plans	National Goals	ICAP Targets
Sustainable Development Goals (SDGs) Viz. SDG3/7/9/10	Smart City Missions NMSH, NMEEE, Zero poverty, SC&P	Affordable energy efficient housing, DSM, S&L, ECBC, Reduced mortality, Healthcare coverage	Doubling Farmers' Income, Cooling for All, Housing for all, Healthcare for all	Reduction of cooling demand (requirement) across sectors by 20-25% by 2037
Paris Agreement	Overarching NAPCC; NDC Targets	RE expansion, Energy Efficiency, GHG emissions reduction; Electrification	Emissions intensity, RE share,	Reduction of cooling energy requirements by 25% to 40% by year 2037-38
Montreal Protocol (Kigali Amendment)	Phasing-out production and consumption of HCFCs	HFC & HCFC Reduction, Alternative cooling, Passive cooling	HFC (Avg. 2024-26)+ 65% HCFC baseline	Reduction of refrigerant demand by 25% to 30% by year 2037-38

Source: Complied using information from ICAP, 2019, NITI Aayog SDG Development Index Report, 2019.

Based on the above mentioned International and domestic developmental plans and targets, ICAP has taken a synergistic approach to achieve the set targets. While developing the baseline and scenarios, the following indicators are compared to determine the ICAP implementation pathways:

- ✓ Cooling for all
- ✓ Reduction of cooling demand
- ✓ Reduction and transition of refrigerant
- ✓ Enhancing energy efficiency
- ✓ introducing advance technology options

6.1 Contextualization of ICAP for Cooling for All

Given the goals and objectives of Cooling for All for India, it is imperative that providing cooling comfort to more than 1.3 billion population is a daunting ask. It needs thorough assessment of the sectors directly or indirectly linked to the cooling sector to understand the requirement and demand for cooling. Here we have contextualized the national target of cooling for all to study scenarios through the filter of ICAP 2019. The study identifies through rigorous literature review that there could be three major options of providing cooling to all. Direct cooling is the standard option of providing cooling which is the easiest option as well. If all the households and commercial spaces get access to cooling technologies achieving the cooling for all is possible. Also, direct cooling can be provided under different set point temperatures which have different impacts on energy demand for cooling. Though there is no regulation as of now in terms of set point temperature for direct cooling in India, however, based on literature review and experts' comments two possible temperatures are identified i.e 26°C and 28°C. The third option of providing cooling to all could be through combination of passive cooling method and by mandating use of highly efficient cooling equipment (Decent Living Standard). In the previous sections the report describes in detail all these options and their potential impacts on national energy and environment system to contextualize the Indian Cooling Action Plan of Govt. of India published in 2019. It is observed that for all direct cooling options there are massive increase in energy demand in the country which is adversely affecting the environment as well as the country's energy supply security. It also increases the consumption of refrigerant which is also an environmental threat and risk towards ozone depletion. However, the passive cooling option under the Decent Living Standard option could provide desired level of cooling with much less energy consumption and less threat to environmental degradation. However, the option needs comprehensive policy for building construction and use of materials to improve the building envelope condition and the corresponding RETV values. It also requires stricter implementation of standard and leveling of cooling equipment and its use in the market.

ICAP 2019 is an excellent document in terms of providing a comprehensive guidance toward Cooling for All while considering India's commitment towards GHG emissions reduction and HFC reduction under the Montreal Protocol and subsequent Kigali Agreement. While developing the ICAP implementation strategy, the study first identifies the ICAP Baseline which is the reference for all the future policy initiatives simulated in the study. The ICAP baseline is developed considering the facts and information adopted from the ICAP Report and other technical details from the three different options of achieving the Cooling for All goals. Finally, the ICAP implementation scenarios are built on technical parametric values directly adopted from the cooling options and ICAP baseline. Scenario building process iterated through the feedbacking and validation process of results and findings. Figure 23 below shows the schematic of the overall process of developing the ICAP implementation scenarios.

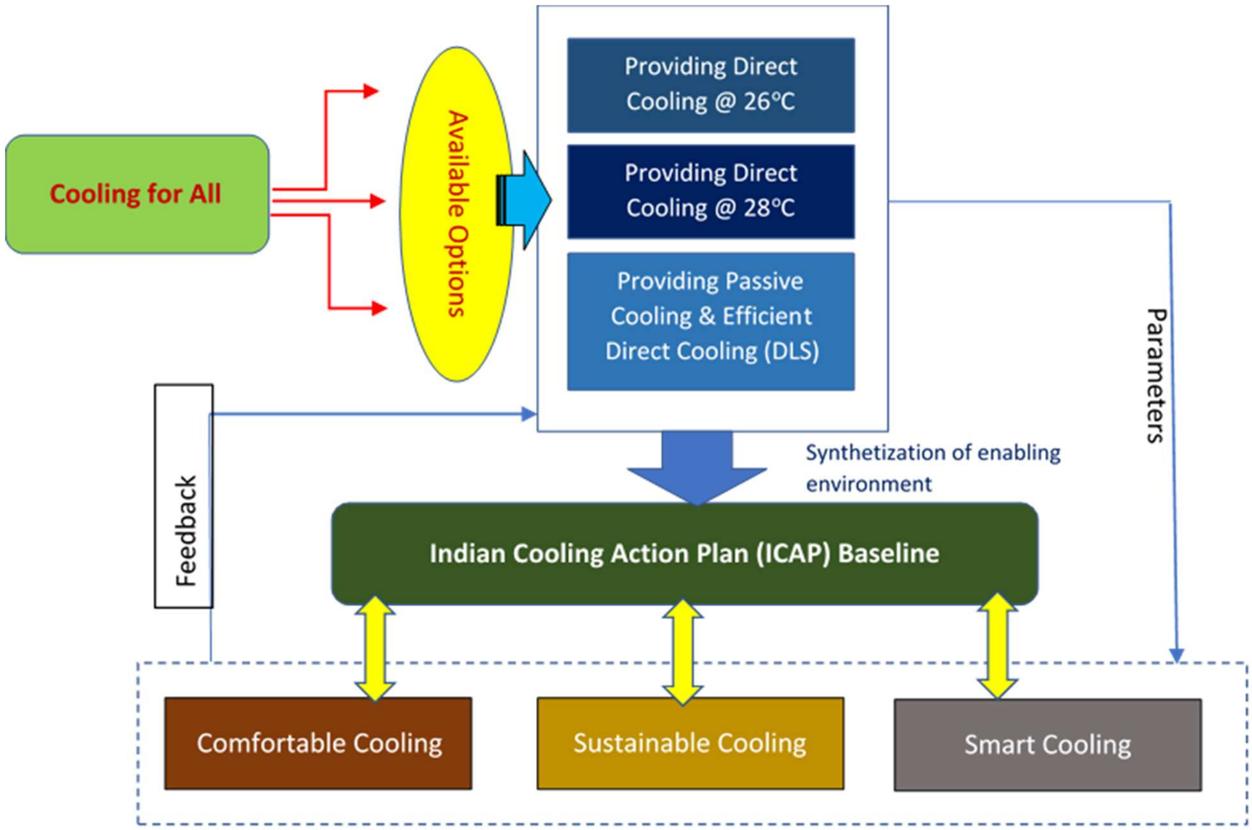


Figure 23: Development process of ICAP implementation scenarios

6.2 Setting up the ICAP Implementation Baseline for Space Cooling

Based on the ICAP Development Matrix the baseline for space cooling is developed with the following principles and assumptions. It is assumed that though India is aiming for Cooling for All, it will take time to reach full capacity until 2047. Till that time, there will be certain unmet demand for space cooling in the country which will be primarily in the rural areas and urban slums. Unmet demand will be existing in the system mainly due to lack of access to cooling technologies due to various reasons, not having refrigerant based cooling technologies like ACs and also for not having access to electricity as well.

Considering the rate of penetration of ACs in urban household of 10% and fans of 100% followed by AC penetration of less than 5% with fan penetration of around 30% (ICAP, 2019 &Prayas Energy Group, 2012) in the baseline we assumed that during 2017 the level of unmet cooling demand will be around 60~65% which will be further reduced to nil by 2047 while implementing ICAP. Table 9 below shows the basic assumptions of developing the ICAP Baseline for this study.

Table 9: Assumptions of ICAP Implementation Baseline

Indicators	Target Values	ICAP Target
Cooling requirement	Meeting % of TCR: (Reduction of un-met cooling demand over the time) Residential: 34% in 2017→ 100% by 2047 Commercial: 38% in 2017 → 100% by 2047	Thermal comfort for all (Cooling for all)
Set-point Temperature	26 Degree C	Sustainable cooling and reduction in cooling demand
Cooling efficiency	EER Improvement → 2-4% p.a across all technologies	Enhancing energy efficiency
Non-refrigerant cooling	Share of fans/cooler remains in the system but reduced from 30% in 2017 to 8% in 2047	Reduction and transition of refrigerant and sustainable cooling (especially for rural households)
Advance technology options	Introduction of District Cooling System with limited capacity (1% of total cooling demand)	Introducing advance technology options

6.3 Assessment of Baseline

Using the MESSAGEix India Cooling Model, four major aspects of the ICAP implementation have been assessed under the baseline condition as follows:

1. **Cooling energy demand**: It is estimated that the baseline space cooling energy demand is expected to reach up to 950 Twh by 2037 from just 125 Twh in 2017. Per capita cooling energy dem (450and also increases from 97 kwh/person in 2017 to 570 kwh/person by 2037. Figure 24 shows the BAU cooling energy demand in India. Which indicates around 600% increase between 2017 and 2037 in terms of providing cooling to all. Figure 24 shows the cooling demand projection under ICAP baseline scenario.

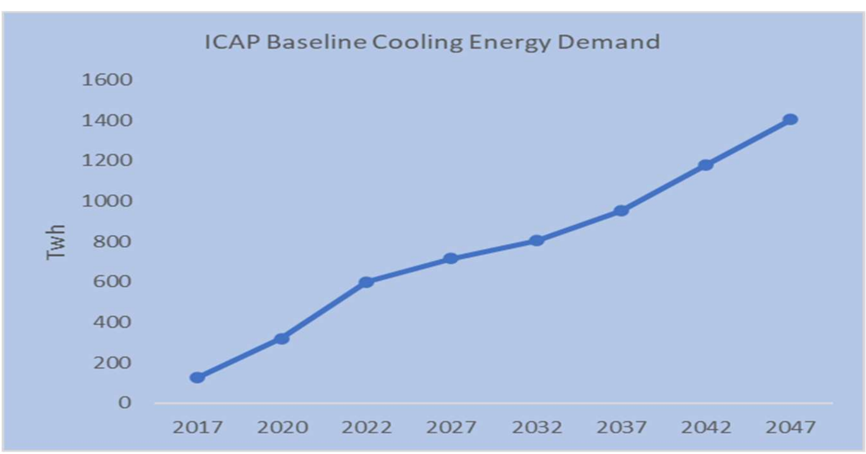


Figure 24:Cooling energy demand for BAU

2. **GHG Emissions**: It is estimated that under the ICAP baseline the total CO_2 emissions of India may go up to 5763 Million ton by 2037 compared to 2800 Million ton in 2017. CO2 emissions from electricity generation may also go up to 2000 Million ton by 2037 compared to 1000 million ton in 2017. An exclusive contribution of cooling to GHG emissions by 2037 could be around 765 MtCO2 which is around 13% of total national CO2 emissions by that time. Figure 25 shows the CO2 emissions under the ICAP BAU scenario until 2047.

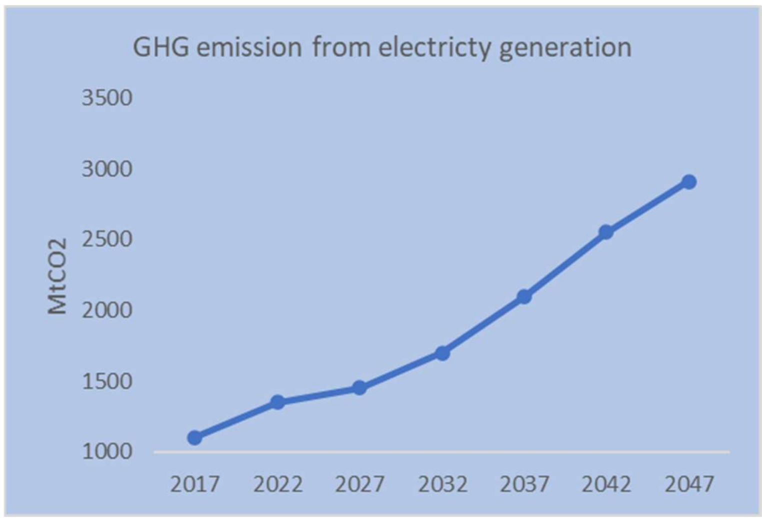
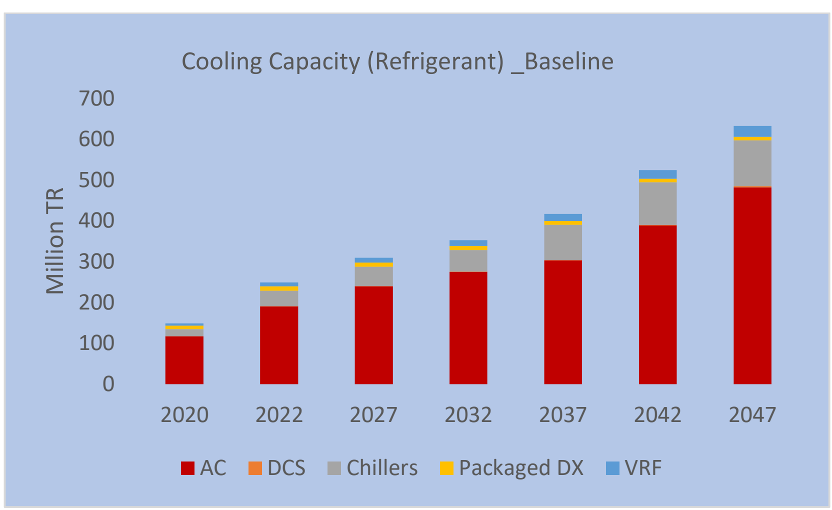


Figure 25:CO_2 emissions under ICAP baseline

3. **Cooling capacity addition:** It is estimated that implementing the ICAP Baseline scenario there would be 417 Million TR of refrigerant based cooling capacity addition required in India by 2037-38 compared to 70 Million TR in 2017 which may further go up to 630 Million TR by 2047. Room AC capacity requirement can move up to 305 Million TR by 2037 and 480 Million TR by 2047. It is also estimated that there would be a capacity requirement of approximately 1.8 billion units of fans and 250 million units of evaporative coolers in the country by 2037 (see Figure 26).



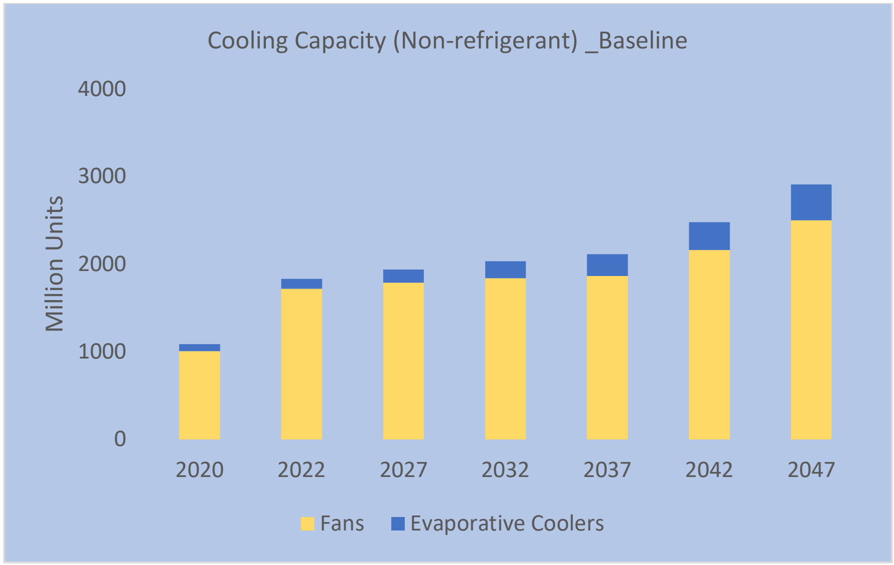


Figure 26: Cooling capacity addition requirement

4. **Refrigerant demand**: It is estimated that the total refrigerant demand under the ICAP baseline will be around 217,000 Metric Ton by 2037 compared to 47,000 metric ton in 2017 which is almost 400% jump from 2017. Figure 27 shows the projected refrigerant demand under the ICAP-BAU scenario until 2047.

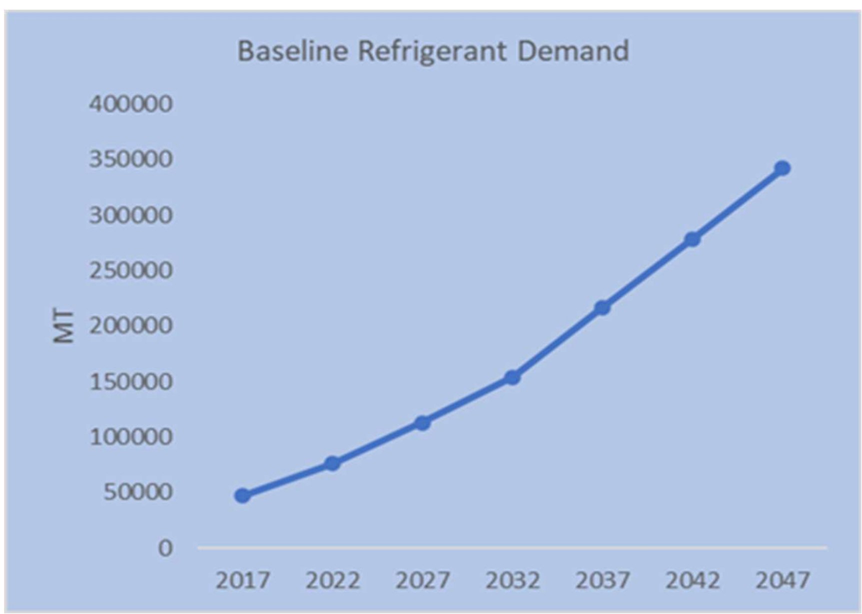


Figure 27: Refrigerant demand for cooling in BAU

5. **Cooling market size:** It is also estimated that implementing ICAP Baseline there is an investment demand and market creation for cooling equipment of around USD 200 billion by 2037 compared to USD 45 Billion in 2017. By 2047 the total cooling investment and market size under baseline condition can reach up to USD 300. These investments are only cost of cooling equipment and does not include any other infrastructural cost required to set up the plants. This indicates the cooling sector in India

in going to be a significant market for investment and related financial activities. Figure 28 shows the cooling technology wise projected investment demand until 2047

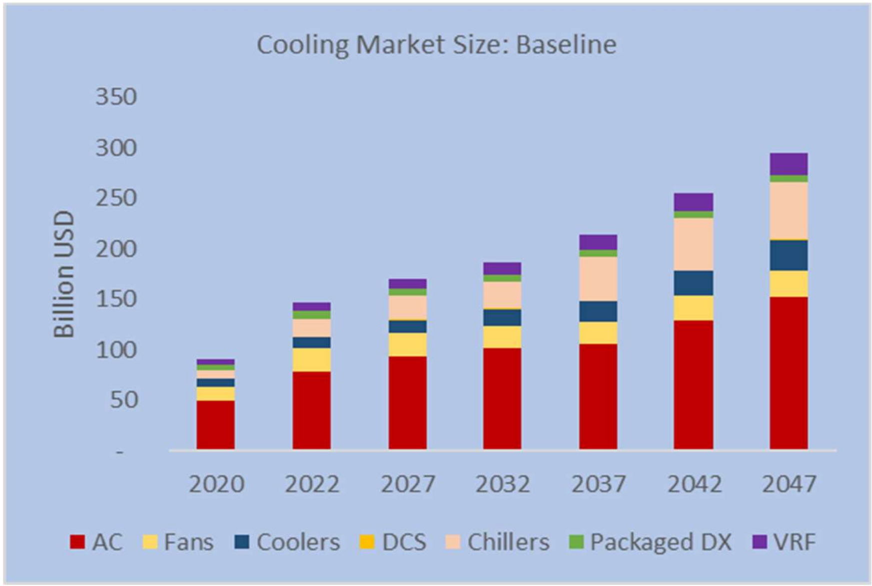


Figure 28: Cooling market size in ICAP Baseline

In summary the space cooling Baseline of India warrants for massive energy demand, emissions load and refrigerant demand. It also demands for significant amount of investment as well. However, the baseline cooling will still keep Indian per capita cooling energy demand (570 Kwh) by 2037 far below the world average of more than 1000 Kwh/ person. Figure 29 below shows the critical indicators relevant for ICAP implementation under the Baseline condition.

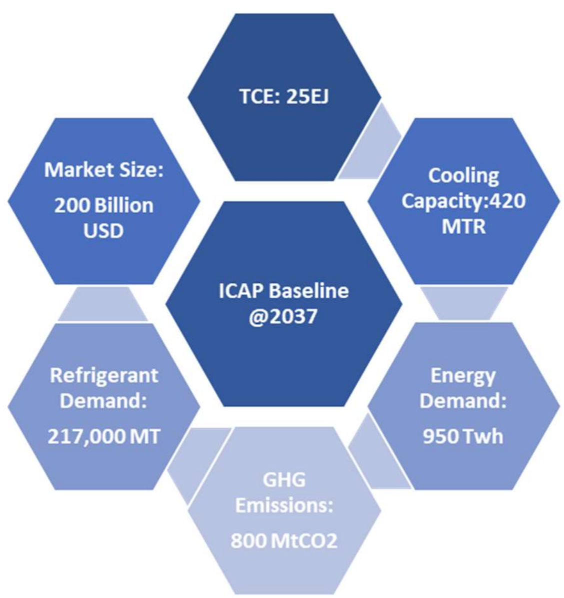


Figure 29:Baseline ICAP Indicators in 2037

6.4 ICAP Implementation scenarios

As mentioned in the Table 8 that there are three main targets of ICAP implementation in India which includes reduction in cooling demand, reduction in cooling energy demand and reduction in refrigerant use, the ICAP implementation scenarios are built to address those targets accordingly. The purpose of the scenarios is to observe how India can implement ICAP in a staged manner to achieve the given targets in a least cost manner.

6.4.1 Description of the scenarios

In this study we have crated four different scenarios to investigate the potentiality of the ICAP to achieve the given targets mentioned above. Scenarios are developed based on the basic principles of ICAP i.e providing cooling for all while meeting the goals of SDGs, NDCs and Kigali Amendment. Table 10 below shows the array of scenarios with details for ease of understanding.

Table 10: Description of the scenario

Scenario-Name	Purpose	Description
Comfortable Cooling (CCS)	Providing Adaptive Thermal Comfort (ATC) level cooling to all while meeting the country's total cooling requirement with less energy and refrigerant use	Keeping all other conditions of ICAP Baseline unaltered increasing the set-point temp of AC & other refrigerant cooling equipment to 28C. Subsequently adjusting the Total Cooling Requirement and performance efficiencies of the cooling technologies.
Sustainable Cooling (SCS)	Achieving sustainable cooling pathway through architectural, technological and behavioural change and to reduce overall space cooling requirement and accrue other benefits of reduced energy, refrigerant and GHG emissions.	Keeping all other conditions of ICAP Baseline unaltered adjusting the Total Cooling Requirement and performance efficiencies of the cooling technologies through passive cooling route. Change is building architecture, implementation of ECBC codes etc. reduces the space cooling requirement of the country. Set-point temperature remains at 26C.
Smart Cooling (STS)	Providing cooling for all with the use of advance and new technologies. It is to meet the burgeoning space cooling requirement with less energy and refrigerant use.	Keeping all other conditions of ICAP Baseline unaltered introducing advance and efficient cooling technologies like District Cooling System to meet the urban space cooling requirement only. Enhanced use of efficient but existing cooling technologies with two different set point temperatures of 26C and 28C.

6.4.2 Comfort Cooling Scenario

The Comfort Cooling Scenario (CCS) is to provide endurable but acceptable cooling to all, while meeting the country's total cooling requirement with less energy and refrigerant use. It is a representation of the Adaptive Thermal Comfort (ATC) in the overall space cooling system in India. Referring to the study on ATC Standard in 2030 by AEEE & CEPT University (2018) it is observed that 26~28°C could be universally applied as ATC level set point temperature for both commercial as well as residential spaces across the climatic zones with natural & AC ventilation. While 26°C is considered as the baseline set-point temperature for ICAP, 28 °C is thus considered as ATC Comfortable Cooling Scenario set point temperature condition. In this scenario keeping all other conditions of ICAP Baseline unaltered, the total cooling requirement is estimated with the increased set-point temp of AC & other refrigerant cooling equipment to 28 °C. In this scenario performance efficiencies of the cooling technologies are also revised upward in the range of 2~6% depending upon the place of use like residential or commercial. Performance of the scenario is assessed based on the four ICAP indicators as follows:

1. **Total cooling requirement:** Under the CCS, it is observed that the Total Cooling Requirement for India to meet the target of Cooling for All reduces by 12% compared to the Baseline requirement by 2037 which is around 22 EJ (Baseline TCR: 25 EJ in 2037). Figure 30 below shows the comparison of Total Cooling Requirement (demand) for the scenarios along with % of reduction.

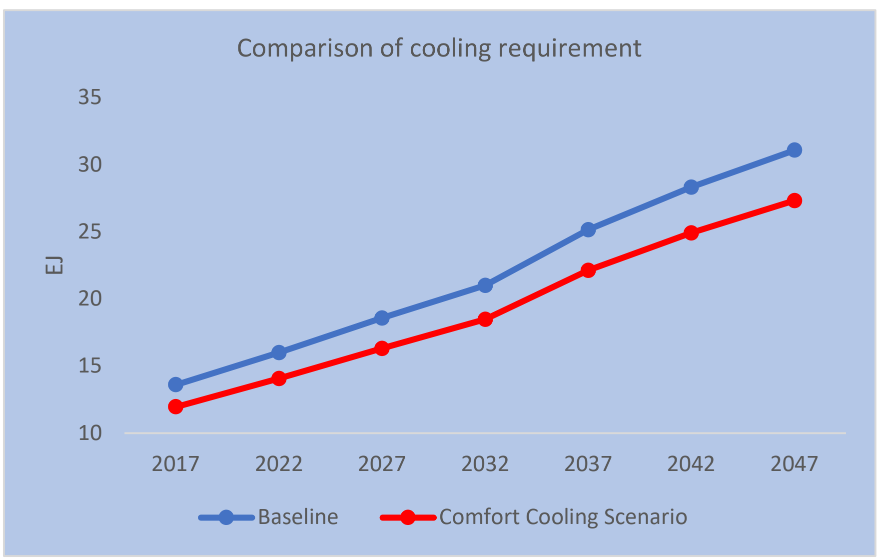


Figure 30: Comparison of total cooling requirement between BAU & CCS

2. **Cooling energy demand:** It is estimated that under the CCS Scenario the total cooling energy demand also declines significantly compared to baseline energy demand by 2037. Total cooling energy demand is expected to around 840 Twh by 2037 compared to 125 Twh in 2017. The estimated reduction is around 12% of the baseline which does not satisfies the ICAP target of 25~40% reduction. Figure 31 shows the percentage change in cooling energy demand compared to the Baseline condition.

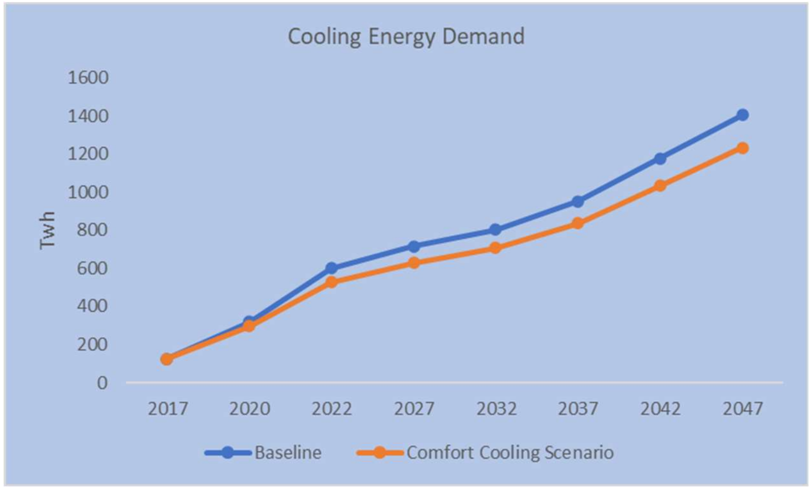


Figure 31: Change in cooling energy demand under CCS

3. **GHG Emissions:** It is estimated that under the CCS scenario, the total CO_2 emissions may go up to 5580 Million ton by 2037 compared to 2800 Million ton in 2017. CO_2 emissions from electricity generation may go up to 1980 Million ton by 2037 compared to 1000 million ton in 2017. Therefore, around 6% emissions reduction is envisaged under this scenario which can contribute towards NDC achievement a bit. Expected emissions reduction contribution is around 100 Million ton of CO_2 in 2037. Figure 32 below shows the comparison of GHG emissions between Baseline and CCS scenario.

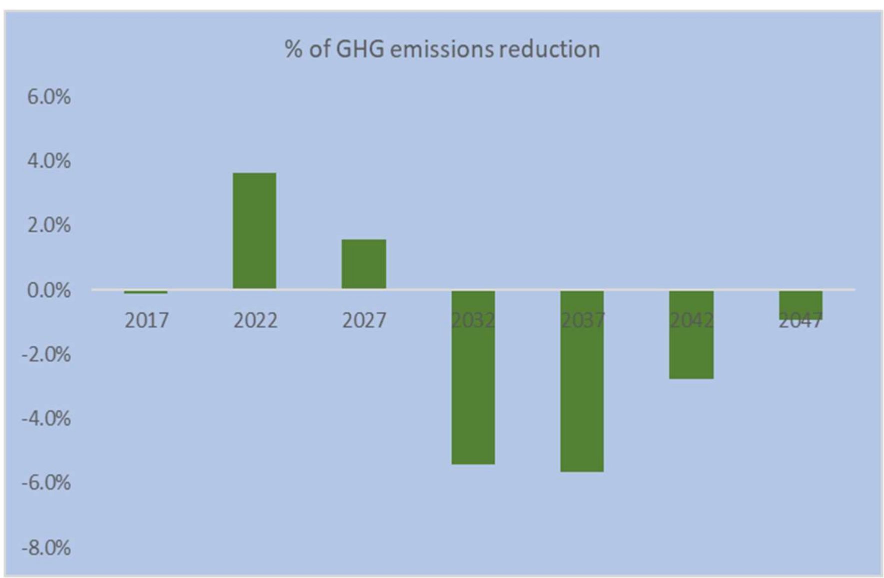


Figure 32: GHG Emissions comparison between BAU and CCS

4. **Refrigerant Demand**: It is estimated that the total refrigerant demand under the CCS scenario will be around 190,000 Metric Ton by 2037 compared to 41,000 metric ton in 2017. It is estimated that the reduction of refrigerant demand could be around 14% by 2037 compared to the ICAP Baseline which does not satisfies the ICAP target of 25~30% reduction. Figure 33 below shows the comparison of GHG emissions between Baseline and CCS scenario.

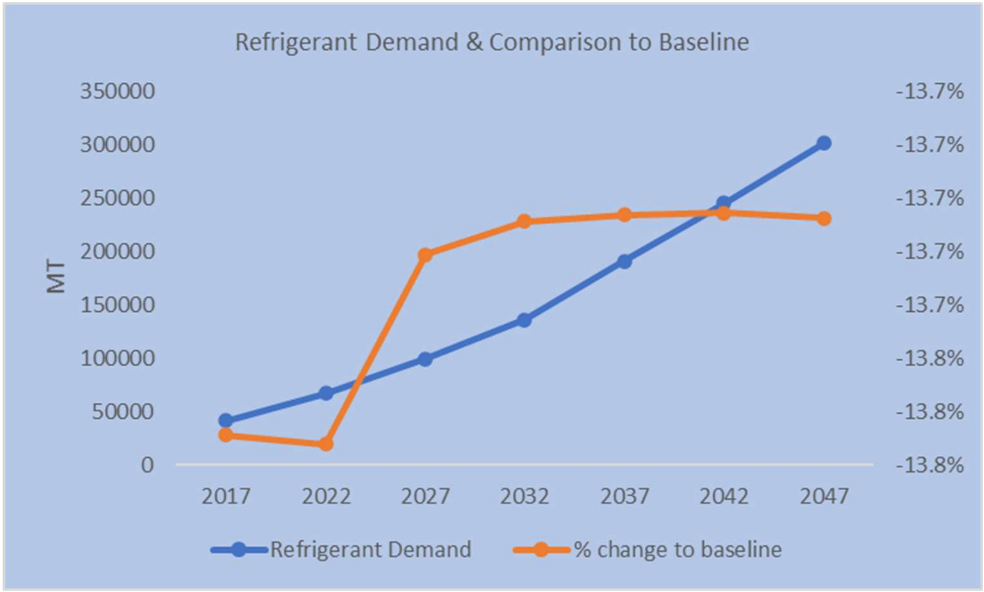
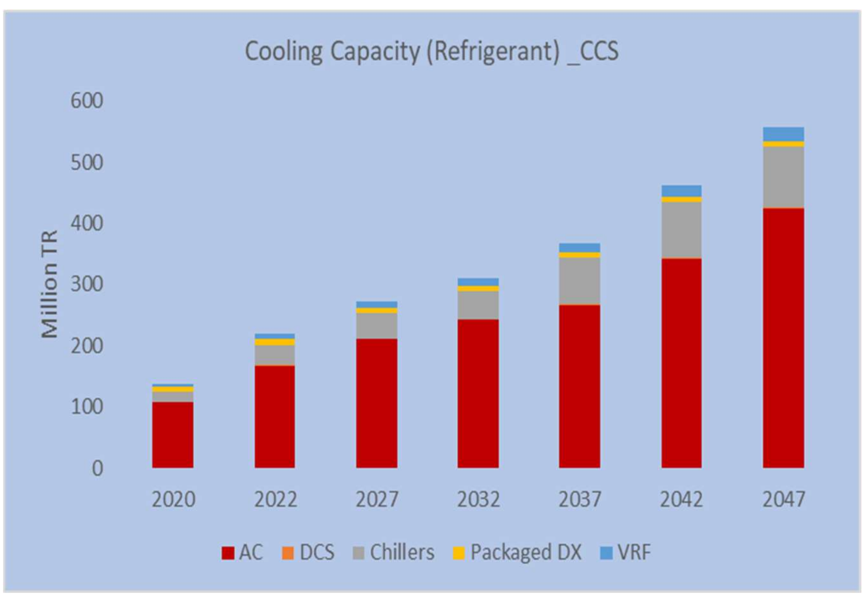


Figure 33: Refrigerant demand comparison between BAU & CCS

5. **Cooling capacity addition:** It is estimated that implementing the ICAP CCS scenario there would be around 370 Million TR of refrigerant based cooling capacity addition is required in India by 2037-38 compared to 70 Million TR in 2017 which may further go up to 550 Million TR by 2047. It is also estimated that there would be a capacity addition requirement of approximately 1700 million units of fans and 220 million units of evaporative coolers in the country to meet the cooling demand by 2037. Figure 34 shows the total cooling capacity addition requirement under the Comfort Cooling scenario of ICAP implementation.



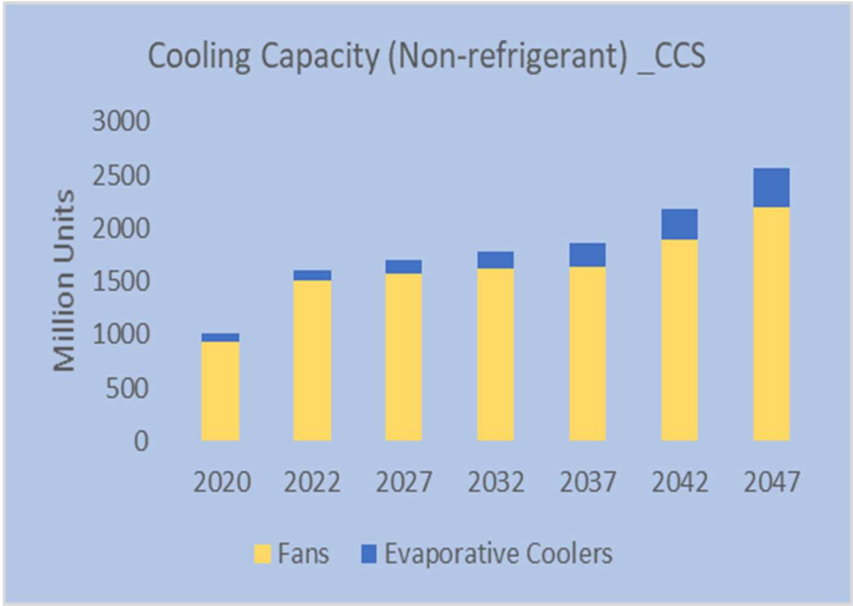


Figure 34:Cooling Capacity addition in CCS

6. **Cooling investment demand:** It is also estimated that implementing ICAP CCS scenario there is an investment requirement of around USD 180 billion by 2037 compared to USD 45 Billion in 2017. In this scenario investment requirement reduces by around 10% compared to the Baseline investment demand. By 2047 the total cooling investment demand under in the CCS scenario may reach up to USD 245. These investments are only cost of cooling equipment and does not include any other infrastructural cost required to set up the plants. This indicates the cooling sector in India in going to be a significant market for investment and related financial activities. Figure 35 shows the cooling technology wise projected investment demand until 2047.

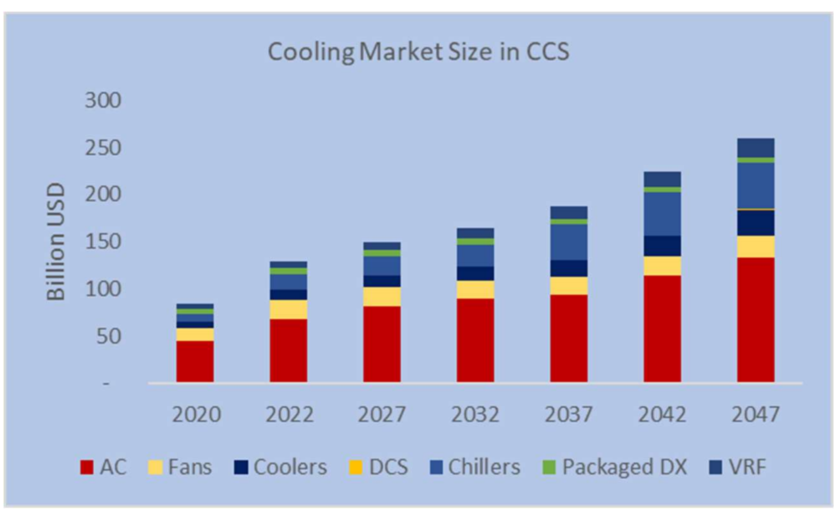


Figure 35:Cooling market in CCS scenario

In summary the Comfort Cooling Scenario cannot directly help India to achieve the ICAP targets by 2037. Figure 36 shows the performance of CCS scenario in the year of 2037-38 for all the indicators relevant for ICAP implementation. Comparing these to BAU it is concluded that only by introducing higher set-point temperature (alias ATC) ICAP Targets cannot be achieved. It needs additional effort

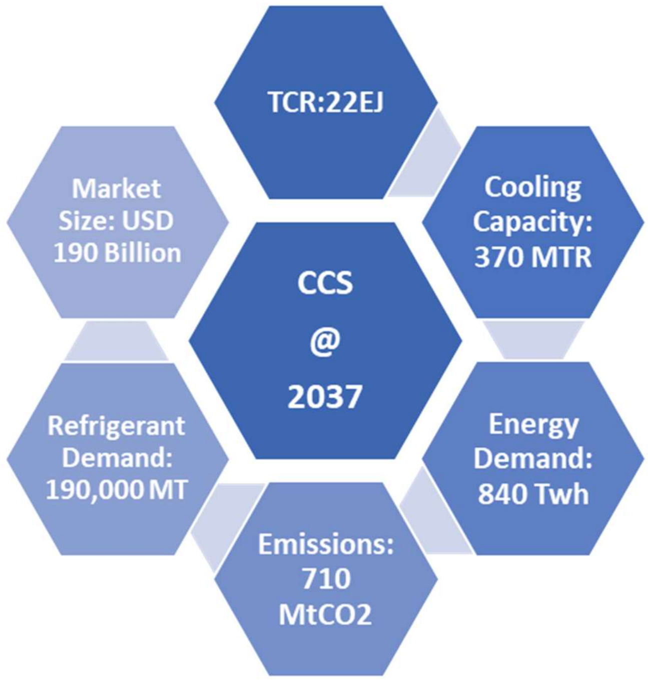


Figure 36: ICAP indicators in CCS in 037

6.4.3 Sustainable cooling scenario

As discussed in the section 4.2 under the Decent Living Standard option of cooling, there are four different control variables which predominantly determine the operational energy requirement for the buildings. Sustainable Cooling Scenario (SCC) assumes that all future building stocks in the country will follow the corresponding parametric benchmarking (see Table-7) for construction and occupation and will help to reduce the energy performance index (EPI) of both commercial and residential buildings. Given India's burgeoning population and urbanization (more than 400 million additional urban population by 2050), space cooling is envisaged to be the major consumer of energy in country (around 40% of total energy consumption). In this scenario overall residential building operation energy required is considered to be around 40 Kwh/m2 which is around 25~30% less than the national average EPI (50~70 Kwh/m2) (BEE, 2014). In this scenario it is also assumed that Cooling for All target will be achieved by 2047. In the base year of 2017, it is estimated that following the sustainable space cooling measures (architectural, materials, technological and behavioral etc.) the energy consumption for the same could be around 650 Twh/year (see Table 9) to provide cooling for all. In this scenario, the achievement of Cooling for All is staggered to 2047 including continuous improvement in efficiency standard of cooling technologies.

1. **Total cooling requirement:** Under the SCS scenario, it is assumed that the Total Cooling Requirement for India to meet the target of Cooling for All substantially reduces by 65-70% compared to the Baseline requirement by 2037. Figure 37 below shows the comparison of Total Cooling Requirement (demand) for the scenarios along with % of reduction.

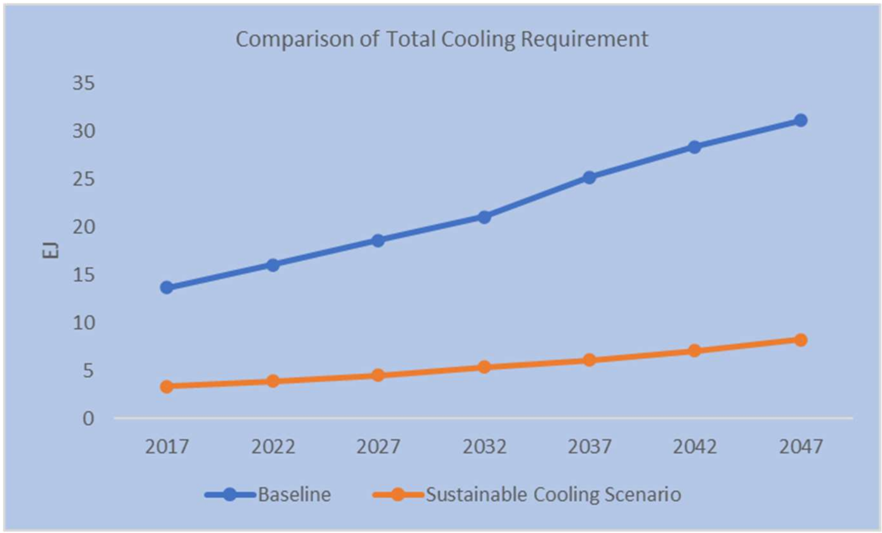
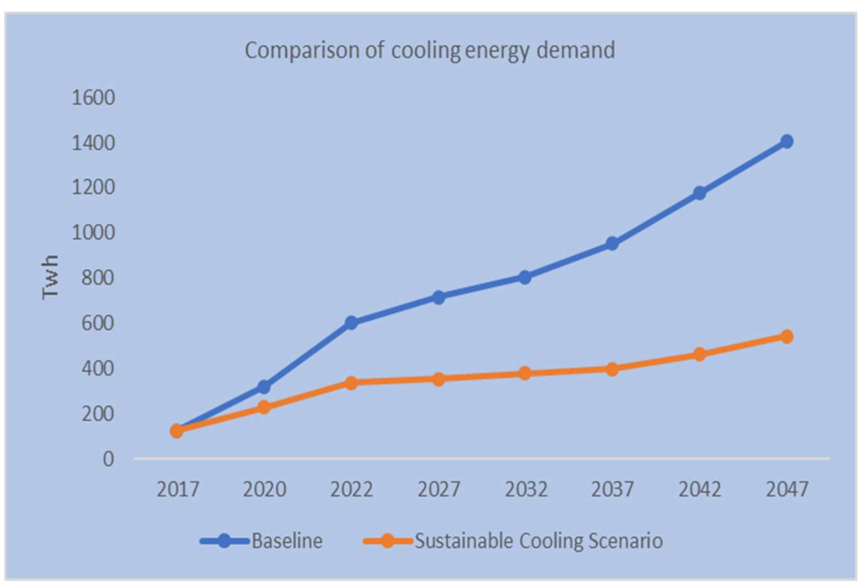


Figure 37: Reduction of total cooling requirement under Sustainable Cooling Scenario

2. **Cooling energy demand:** It is observed that under the Sustainable Cooling Scenario the total cooling energy demand also declines significantly compared to baseline energy demand by 2037. The estimated reduction is more than 50% of the baseline which clearly satisfies the ICAP target of 25~40% reduction. Figure 38 shows the percentage change in cooling energy demand compared to the Baseline condition.



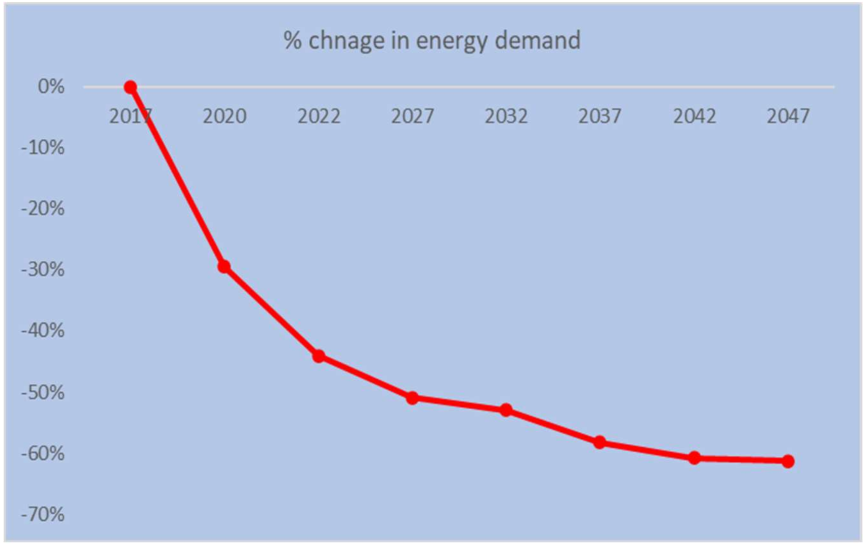
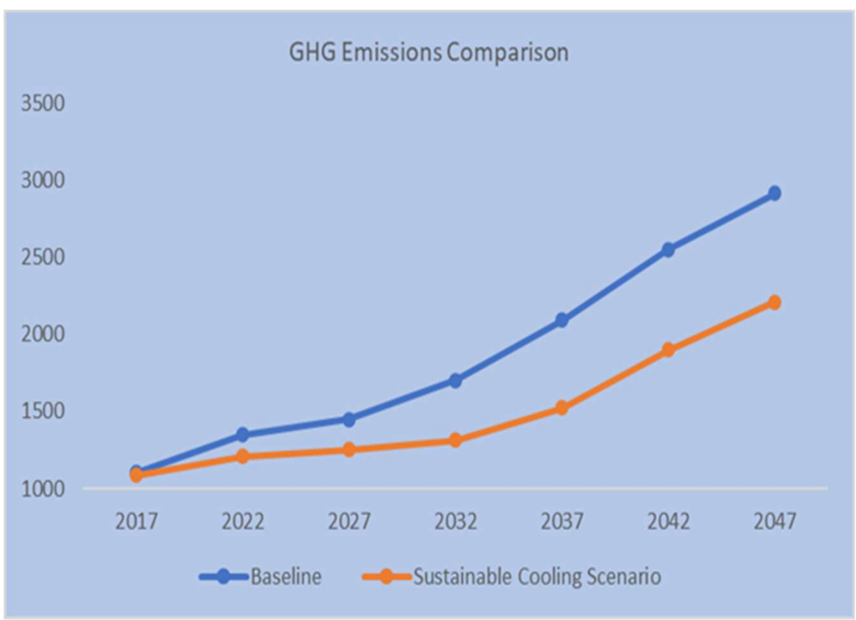


Figure 38: Change in cooling energy demand under Sustainable Cooling scenario

3. **GHG Emissions:** It is estimated that under the Sustainable Cooling scenario, the total CO_2 emissions may go up to 5200 Million ton by 2037 compared to 2800 Million ton in 2017. CO_2 emissions from electricity generation may up to 1525 Million ton by 2037 compared to 1000 million ton in 2017. Therefore, around 25% emissions reduction is envisaged under this scenario which can significantly contribute towards NDC achievement. Expected contribution is around 425 Million ton of CO_2 (see Figure 39).



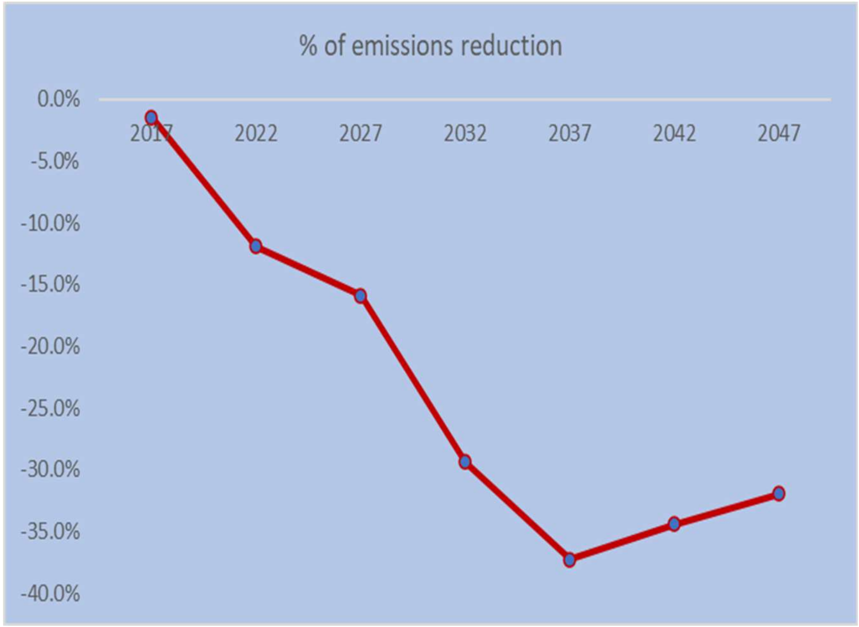


Figure 39: GHG Emissions comparison of Sustainable Cooling scenario

4. **Refrigerant Demand:** It is estimated that the total refrigerant demand under the Passive Cooling scenario will be around 82000 Metric Ton by 2037 compared to 47,000 metric ton in 2017. It is estimated that the reduction of refrigerant demand could be more than 65% by 2037 compared to the ICAP Baseline. This clearly helps India to achieve the ICAP target of refrigerant demand reduction up to 30% by 2037. Figure 40 shows the refrigerant demand and reduction in refrigerant demand compared to Baseline.

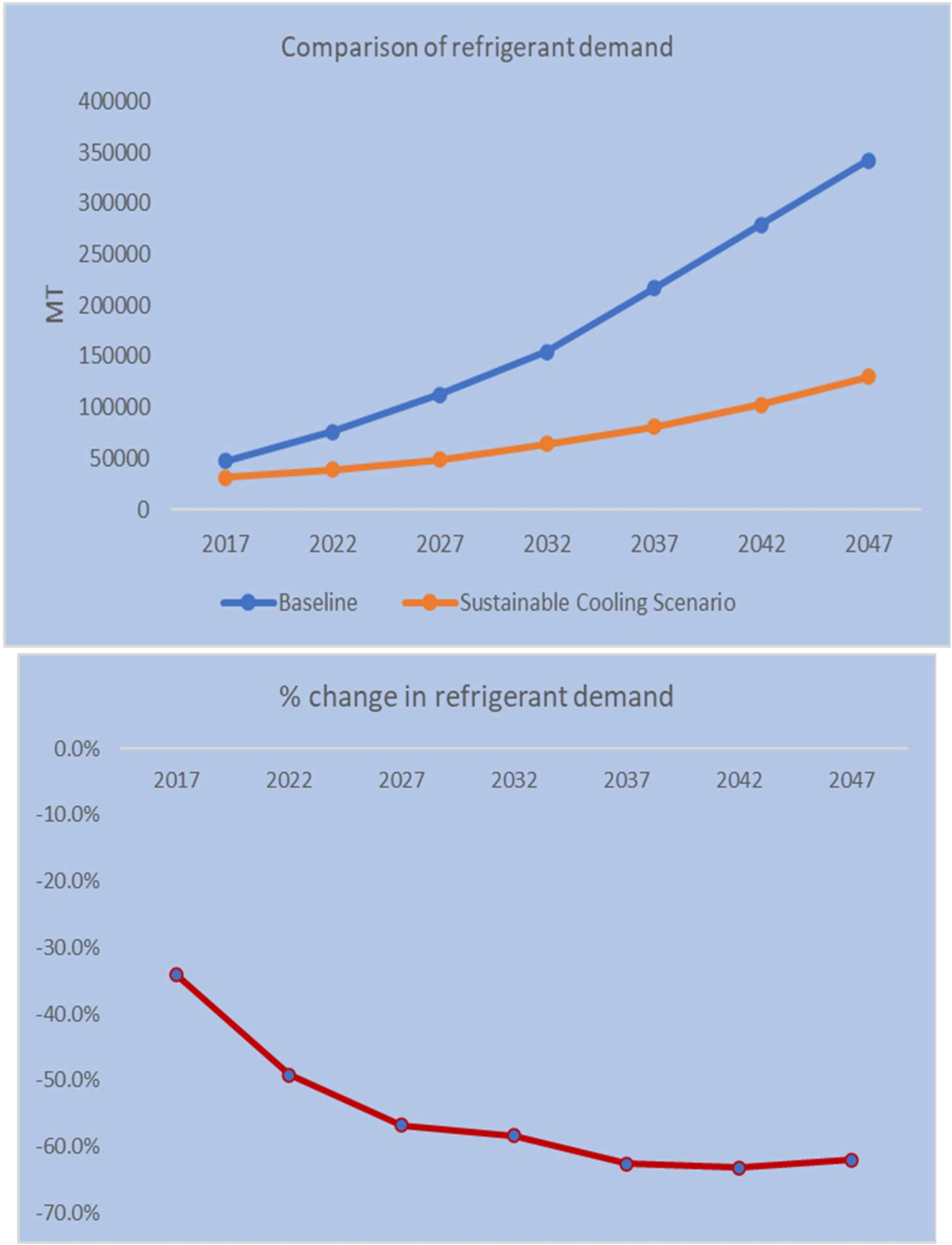
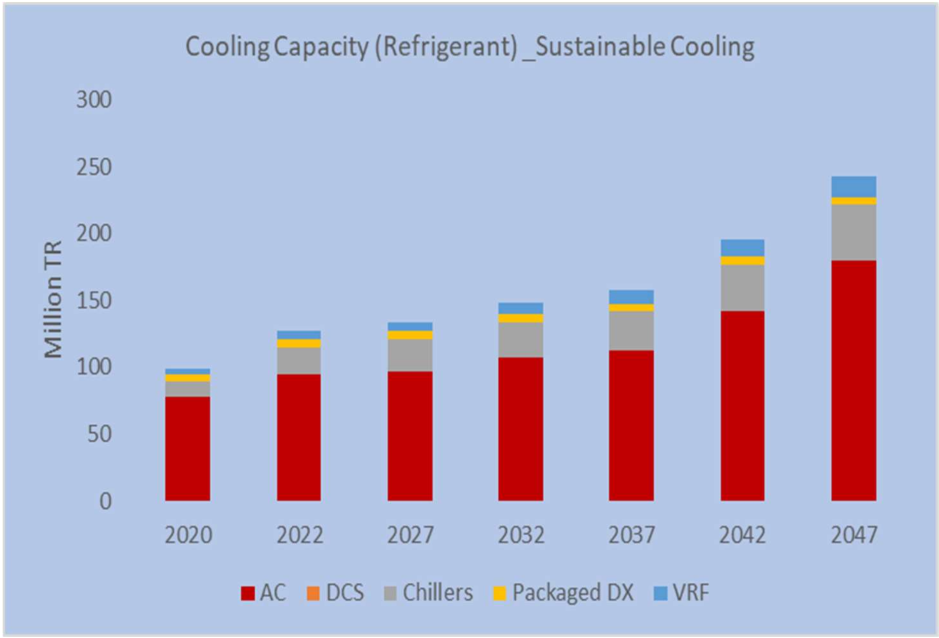


Figure 40:Refrigerant demand comparison of Sustainable Cooling Scenario

5. **Cooling capacity addition:** It is estimated that implementing the ICAP SCS scenario there would be around 160 Million TR of refrigerant based cooling capacity addition is required in India by 2037-38 compared to 70 Million TR in 2017 which may further go up to 250 Million TR by 2047. It is also estimated that there would be a capacity addition requirement of approximately 1250 million units of fans and 70 million units of evaporative coolers in the country to meet the cooling demand by 2037. Figure 41 shows the total cooling capacity addition requirement under the Sustainable Cooling scenario of ICAP implementation



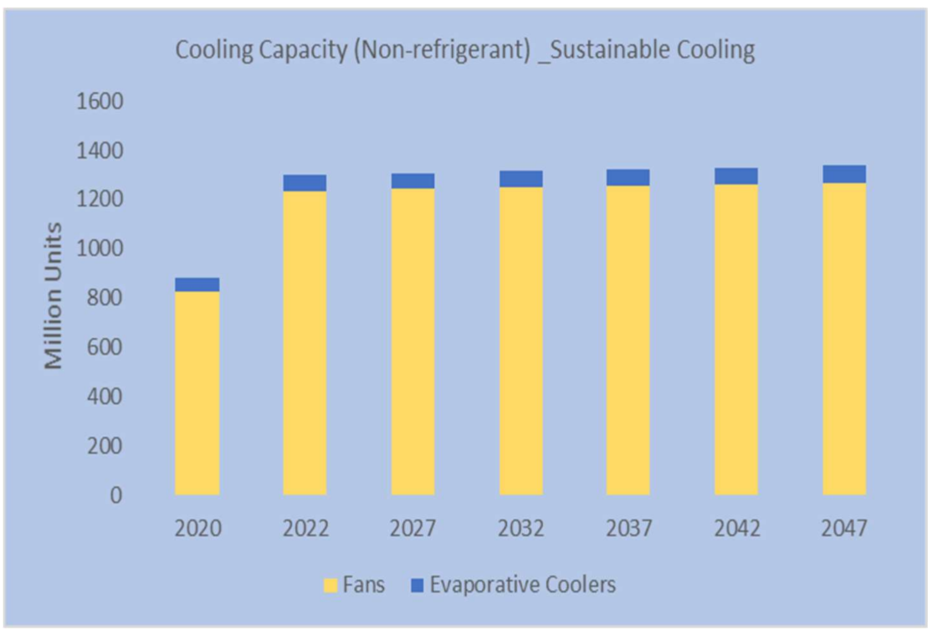


Figure 41: Cooling capacity addition in SCC

6. **Cooling investment demand:** It is also estimated that implementing ICAP SCS scenario there is an investment requirement of around USD 90 billion by 2037 compared to USD 45 Billion in 2017. In this scenario investment requirement reduces by around 55% compared to the Baseline investment demand. By 2047 the total cooling investment demand under in the SCS scenario may reach up to USD 115. These investments are only cost of cooling equipment and does not include any other infrastructural cost required to set up the plants. Figure 42 shows the cooling technology wise projected investment demand until 2047.

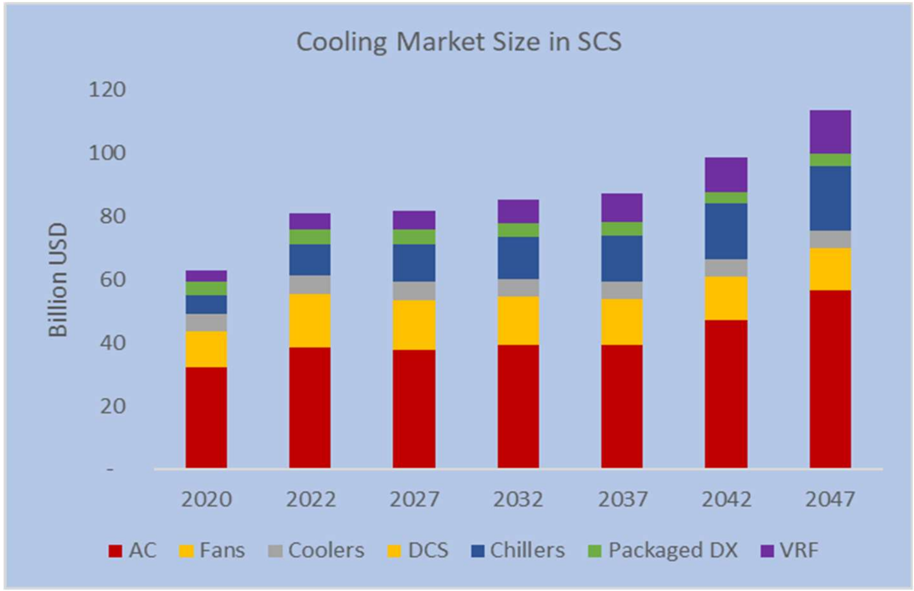


Figure 42: Cooling market size under SCS

In summary the Sustainable Cooling Scenario can help India to achieve the ICAP targets by 2037. Figure 44 shows the performance of SCS scenario in the year of 2037-38 for all the indicators relevant for ICAP implementation. Comparing these to BAU it is concluded that through passive cooling, building energy efficiency improvement and improving building envelope, ICAP can successfully achieve all its target. However, it requires significant amount of changes in overall approach of building energy conservation and efficiency improvement activities.

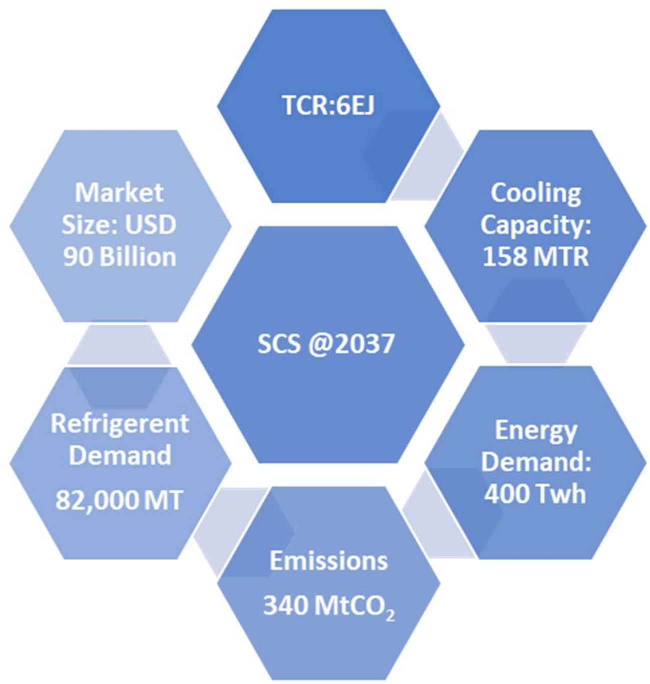
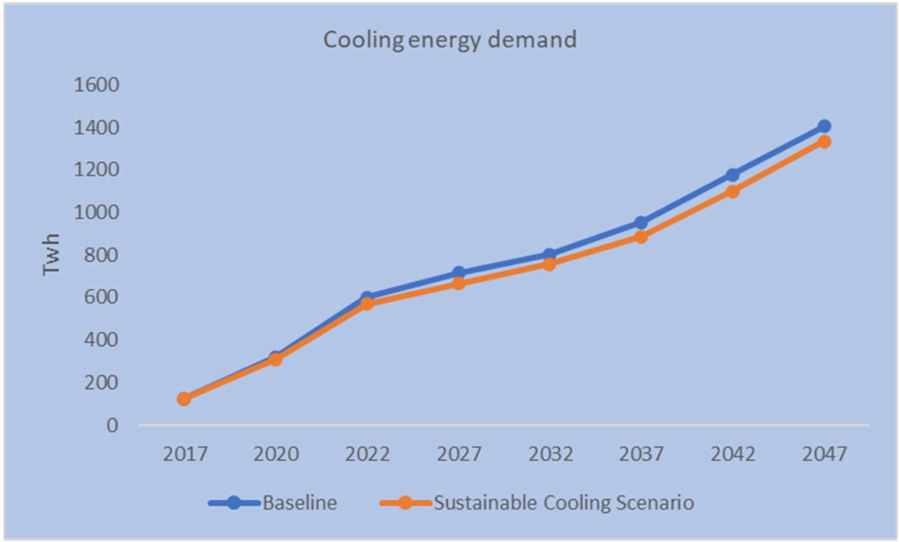


Figure 43: ICAP indicators in CCS in 2037

6.4.4 Smart Cooling Scenario-26C

The Smart Cooling Scenario (STS) is to provide sustainable cooling to all, while meeting the country's total cooling requirement with less energy and refrigerant use. The scenario is assumed to introduce advance and efficient cooling technologies and system. District Cooling System is considered to be one of the most promising technologies for space cooling. It is around 50% more efficient than any other commercial chillers. Its thermal performance is almost three times the standard air conditioning machines used for room cooling. DCS also reduces the use of refrigerant significantly to remove same amount of space heat. Its centralized design helps to optimize the capacity of the chiller units in terms of eliminating peak load capacities. In general, DCS capacity is designed to its average load rather than peak load and subsequently helps to reduce the cost (UNIDO). The size of DCS is much larger than any commercial chiller and functions as cooling water supply system within a large area of habitation. Though its initial investment is very high compared to individual building cooling system and it needs a complete system development planning aligned to city planning but its O&M cost is very low which makes it a reasonably good investment option. Another important advantage of DSC is use of renewable energy and gas which can further help the cooling system to reduce the GHG emissions. Solar assisted DCS is also a possibility in the rural areas for space cooling which can used for residential or for commercial purpose especially preservation of agricultural produces. In this scenario, all other cooling technology efficiency improvement is kept same as baseline. However, use of commercial chillers, VRF and Packaged DX is promoted through additional efficiency improvement and cost reduction. Use of fan and evaporative coolers are considered to be important cooling technologies in India which cannot be eliminated completely. For enhanced thermal comfort, fans can be used along with ACs which can help to increase the set point temperature high as well. It is assumed that fan is a staking technology in Indian space cooling whose presence is important to provide cooling to all. In fact, fan can be the part of sustainable and smart cooling system of India to implement ICAP. Performance of the scenario is assessed based on the four ICAP indicators as follows:

1. **Cooling energy demand:** It is estimated that under the STS:26C Scenario the total cooling energy demand decreases until 2030 and then increases due to increasing cooling demand. However, overall energy consumption is around 5% lower than the Baseline scenario until 2037. Therefore, in terms of cooling energy demand, the STS:26C scenario could not satisfy the ICAP target of 25~30% reduction of cooling energy demand while meeting the goal of Cooling for All. Figure 44 shows the percentage change in cooling energy demand compared to the Baseline condition.



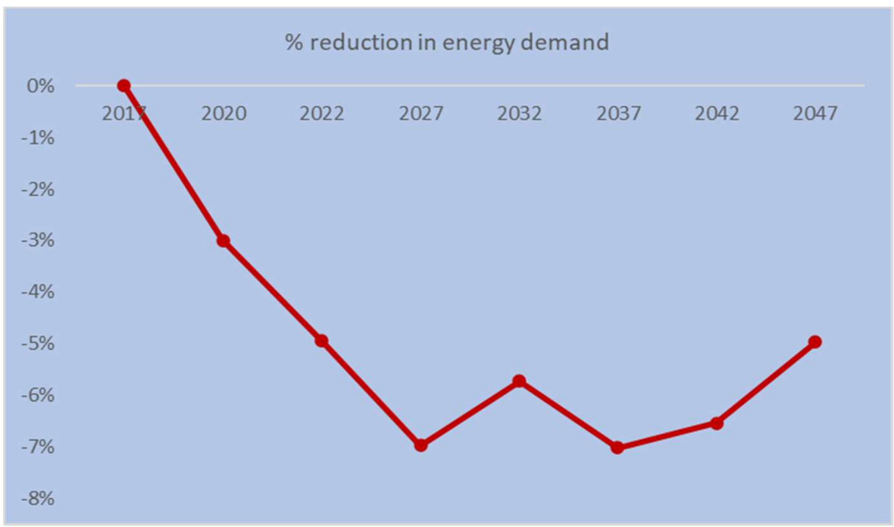
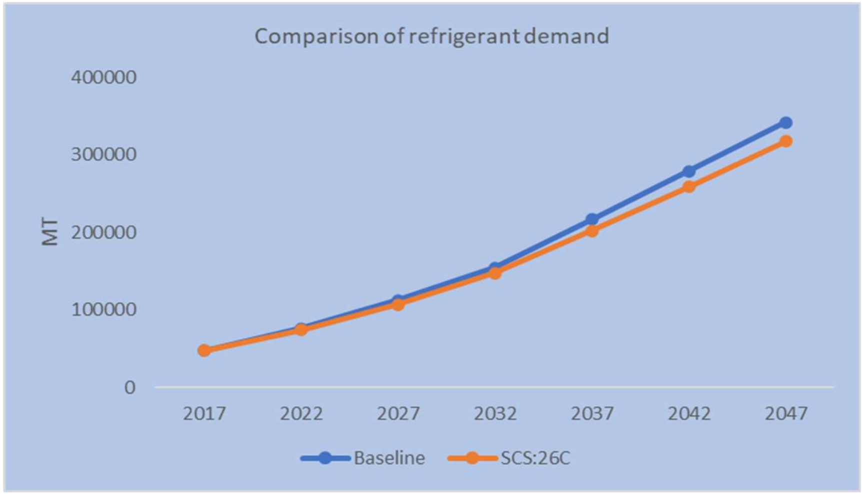


Figure 44: Comparison of cooling energy demand between BAU & STS:26C

2. **GHG Emissions:** It is estimated that under the STS:26C scenario, the total CO_2 emissions may go up to 5580 Million ton by 2037 compared to 2800 Million ton in 2017. CO_2 emissions from electricity generation may go up to 2000 Million ton by 2037 compared to 1000 million ton in 2017. Therefore, around 2% emissions reduction is envisaged under this scenario which can contribute towards NDC achievement a bit. Expected emissions reduction contribution is around 10 Million ton of CO_2 in 2037. Figure 45 below shows the comparison of GHG emissions between Baseline and STS:26C scenario.

Figure 45: GHG Emissions comparison between BAU and STS:26C

3. **Refrigerant Demand:** It is estimated that the total refrigerant demand under the STS:26C scenario will be around 202,000 Metric Ton by 2037 compared to 41,000 metric ton in 2017. It is estimated that the reduction of refrigerant demand could be around 15% by 2037 compared to the ICAP Baseline which does not satisfies the ICAP target of 25~30% reduction either. Figure 46 below shows the comparison of refrigerant demand between Baseline and STS:26C scenario.



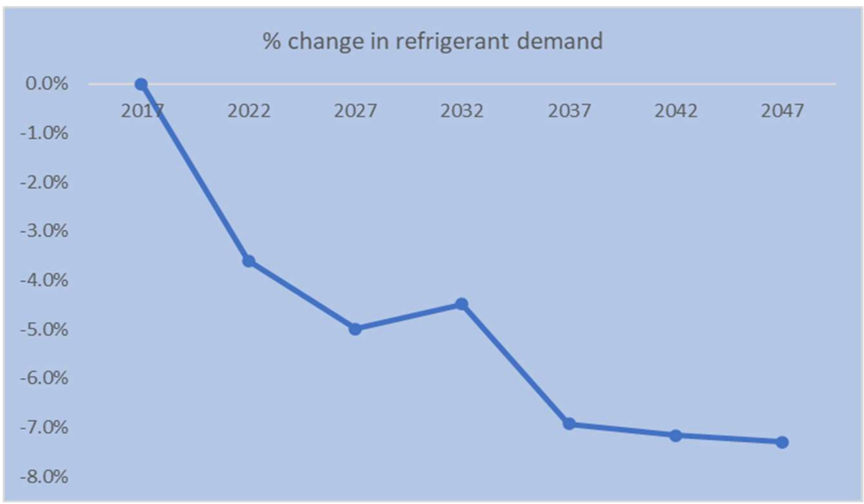
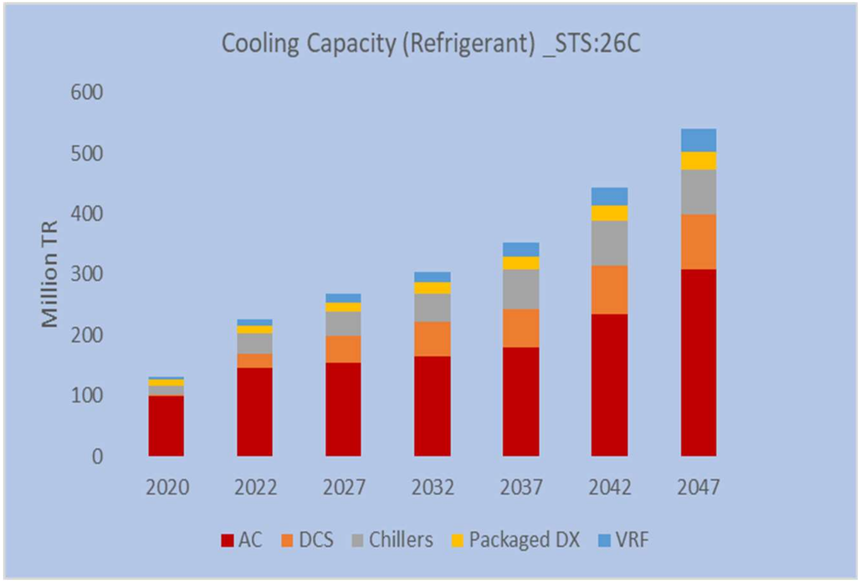


Figure 46: Refrigerant demand comparison between BAU & STS:26C

4. **Cooling capacity addition:** It is estimated that implementing the ICAP STS:26C scenario there would be around 352 Million TR of refrigerant based cooling capacity addition is required in India by 2037-38 compared to 70 Million TR in 2017 which may further go up to 540 Million TR by 2047. It is also estimated that there would be a capacity addition requirement of approximately 2300 million units of fans and 250 million units of evaporative coolers in the country to meet the cooling demand by 2037. Figure 47 shows the total cooling capacity addition requirement under the Sustainable Cooling scenario of ICAP implementation



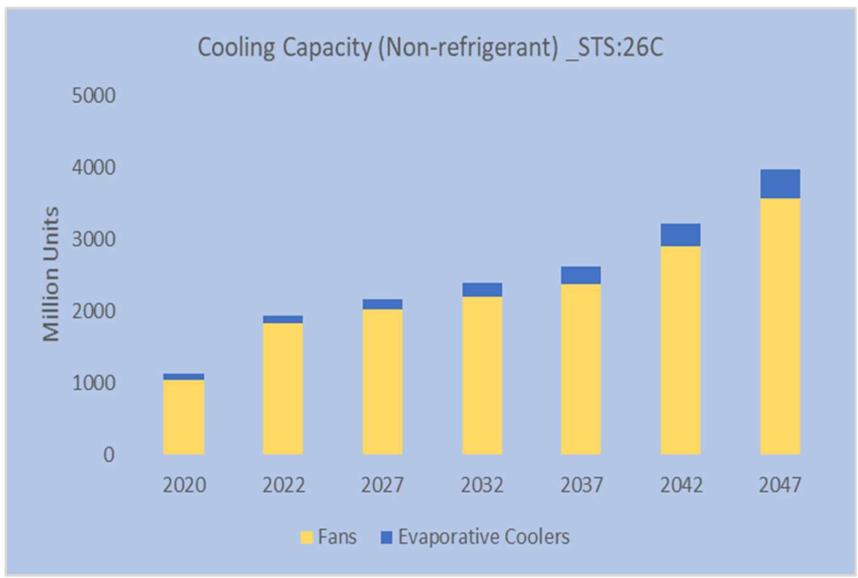


Figure 47: Cooling capacity addition under STS:26C

5. **Cooling investment demand:** It is also estimated that implementing ICAP STS:26C scenario there is an investment requirement of around USD 210 billion by 2037 compared to USD 45 Billion in 2017. In this scenario investment requirement increases by around 5% compared to the Baseline investment demand by 2037. By 2047 the total cooling investment demand under in the STS:26C scenario may reach up to USD 300 Billion. These investments are only cost of cooling equipment and does not include any other infrastructural cost required to set up the plants. Figure 49 shows the cooling technology wise projected investment demand until 2047.

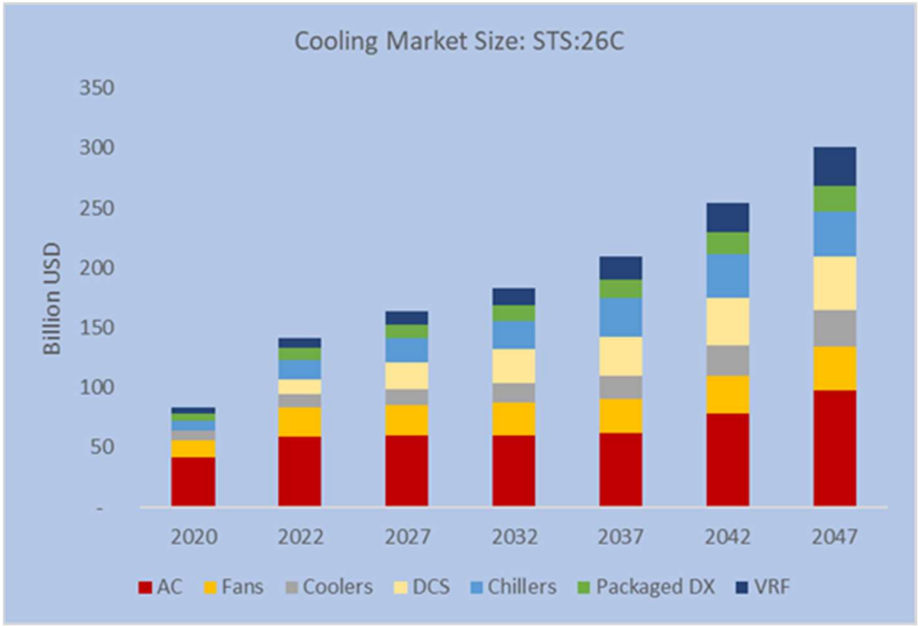


Figure 48: Cooling market size in STS:26C

In summary the Sustainable Cooling Scenario can help India to achieve the ICAP targets by 2037. Figure 50 shows the performance of STS:26C scenario in the year of 2037-38 for all the indicators relevant for ICAP implementation. Comparing these to BAU it is concluded that through passive cooling, building energy efficiency improvement and improving building envelope, ICAP can successfully achieve all its target. However, it requires significant amount of changes in overall approach of building energy conservation and efficiency improvement activities.

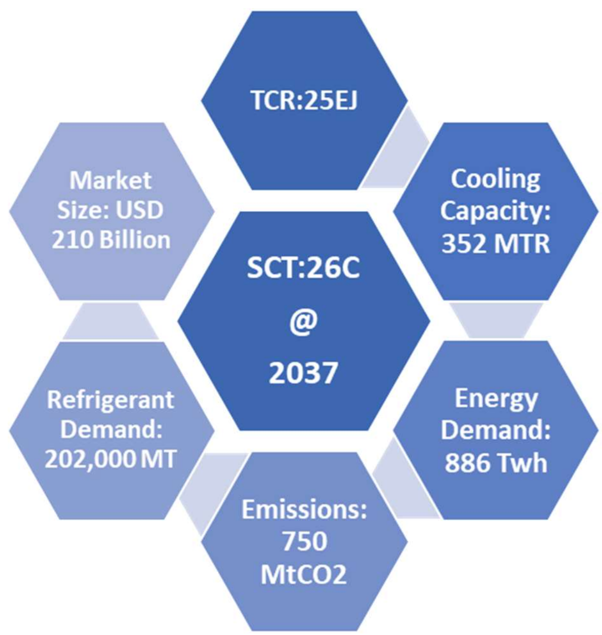


Figure 49:ICAP indicators under STS:26C in 2037

6.4.5 Smart Cooling Scenario-28C

This is the scenario same as STS:26C with only change in set point temperature to 28 degree C. The Smart Cooling Scenario (STS) with higher set point temperature is to provide endurable but acceptable cooling to all, while meeting the country's total cooling requirement with less energy and refrigerant use. It is a representation of the Adaptive Thermal Comfort (ATC) in the overall space cooling system in India along with the use of advance cooling technologies including District Cooling System. While 26 degree C is considered as the baseline set-point temperature for ICAP, 28C is thus considered as ATC Comfortable Cooling Scenario set point temperature condition. In this scenario keeping all other conditions of ICAP Baseline unaltered, the total cooling requirement is estimated with the increased set-point temp of AC & other refrigerant cooling equipment to 28C. In this scenario performance efficiencies of the cooling technologies are also revised upward in the range of 2~6% depending upon the place of use like residential or commercial. Performance of the scenario is assessed based on the four ICAP indicators as follows:

1. **Total cooling requirement:** Under the STS:28C, it is observed that the Total Cooling Requirement for India to meet the target of Cooling for All reduces by 12% compared to the Baseline requirement by 2037. Figure 50 shows the comparison of Total Cooling Requirement (demand) for the scenarios along with % of reduction.

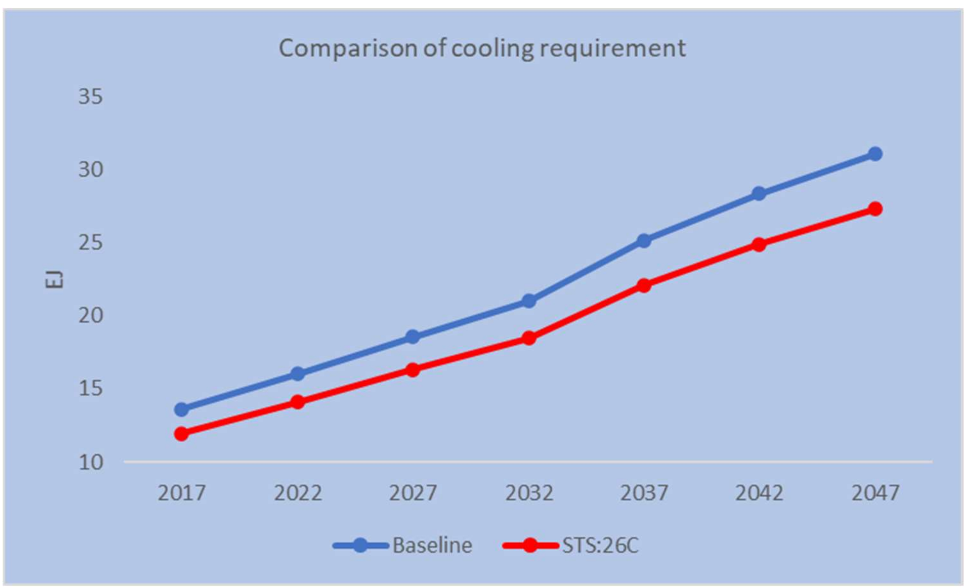
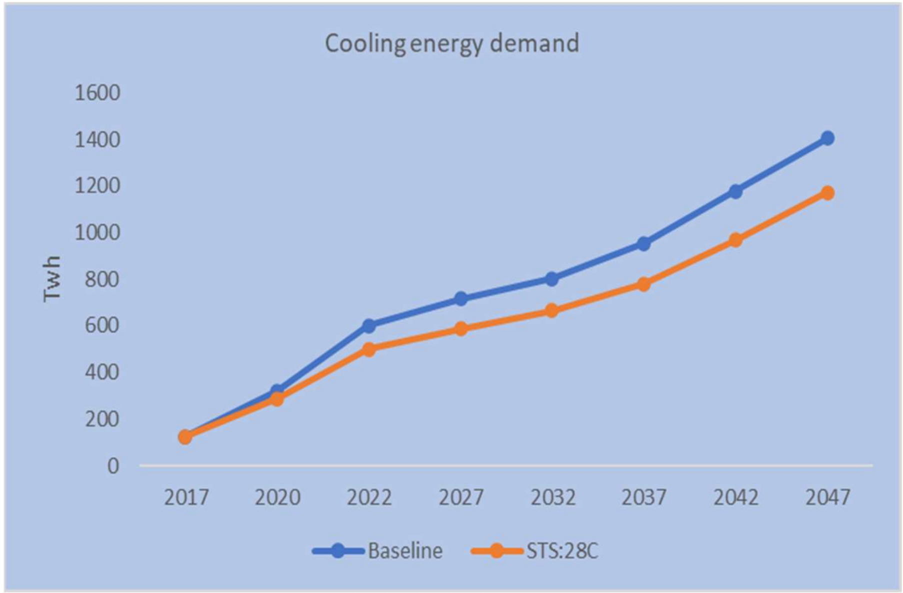


Figure 50:Comparison of total cooling requirement between BAU & STS:28C

2. **Cooling energy demand:** It is estimated that under the STS:28C Scenario the total cooling energy demand also declines significantly compared to baseline energy demand by 2037. The estimated reduction is around 15% of the baseline which still fall short of the ICAP target of 25~40% reduction. Figure 51 shows the percentage change in cooling energy demand compared to the Baseline condition.



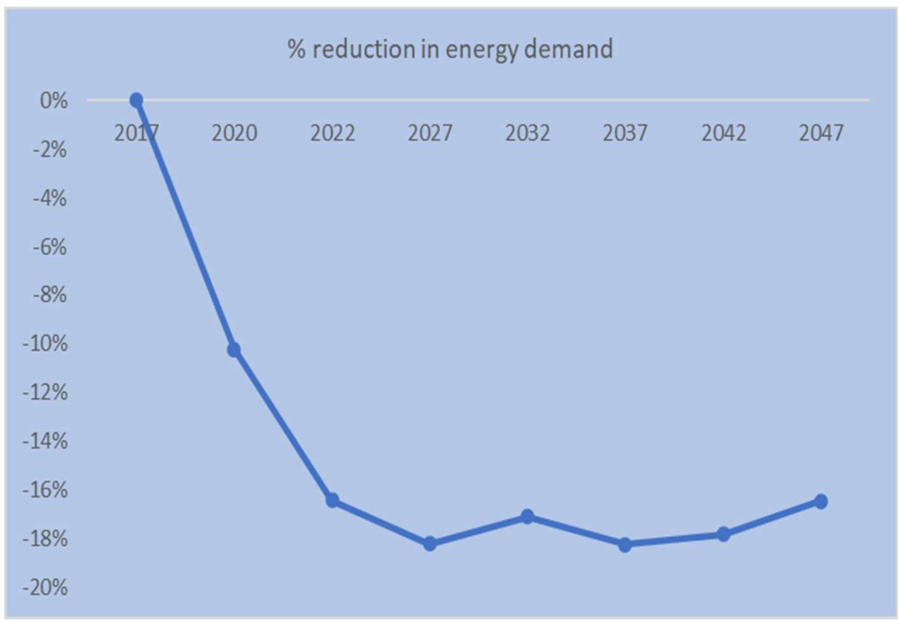
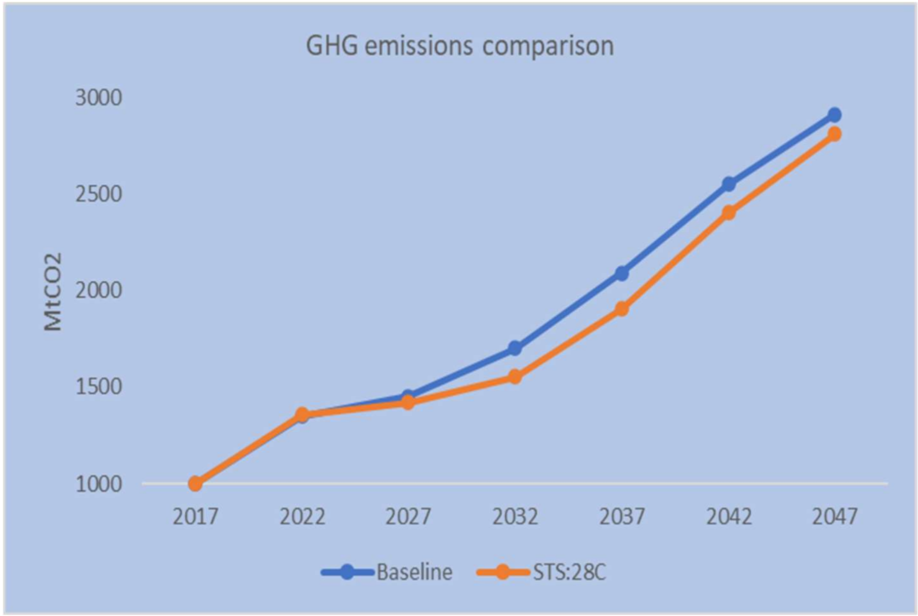


Figure 51: Comparison of cooling energy demand between BAU & STS:28C

3. **GHG Emissions:** It is estimated that under the STS:28C scenario, CO_2 emissions from electricity generation may go up to 1900 Million ton by 2037 compared to 1000 million ton in 2017. CO2 emissions exclusively for cooling is estimated to be around 662 $MtCO_2$ by 2037. Therefore, around 5% emissions reduction is envisaged under this scenario which can contribute towards NDC achievement a bit. Expected emissions reduction contribution is around 100 Million ton of CO_2 in 2037. Figure 32 below shows the comparison of GHG emissions between Baseline and STS:28C scenario.



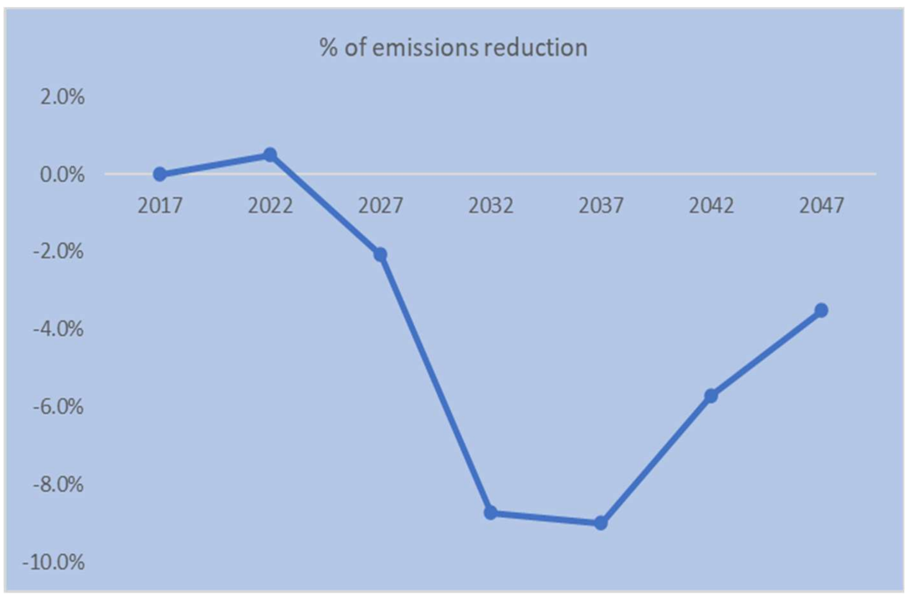


Figure 52: GHG Emissions comparison between BAU and STS:28C

4. **Refrigerant Demand:** It is estimated that the total refrigerant demand under the STS:28C scenario will be around 177,500 Metric Ton by 2037 compared to 41,000 metric ton in 2017. It is estimated that the reduction of refrigerant demand could be more than 25% by 2037 compared to the ICAP Baseline which satisfies the ICAP target of 25~30% reduction. Figure 53 below shows the comparison of GHG emissions between Baseline and STS:28C scenario

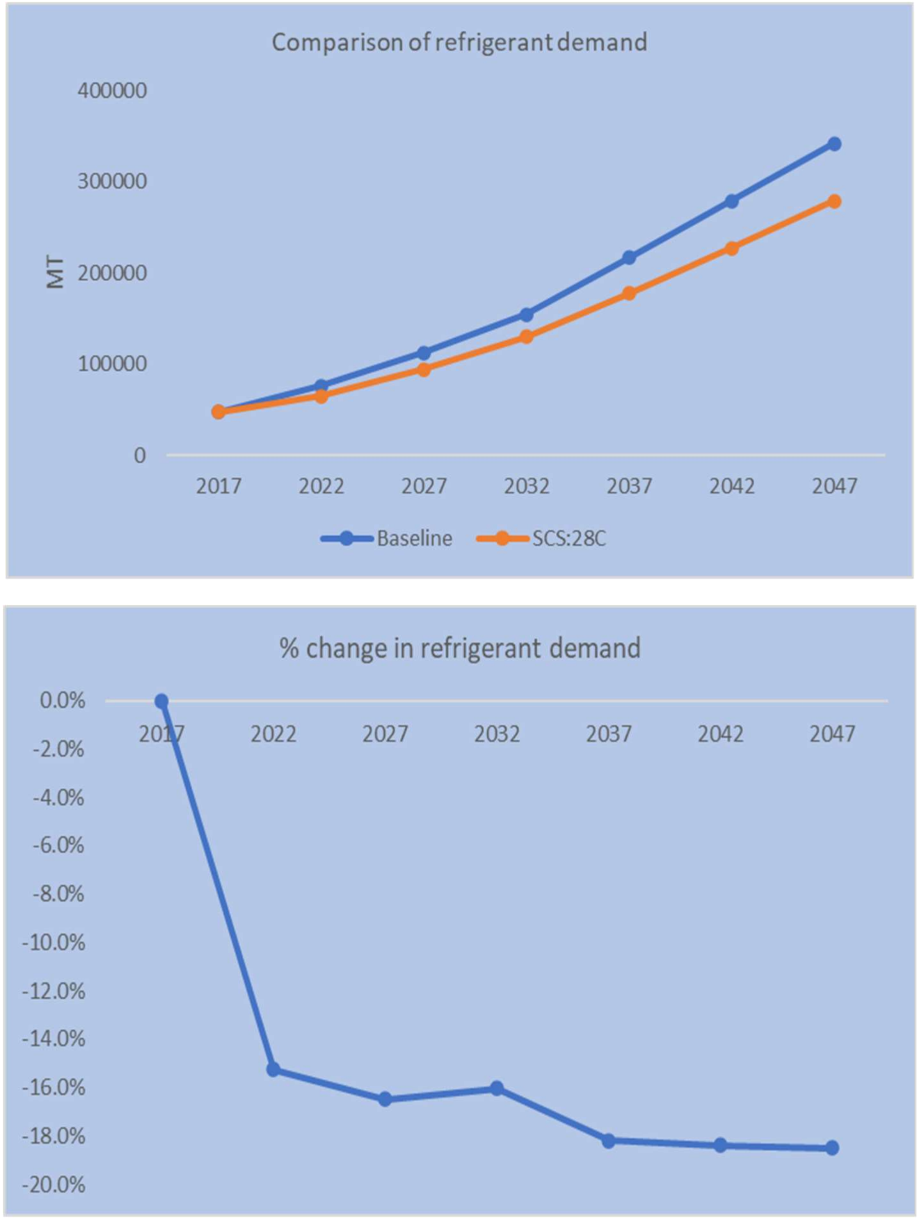
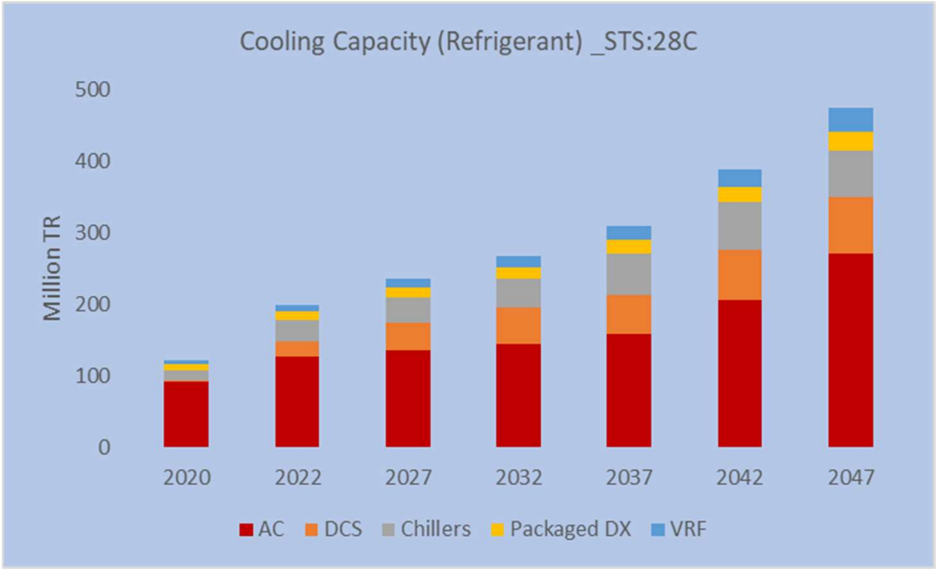


Figure 53: Refrigerant demand comparison between BAU & STS:28C

5. **Cooling capacity addition:** It is estimated that implementing the ICAP STS:28C scenario there would be around 310 Million TR of refrigerant based cooling capacity addition is required in India by 2037-38 compared to 70 Million TR in 2017 which may further go up to 475 Million TR by 2047. It is also estimated that there would be a capacity addition requirement of approximately 2080 million units of fans and 217 million units of evaporative coolers in the country to meet the cooling demand by 2037 under the STS:28C scenario. Figure 54 shows the total cooling capacity addition requirement under the Smart Cooling scenario of ICAP implementation



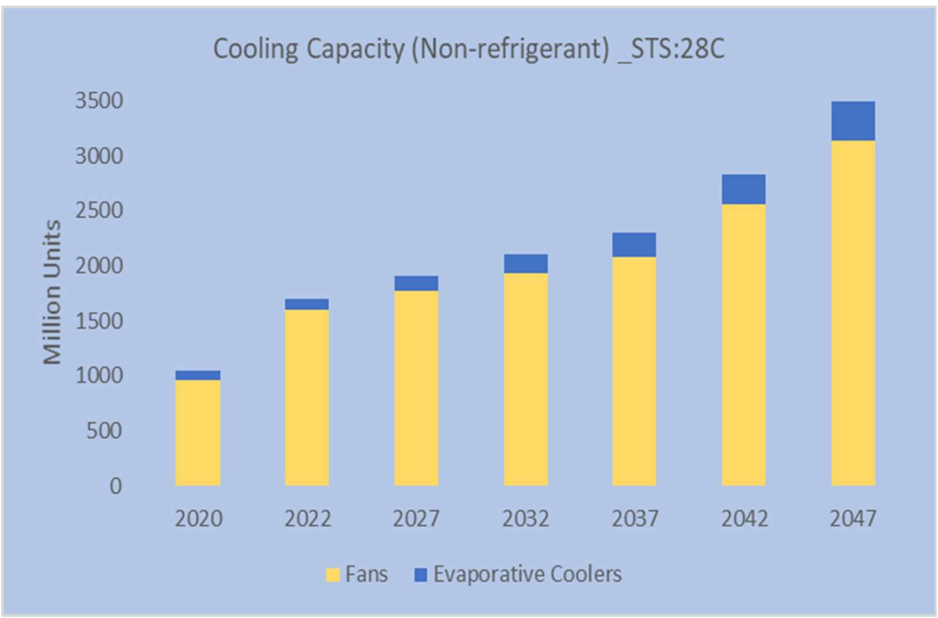


Figure 54:Cooling capacity addition in STS:28C

6. **Cooling investment demand:** It is also estimated that implementing ICAP STS:28C scenario there is an investment requirement of around USD 184 billion by 2037 compared to USD 45 Billion in 2017. In this scenario investment requirement reduces by around 10% compared to the Baseline investment demand. By 2047 the total cooling investment demand under in the STS:28C scenario may reach up to USD 265 Billion. These investments are only cost of cooling equipment and does not include any other infrastructural cost required to set up the plants. Figure 55 shows the cooling technology wise projected investment demand until 2047.

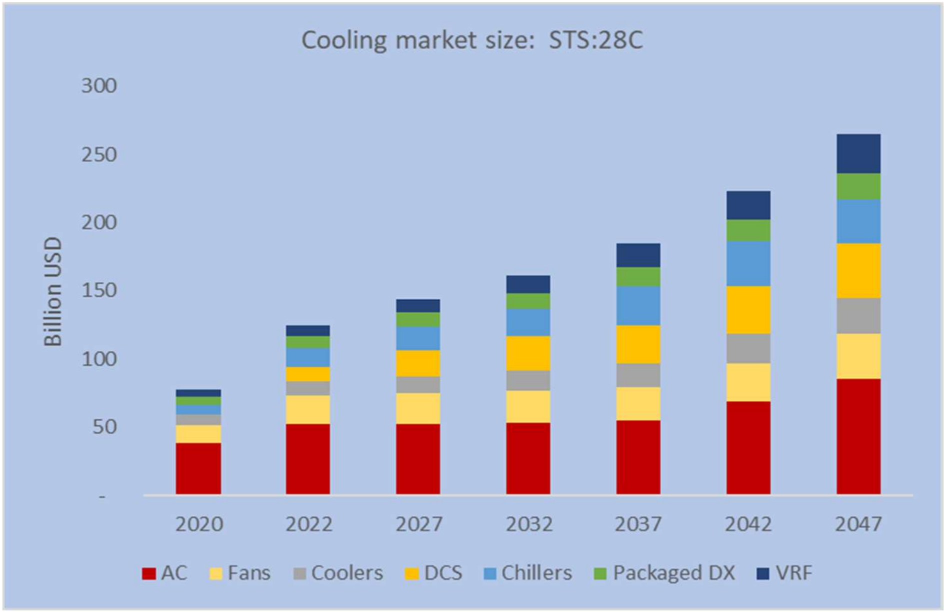


Figure 55: Cooling market size in STS:28C Scenario

In summary the Sustainable Cooling Scenario can help India to achieve the ICAP targets by 2037. Figure 56 shows the performance of SCS scenario in the year of 2037-38 for all the indicators relevant for ICAP implementation. Comparing these to BAU it is concluded that through smart cooling, building energy efficiency improvement and improving building envelope, ICAP can successfully achieve some of its targets, but it requires significant amount of changes in overall approach of building energy conservation and efficiency improvement activities to meet all.

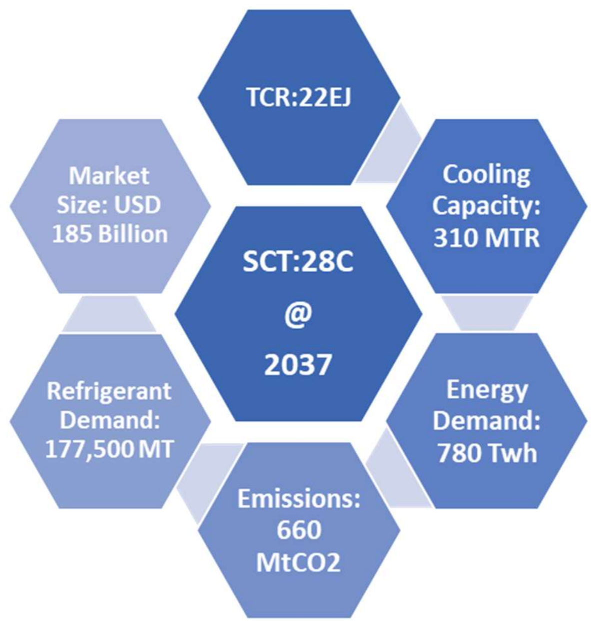


Figure 56:ICAP indicators under STS:28C in 2037

7.0 Summary and conclusions

It has been observed that all the above-mentioned scenarios are not equally capable to meet the ICAP target by 2037. In this section a summary is prepared to assess the scenarios in each context of ICAP targets. Table 11 below shows the summary of the findings:

Table 11: Summary of findings of all cooling scenarios

Scenario / ICAP Targets →	Reduction of cooling demand (20-25%)	Reduction in cooling energy requirement (25-40%)	Reduction of refrigerant demand (25% to 30%)
Comfort Cooling (CCS Scenario)	No Achievement: 12~15%	No Achievement: 12%	No Achievement: 12%
Sustainable Cooling (SCS Scenario)	Yes Achievement: 60~65%	Yes Achievement: 50~55%	Yes Achievement: 50~60%
Smart Cooling (STS: 26C)	No Achievement: N/A	No Achievement: 5%	No Achievement: 15-17%
Smart Cooling (STC:28C)	No Achievement: 12~15%	No Achievement: 14~16%	Yes Achievement: 20~25%

It is observed that, implementation of ICAP in India is a challenging task indeed. Given the goals of providing cooling and thermal comfort to more than a billion pollution is a daunting task. It is estimated that during 2107-18, only around 30% of total cooling requirement or demand is met with an estimated energy use of 120 Twh with a per capita cooling energy consumption is only around 100 unit per annum including the commercial space cooling. Global average of per capita cooling energy is around 1000 unit per annum. As a matter of fact, India is far behind the global average in terms of achieving the cooling demand for thermal comfort. However, ICAP aims to increase the cooling coverage to across the country with the focus of sustainable development covering aspects of economics, environmental and socials developmental issues.

While investigating the ICAP implementation in India, the study observes that there is an urgent requirement of a fixed baseline of cooling pathway in India which can be further used as the benchmark for other cooling scenarios. Considering the factors of technological development, scope of efficiency improvement, increasing cooling demand including population and economic development (in terms of rate of urbanization), the study set the baseline with 26°C set point temperature for cooling with an average efficiency improvement growth rate of 4% per annum between 2017 and 2037. It also considers to provide cooling to all possible corners of the country including urban and rural areas which is around 16 billion square meter areas of residential and commercial areas in 2017. It is estimated that the total cooling space could reach up to 50 billion square meters by 2037. It is estimated that during the period of ICAP first target years of 2037-38 the total electrical energy consumption of India for cooling would be 30% of total electricity consumed which is around 950 Twh. It is also estimated that to meet the cooling requirement of around 25EJ around 450 Million TR of total installed cooling capacity is required in the country which is closely around 6 times of current installed capacity in the country (aprox. 70~80MTR). It is observed that cooling efficiency is an important parameter to keep the growth the cooling capacity addition under control. It is estimated that for every 1% drop in annual growth rate of efficiency improvement can cause 17% increase in cooling energy demand in India. For example, if the growth rate of annual RAC efficiency improvement drops from 4.5% to 3.5%, electricity consumption for RAC in 2037 increases from 500 Twh to 633 Twh. Therefore, cooling technology efficiency plays a pivotal role in ICAP implementation in India. Nevertheless, it is observed that increasing demand for cooling is outpacing the benefit of efficiency improvement in terms of curbing the demand growth for cooling energy and refrigerant.

Comfort Cooling Scenario further indicates that reduction in set point temperature though reduces the overall cooling requirement and subsequently reduces energy and refrigerant demand, but 28 degree C set point also could not bring down the energy and refrigerant demand to the level of 25~30% of the Baseline consumption. It indicates that, just by adopting the measure for Adaptative Thermal Cooling with higher set point temperature ICAP targets may not be achieved.

Sustainable Cooling scenario is found out to be the best possible solution for India not only to achieve the ICAP targets but also to get additional benefits of GHG emissions reduction and sustainable development for all. It is observed that only active strategies for cooling efficiency and energy consumption reduction is not sufficient to achieve the ICAP targets. Passive strategies are essential to implement indeed. Thus SCS is a representation of the paradigm shift in building construction material use, designing and architype which can best fit India's climatic conditions and corresponding thermal comfort. Following the study of Mastrucci & Rao, 2019 the decent living standard for Indian people across varied climatic zones have been estimated based on cooling/heating energy required for sustainable living. Ranging between 40~50 Kwh/m2 is estimated to be the cooling demand across the country which is around 40% lower than the national average of residential and commercial space cooling requirement. It is observed under the Sustainable Cooling scenario the cooling requirement reduces more than 60% by 2037 compared to Baseline and subsequently its cooling energy and refrigerant demands are also lower than Baseline to the level of 50~60%. This scenario clearly helps India to achieve its ICAP targets. However, it also warrants for policy level changes in terms of stricter implementation of ECBC, GRIHA, LEED etc. to improve the building energy efficiency and reduction in operational energy requirement.

Smart Cooling Scenario with two different set point temperatures are scenarios with advance cooling technologies and system in place. It is observed that there is a limitation of increasing efficiency of the existing cooling technologies like RACs, Chillers, VRFs etc. Cost of efficiency improvement is also incremental with higher efficiency targets in these technologies. Therefore, it is important to look for alternative cooling technologies to strike a balance between energy efficiency and cost. In this context, the study experimented with District Cooling System which is one of the most promising cooling/heating systems which can provide cooling services at much lower cost and resources. DCS is estimated to be 50% more efficient at system level compared to the commercial chiller and thus can provide same amount of cooling with half of the energy input and refrigerant. As an experiment, the study assumed that by 2037 around 30% of the space cooling load will be served by the District Cooling network. Under this assumption, it is observed that introduction of DSC can displace around 150 Million TR of AC capacity with only 64 Million TR of DSC capacity. Therefore, every million TR of District Cooling System can replace 2.3 million TR of ACs. However, it is observed that in spite of having such saving potential, Smart Cooling Scenario also cannot help ICAP to achieve its set targets. Nevertheless, Smart Cooling Scenario with 28 C set point temperature could go close to the ICAP target which are 14~16% reduction in energy demand and 20~25% reduction in refrigerant use.

Therefore, it could be concluded that, to achieve the ICAP targets with the given level of efficiency improvement in cooling technologies successful implementation of all passive cooling strategies are absolute necessary. All the passive cooling techniques and methods should be fully adopted and implemented to construct new building stocks in the country and with all possible retrofitting in the existing building stocks. As a successful implementation strategy ICAP can thus adopt a mix pathway combining adoption of advance cooling technologies like DSC along with implementation of passive cooling techniques.

8.0 Recommendations and Plan of Action

Based on the analysis conducted in the study to evaluate the implementation of ICAP in India, it is understood that a combination of passive cooling and energy efficient cooling is the key to success. Thus, the study recommends to implement the ECBC and other building energy efficiency policies to its fullest extent and also adoption of efficient cooling system including District Cooling. Based on this recommendation, a set of action plans have been identified in a phased manner and describe below.

The Action plans have been split in three timelines which are defined as

- **Short Term:** The timeline of assessment is up to five years from the base year (2017-2022).
- **Medium Term**: The timeline of assessment is up to a decade from the base year (2022-2027).
- **Long Term:** The timeline of assessment is beyond a decade from the base year (2027-2037).

The Action plans have been developed to follow sustainable cooling practices. In a nut shell these actions would require certain transformations within the current HVAC systems that would incorporate

- ✓ Building designs to cap the operational energy requirement pertaining to state-of-the-art building materials. The benchmarking of required building material can be seen from Table-7.
- ✓ Prioritization of commercial chillers and VRF based refrigerant technologies over conventional AC units.
- ✓ Increased utilization of passive cooling technologies, with special emphasis on DCS.

The Table-12 describes the actions to be performed within the above-mentioned categories to implement the ICAP targets. The pivotal point of the action plan would be incorporation of benchmarking for building retrofitting. In case of short-term analysis, the results presented are only when building retrofitting has been done, because without it there would be no significant changes over the baseline scenario.

Table 12 Implementation plan of ICAP.

Activities	Impacts	Capacity/ Efficiency Target	Market Size	Timeline
A. Switch to commercial chillers and VRF units over conventional air conditioners with 30% growth of commercial chillers and 15% growth of VRF. B. ECBC notification across the country	1. 14% reduction of cooling energy demand over BAU. 2. 18% reduction of refrigerant demand over BAU. 3. 2% growth in CO_2 emissions from power generation 4. All states notify ECBC implementation mandatory	Chiller: 30 MTR VRF: 9 MTR Package DX:12 MTR Efficiency Improvement RAC: 4.06 EER Chiller: 3.5 EER VRF: 4.4 EER DX: 2.95 EER	Expected new market size = USD 20 Billion	Achieved by 2022 (Short Term)
A. Adoption of district cooling system by the municipal corporation after 2022 under a required growth of 5% until 2027. Linking DSC program to Smart Cities. B. 30% space area brought under ECBC Implementation (10 Billion m^2)	1. 45% reduction of cooling energy demand. 2. 45% reduction of refrigerant demand over BAU. 3. 10% reduction in emissions over BAU. 4. DSC Implementation in 10 cities	DSC: 20~35 MTR Other Capacity: Chiller: 35 MTR VRF: 11 MTR Package DX:14 MTR Efficiency Improvement RAC: 5 EER Chiller: 3.9 EER VRF: 4.6 EER DX: 3.25 EER	Expected new market size = USD 80~100 Billion	Achieved by 2027 (Medium Term)
A. Strategize nationwide adoption of DCS.	1. 50% reduction of cooling energy demand.	DSC: 50~60 MTR Other Capacity: Chiller: 45 MTR		

B. 75% space area brought under ECBC implementation (35 Billion m^2)	2. 55% reduction of refrigerant demand over BAU. 3. 20% reduction in emissions over BAU. 4. DSC Implementation in 30 cities	VRF: 20 MTR Package DX:20 MTR Efficiency Improvement RAC: 7 EER Chiller: 4.8 EER VRF: 5.2 EER DX: 3.9 EER	Expected new market size = USD 100~180 Billion	Achieved by 2037 (Long Term)

Reference

1.0 International Energy Agency, 2018. “ The Future of Cooling : Opportunities for energy efficient air conditioning” . Paris

2.0 Ministry of Environment, Forest & Climate Change (2019). “India Cooling Action Plan”. New Delhi: Ministry of Environment, Forest & Climate Change.

3.0 Motilal Oswal. 2018. Sector Update: Room Air conditioner.

4.0 Matrucci, A. and Rao, Narasimha. 2017. Decent housing in the developing world: Reducing life-cycle energy requirements. Energy and Buildings 186,p 405-415.

5.0 Matrucci, A. Edward, B., Shonali Pachauri, and Rao, Narasimha. 2019. Improving the SDG energy poverty targets: Residential cooling needs in the Global South. Energy and Buildings 152.

6.0 Alessio Mastrucci & Narasimha D. Rao (2019) Bridging India’s housing gap: lowering costs and CO2 emissions, Building Research & Information, 47:1, 8-23,

7.0 Kumar, S., Sachar, S., Kachhawa, S., Goenka, A., Kasamsetty, S., George, G. (2018). Demand Analysis of Cooling by Sector in India in 2027. New Delhi: Alliance for an Energy Efficient Economy.

8.0 GKSP,Energese & CEPT University. 2020. “Developing cost effective and low-carbon options to meet India’s space cooling demand in urban residential buildings through 2050.” Shakti Sustainable Energy Foundation. New Delhi.

9.0 NITI Aayog. (2017). ROADMAP TO FAST TRACK ADOPTION AND IMPLEMENTATION OF ENERGY CONSERVATION BUILDING CODE (ECBC) AT THE URBAN AND LOCAL LEVEL. NITI Aayog, Govt. of India, New Delhi.

10.0 Kumar, S., Sachar, S., Kachhawa, S., Singh, M., Goenka, A., Kasamsetty, S., George, G., Rawal, R., Shukla, Y. (2018). Projecting National Energy Saving Estimate from the Adoption of Adaptive Thermal Comfort Standards in 2030. New Delhi: Alliance for an Energy Efficient Economy.

11.0 BEE (Bureau of Energy Efficiency). 2014. , p. 000. Design Guidelines For Energy-Efficient Multi-Story Residential Buildings (Composite and Hot-Dry Climates). New Delhi: BEE. 000 pp.

12.0 BEE (Bureau of Energy Efficiency). 2018. Eco-Niwas Samhita 2018 (Energy Conservation Building Code for Residential Buildings) Part I: Building Envelope. New Delhi. BEE.000 pp.

13.0 NITI Aayog. 2015. India Energy Security Pathway Calculator 2047 (IESS). Ver 2.0 (& upcoming Ver 3.0-2017). New Delhi.

14.0 B. V. Venkatarama Reddy, K. I. Praseeda & Monto Mani (2017): Embodied and operational energy of rural dwellings in India, International Journal of Sustainable Energy, DOI: 10.1080/14786451.2017.1418742

15.0 K.I. Praseeda, B.V.V. Reddy, M.M. Embodied and operational energy of urban residential buildings in India, Energy and Buildings (2015), ttp://dx.doi.org/10.1016/j.enbuild.2015.09.072

16.0 Satish Kumar, Neha Yadav, Mohini Singh & Sandeep Kachhawa (2018): Estimating India's commercial building stock to address the energy data challenge, Building Research & Information, DOI: 10.1080/09613218.2018.1515304

17.0 EDS, 2011. Addressing Climate Change with Low Cost Green Housing. [Online] Available at: http://siteresources. worldbank.org/FINANCIALSECTOR/Resources/Low_ Cost_Green_Housing_Project_Report.pdf .

Key Project Contacts

Dr. Anindya Bhattacharya
Executive Director
The Celestial Earth
E-mail: Anindya.b@thecelestialearth.org
Phone: +91-9717773112

Report Contributors

Mr. Avishek Rauniyar, Energy Systems Modeller and Data Analyst, The Celestial Earth

Mr. Yash Khanna, Energy Systems Analyst, The Celestial Earth

Mr. Shankho Ghosh, Energy Modeller, The Celestial Earth

The Celestial Earth

319 , 3rd Floor, Ocus Quantum, Sector -51, Gurugram Haryana, INDIA

Ph.: +91-124-4009082 | E-Mail: info@thecelestialearth.org | www.thecelestialearth.org