How the cold crunch has impacts on Delhi, India in terms of residential AC adoption & space cooling energy demand

By Ali Metehan Gençmazlumo

Radboud University Nijmegen – Nijmegen School of Management
Master Thesis Business Administration – Business Analysis and Modelling

Supervisors: Dr. Sibel Eker & Dr Bareerah Hoorani

Student Number: S1039211

Radboud University

Abstract

Due to the rising temperatures nowadays, the need for cooling increases and boosts the adoption of AC, triggering more and more space cooling energy consumption. This phenomenon called the cold crunch is one of the most critical yet often overlooked energy issues of our time. The external main drivers of the problem, i.e. economic growth, population growth, and climate change, boost the problem to extent that developing countries in a hot climate might face looming disturbances in the near future. With the system dynamics methodology, a model has been developed to examine the cold crunch in Delhi, India with the aim of understanding how the major drivers shape the system and testing the effectiveness of suggested policies. Different scenario analysis has been conducted to capture plausible futures. The results highlighted that the logistic growth in AC adoption produces exponential growth in energy consumption and the different scenario analysis shows that economic growth is the most effective factor that boosts the adoption of AC. Suggested policies, which are increasing both efficiency of ACs and infrastructure conditions, decreased the space cooling energy demand by % 10 by 2050. The significant takeaway point from this study is that due to AC adoption being in the acceleration phase in Delhi, India, actions that are taken soon have more effectiveness overall.

Table of Contents

1. Introduction

1.1 Introduction to Topic

Life on earth is always in change. As acknowledged by the majority of people, the most impactful change happening to our world is that its climate is changing and getting warmer and warmer over the past decades. Climate change damages all living species' ecosystems and puts species a challenge to adapt to these changes. These crucial integrated changes affect humans both directly and indirectly. While humanity is trying to ease the causes of climate change, we are also adapting new lifestyles to cope with its consequences. One of the direct effects on humankind is that extreme temperature dangers human health and comfort. To deal with that problem, humanity already developed a cooling system appliance a while a few decades ago. Lately, rising temperatures and its effect which can be felt more and more around the globe, driving cooling appliances to be more commonly and frequently used. Naturally, this sharp increase in the usage and ownership of cooling appliances also creates more and more need for energy demand. While aiming for high ownership of cooling appliances due to sustain human health and comfort, it is challenging to manage and forecast the energy consumption caused by it.

This phenomenon in hand is called a “cold crunch” and it is expected that the world might face looming disturbances caused by this problem in the near future if it is not tackled soon.

1.2 Cause and relevance of problem

The cold crunch remains a blind spot for many authorities, it is one of the most critical yet often overlooked energy issues of our time. If the necessary precautions measures are not taken in time, it threatens not only human health and well-being but also access to clean and affordable energy.

There are many drivers that are causing the cold crunch phenomenon to raise, the basic and obvious one is climate. The heat arising from the combination of humidity and temperature put great thermal stress on populations, especially in hot climate countries. Furthermore, climate change is not just increasing the temperature it also causes more natural events like heat waves which eventually intensify the need for cooling appliances. The other crucial driver is economic growth and affordability. While the main underlying cause of demand and need for cooling is the climate, the extent to which that demand is satisfied is strongly influenced by income and wealth (IEA,2018).

_Currently, in developed countries, almost every household has cooling appliances while this ratio is very low in developing countries even where the climate is hot and humid. For instance, While %8 of the current Indian households have room ACs, this is predicted to grow six-fold in less than 20 years due to India ranks first among lower middle-income countries with an increasingly affluent middle class purchasing their first AC (Indian Cooling Action Plan,2019)

. This point out the fact that such countries in a hot climate with a growing economy are more on the target of a cold crunch which leads them to feel the effect more than others. There are more causes for the cold crunch such as urbanization, and population growth which will be explained in detail further in the document and also It is important to bear in mind that these causations are interconnected with each other, so they need to analyze together as a system.

There is a lot of information out there concerning the negative effects of severe heat on human health and function. Heat stress, in particular, has been associated with an increased risk of illness and mortality, as well as cognitive impairment, reduced productivity, and financial losses (Mastrucci et al., 2019).This has a direct relationship with Sustainable Development Goal 3(SDG3); good health and well-being (Khosla et al., 2020). .It is estimated that under current climate and socioeconomic conditions, three-quarters of humanity will face health risks from deadly heat (Mcgregor et al., 2015).

This clearly points out that access to cooling systems in many parts of the world can no longer be considered a luxury, it is a necessity for the survival and well-being of humans. In short, the ownership of cooling systems must be enhanced to meet SDG3, especially where countries are located in hot climates.

Secondly, the rise in the ownership of cooling systems works as a boosting factor on the amount of energy needed for cooling systems which will be stated as space cooling energy in the rest of this document. The rising demand for space cooling is already putting enormous strain on electricity systems in many countries, as well as driving up emissions. The energy needed for space cooling alone is projected to triple by 2050 (International Energy Agency,2018). This dynamic is highly probable to create an energy gap if it is not managed meticulously. Sudden overload of the demand for energy threats the supply chain and that might lead to disruptions in accessing affordable and clean energy (SDG7). Therefore, careful investigations and accurate trajectories must be developed to draw a road map for energy providers and necessary authorities so that it would be manageable (Mastrucci et al., 2019).

Overall, while aiming for high rates of access to cooling systems, the energy gap that might emerge must not be overlooked. This integrated nature of these two variables creates a dynamic that needs to be tracked and analyzed for a sustainable future.

1.3 Problem framing in literature

The problem on hand has a wide domain and high complexity due to its broad nature. Therefore, there are different approaches taken to research this topic. These different perspectives have been used in different frameworks to forecast trajectories of cooling demand and energy consumption on global and country levels. There are many predicted results under various boundary assumptions. However, all empirical evidence is in the same direction when it comes to the expected behavior of cooling demand and energy which is the adoption of cooling appliances shows an S-shape increase in the near future while boosting energy consumption incrementally.

Generally, when problem variables are framed, there are main classifications and differentiation for cooling devices and space. The often-used ones in the growing literature are AC because it is the most adequate, common technology for cooling, and residential space is in the spotlight. Approximately, there are 2 billion AC units now in operation around the world, and %70 of them account for residential units (İEA,2021).This paper will also follow the common frame and look into residential AC demand and energy consumption caused by it, due to its widespread impact and trackability. As a consequence of the problem complexity and many variables associated with the problem, researchers in this field examine cooling as a system comprised of main drivers with key factors and lever points (Khosla et al., 2020). These identified strong drivers and lever points have been followed to form the basis of this research.

The first and foremost important drivers are the country's economic growth and climate change. Generally, while developed countries highly have cooling appliance ownership rates, developing countries have very low rates even though most of these countries are in the hottest areas of the world. Only 8% of the 2.8 billion people living in the hottest regions of the world possess AC (IEA,2018).This hinders great potential demand for AC in developing countries with rising income and rising temperatures. Population growth is another significant driver for rising cooling demand as it is for many other phenomena. The combination of global warming, population increase, and income growth creates reinforcing impacts on the energy consumption for cooling. The other impactful driver is urban heat island (UHI) which affects highly populated cities to get significantly warmer than their surroundings due to human activities and modification of land. This leads to an increase in the need and consumption of ACs in UHI areas comparatively more than in rural areas.

Moreover, the energy gap not only depends on the amount of AC in usage, but it is also strongly dependent on lifestyle, social, and behaviors which are determinants of consumption patterns (Creutzig et al., 2018).These behavior patterns of individuals consist of levers points that might create change in the system. Prior studies have noted the importance of a couple of factors which are; the efficiency of AC units, the efficiency of buildings, preferred set temperature, and average hours of usage. These variables form the basis for understanding the dynamics of a household's energy consumption and where interventions can happen for the transition towards sustainable cooling. Whereas these major factors play a role, the dynamics of air-conditioning are country-specific and relate to demographic and infrastructural characteristics (Pavanello et al., 2021).Therefore, the variables defined above differ from region to region and also underline the importance of examining space cooling demand regionally rather than globally or continentally for sake of accuracy.

According to the in-depth analyses from International Energy Agency, there are two strong policies that might help to curb the potentially huge growth in demand for cooling. These are boosting the energy efficiency of cooling equipment and improve the energy performance of buildings. These two policy options have been suggested to governments to implement as soon as possible in order to ease the upcoming impacts in near future and reach the ultimate goal in the long term which is meeting the legitimate needs of consumers for thermal comfort while using the smallest amount of energy and keeping emission and costs to a minimum (IEA,2018).These policies has already started to implement by some governments and they have a promising influence on declining the trajectories for space cooling energy demand. These two policies will be taken as policies analysis for this research.

Models that in developed for projecting the cooling space demand and AC ownership in the existing literature take different values when it comes to estimating the future values of external drivers like population, economic growth, and climate change. This helps to discover possible futures ahead and compare differences. In the light of this, this research will also adopt the framework of scenario analysis too.

1.4 Research Gap

Understanding the growth in cooling demand and finding ways to sustainably shape its trajectory remains a complex multidisciplinary task (Khosla et al., 2020).
Up to now, far too little attention has been paid to a holistic and systemic view of this problem by empirical studies. This research gap motivates us to use the system dynamics approach in this paper to forecast possible trajectories of AC ownership and space cooling energy demand. Mostly because the system dynamics approach provides a holistic view of highly complex dynamic systems via modeling the structure of the system and analyzing its behavior of it (Stermann 2000).

The embedded system of Ac adaptation and energy consumption caused by it has many layers from local to global and many studies used the top-down approach to show the significance of the phenomenon to attract awareness of the problem. However, there is a paucity of literature on the cold crunch and narrowness in its scope (Khosla et al., 2020).This means that there are not many models that specifically calculate AC ownership and energy consumption for local areas. This makes challenging to come up with an accurate trajectory of ACs and energy consumption. Therefore, this paper is motivated to research the bottom-up approach in order to narrow down the scope and to have a more adequate trajectory for the specific ecosystem. The border of our scope will be local city and households' behavior. The chosen city to study for this paper is Delhi, India.

What kind of properties makes Delhi a suitable and highly important case for this research are; the high economic growth rate, one of the most urbanized cities in developing countries, and the city is located in a hot and humid climate. This points out the significance of chosen sample. Due to rising trends of main drivers, many people might face extreme heat conditions without AC in the coming near future, and also government might not provide sufficient, affordable energy due to the unexpected rising energy demands.

Lastly, the majority of the research in this field focuses on the distant future of 2100 while there are many statements in the literature that are pointing out that demand for cooling is at the brink of the steep part of the S- curve and soon the severe impacts could be seen in near future. Therefore, this research will attempt to examine the phenomenon in the near future horizon 2050.

1.5 Objective and research question

In the light of different frameworks of the problem in the literature and research gaps, this research aims to improve the trajectory of AC ownership and energy consumption at the local level towards, a sustainable future, sustainable goals of human well-being, and energy poverty gap. (SDG 3,7)

To support the analysis a System Dynamics model will be developed and implemented by determining the boundaries, important variables, major mechanisms, and performance indicators. Based on this model, the scenario analysis will be developed under different assumptions for highly important and uncertain factors that drive the system's dynamics. The combination of scenarios is expected to develop a wide range of trajectories on plausible futures and improve the insights. For each scenario suggested policies will be implemented and tested to assess their effectiveness.

The scenario will be based on different values of population growth rates, climate change effect, and GDP growth.

For to achieve mentioned objectives by addressing the following research questions.

"How do the major drivers of the system shape its forecast for AC ownership in India, Delhi until 2050?"

"What is the effectiveness of suggested policies for declining space cooling demand in different scenario settings for India, Delhi by 2050?"

"What insights could be drawn from the behavior of the system with respect to meeting SDG goals 3 and 7?

1.5 Outline of the thesis

After this introduction to the topic, the second chapter addresses the theoretical background of the cold crunch problem with a conceptual model which indicates the general overview of casual interrelated relationships of the system variables. Chapter three represents the methods that have been used to investigate the research question and the research ethics which are taken into consideration. The fourth Chapter is explaining the model's key concepts, the assumptions that are made to develop the model, and the validation of the model. Chapter five exemplifies the simulation results of different scenarios and policy analysis. These findings are discussed and concluded with respect to the research aim in the sixth chapter. The final chapter is for reflecting on the findings of the research for limitations and future research.

2. Theoretical background

2.1 Outline of relevant literature

This section will provide different elements from the literature which this paper proceeds as a framework. First, it will present the key drivers causing the behavior and levers points that can change. This will be followed by suggested policies in order to ease up the unwanted consequences. Later, the developed conceptual model will be explained, which would reflect the relationships between the concepts discussed. This would set a framework for further modeling of the whole system which will develop later in the document.

2.2 Drivers of cold crunch: definitions, implications, and measurements

The cooling demand and its trajectory are becoming a very trendy topic to research in the last decade due to the importance and consequences that might create in the near future. The main reason behind this is that external factors have been accepted and proved their powerful impact on driving the space cooling demand and AC ownership. These external factors are known as the main drivers of the behavior that we are experiencing right now. The main drivers feeding this growth is namely, climate change, income growth, population growth, and urbanization. These drivers are explained in detail below.

2.2.1 Climate:

India is located between 6 ° 44' N and 35 ° 30' N parallels and 68 ° 7'E and 9 °25'E meridians showing a variety of its climate regionally and during the last decades, India has experienced an increase in surface temperatures and heat waves (IPCC 207 WG II). This shows that India is perfectly important to examine the cold crunch phenomenon and the necessity of examining regionally.

As global temperatures rise, the number of people who are exposed to non-optimal heat conditions is increasing and the duration of being exposed to it is also increasing. Rising extreme temperatures are changing global requirements for thermal comfort and this leads to shifting demands for cooling systems (Khosla et al., 2020).But also, humidity is an essential factor as well. Because it directly affects the thermal comfort of individuals by holding water vapors in the air which makes it hard for the human body to cool down. The combination of humidity and temperature known as the heat index is the cause of heat stress. As mentioned earlier, heat stress has an influence on the well-being of human health as much as productivity. These effects vary in vulnerabilities based on age, and gender. Furthermore, the adverse impacts of heat stress depend on factors such as local climate, building construction, and individual habitation which means there are differences in estimated temperature thresholds for heat-related negative health outcomes across regions and climates (Mastrucci et al., 2019). The inference from this is that climate change driving heat stress on people and as a solution, people possess cooling appliances more and more. While people who cannot afford it nor do not have access to the cooling appliance are at risk of exposing deadly heat. This goes against to sustainable development goal of good health and well-being (SDG3). Therefore, government and authorities have to identify and map pathways to make cooling appliances accessible and affordable for those exposed to such a situation, in order to meet sustainable development goals.

Generally, literature are using Cooling Degree Days (CDD) as a parameter to evaluate the impact of the local climate. It is a commonly accepted measurement for the calculation of the cooling needs of people in that region. CDD is an index of the energy demand to cool buildings and it is calculated by subtracting the set temperature from the average daily temperature overall, the sum of positive values gives the amount of day for cooling (Sivak, 2009). Biardeau et al (2019) find out that India has the highest exposure to increased CDDs anywhere in the world. However, in order to reflect CDD accurately, it must include the humidity factors as well. This is neglected in many empirical studies, for the sake of accuracy, the humidity will be added to calculations of CDD in this paper.

2.2.2. Economic Growth:

As much as climate set the needs of cooling appliances in order to meet that need households must be able to afford to buy such technologies. According to IEA analysis from across the globe with more than 500 country data points, the relationship between average per-capita income and AC ownership founded to be strong, especially for the countries in the hottest climates.The income has a strong nonlinear relationship with both AC ownership and consumption which starts off slowly and when a household income reaches a certain threshold it follows a steeper rise. This threshold has already been reached by the developed countries leaving developing countries to mostly drive the future cooling demand trajectory.
The other factors that are affecting the affordability of AC are the structure of the economy, the price of ACs, and the cost of electricity. One of the surveys conducted with households in Delhi, India reported that the majority of the non-AC households are not switching to ACs yet due to prohibitive costs, % 90 also nearly %40 percent mentioned high recurring costs like electric bills and maintenance (Khosla et al., 2020). This is why the increase in the family income is associated with a higher capacity for consumption and in particular, with a significant increase in the demand for air conditioners (Santamouris, 2016).This raises the point that with the increasing pace of economic growth in developing countries the transition phase to AC adoption will be faster and more impactful. For instance, while growth in the gross domestic product (GDP) worldwide is assumed to average 3.1% over 2016-2050, it is highest in India with 5.6%.

The literature has commonly used the framework of calculating the income of households with the purchasing power parity (PPP) with respect to GDP per capita and economic growth (Akpinar-Ferrand & Singh, 2010). This way all factors mentioned above are captured by this measurement. This research will also be going to use the same approach.

2.2.3 Population Growth & Urbanization:

The population is another significant driver of space cooling demand as it is related to many other problems as well. This factor is strongly linked to economic growth because fast-growing populations are also expected to be high economic growth as well (IEA,2018). The world population is increasing constantly. According to the United Nation forecasts, the total world population in 2000, was close to 6126 million, and a significant increase up to the end of the century is predicted. Based on the predictions the total population may vary between 8179–8821 million by 2030 and 8710–10721 million by 2050. (McNicoll, 2005).A big share of the increase in World population comes from regions with the hot climate which will add up more to space cooling demand eventually.

Secondly, population growth gives rise to the urbanization factor. Especially in developing countries, the proportion of people living in the cities getting higher and higher every day mainly due to changing living standards. It is a fact that cities are hotter comparably rural areas. This can be explained by the basic principle; any given kind of human activity absorbs energy which causes the surroundings to get warmer and when there are an excessive amount of such activities would change the temperature. This effect is known as the urbanization heat island effect (UHI). UHI influence is bigger when the more densely populated a city and the bigger the land is. An increase in the feeling temperature feeds the need for cooling as well as contributing more to the heat island effect which forms a reinforcing loop. It is estimated that just air conditioning usage can raise temperatures by more than 1°C overnight in some cities (Salamanca et al., 2014).The noteworthiness of UHI can be understood from this statistic and that is why this paper chooses Delhi, India as a case study.

2.3 Lever & Intervention points: definitions, implications, and measurements

Macro-drivers are key to understanding the external conditions which shape the expected behavior of space cooling demand and energy consumption behind it. They are characterized as being external to the cooling system but with an influence over how it evolves (Khosla et al., 2020).Therefore, these drivers cannot be controlled and changed easily. However, there are internal factors that form a dynamic sub-system which hiders lever points to that are capable of the driving system to change. The analytical framework views cooling as a system comprised of interacting social and technical constituents which means cooling energy demand is defined by sociocultural behaviors and satisfied by a set of technological solutions

(Creutzig F. et al., 2018).This approach provides anchoring system dynamics in interaction between people and technologies, behaviors, and norms. (Stephenson J. et al., 2010). These interactions are capable of driving the system into a sustainable path as. Identified concepts are explained more in detail below and certain measurements have been chosen to indicate their role in the system.

2.3.1 Sociocultural Behaviors:

The interaction between consumers and products is known as consumer behavior which varies with regard to many factors depending on context. When it comes to relationships with new technologies such as air conditioners, people frequently readjust and reinvent their needs and priorities which form perpetually new behavioral patterns (Khosla et al., 2020).These patterns show significant distinction across geographies. It can even vary for different households in the same neighborhood. Therefore, the cooling strategies that households use have a great deal of impact on space cooling energy consumption. To reflect this effect, there are two major measurements accepted in the literature that are changing consumed energy which are the set temperature of AC and hours of usage.

- *Set temperature difference:* The range of preferred temperature varies from individuals' behavior patterns due to heterogeneity in the perception of thermal comfort. The Base temperature is observed to be higher in tropical environments comparably other places. The energy use changes close to % a 6 per degree increase (Manu et al., 2016)
- *Hours of usage:* Usage hours are dependent on the household's lifestyle and behaviors. people have a more proactive lifestyle and spend more hours outside of the house and that limits the AC usage hours. India's cooling action plan estimates AC runs for over 8 hours of the day while conducted survey in Delhi find out the average number of 5.5 hours of usage. Every hour of extra AC usage costs an average of around 1kwh more energy.

2.3.1 Technologies:

The cooling equipment varies with their types and each type has different dynamics and working mechanisms. They come in different shapes and sizes. Consumer preferences on which type of appliances to buy have been shaped by a variety of factors such as the space to be cooled, application type, aesthetic preferences, and expected performance. The cooling equipment can be dive into three categories which are window AC, split AC, and central AC systems.

The energy consumption of different types of AC systems depends on their energy efficiency rates. The energy efficiency of ACs currently in use and for sale around the world has been rising in recent years because of incremental improvements in air-conditioning technology and shifting demand (IEA,2018).This rate called as energy efficiency ratio (EER) determines how much input energy is needed to reach the desired cooling capacity. As the rating increase, the energy need decreases. If you double the average AC efficiency estimated to reduce cooling energy demand by 45% (IEA,2018). This points out the potential of effective lever points that could change the trajectory of the cold crunch.

2.3.1 Infrastructure Design:

The last lever point is the infrastructure design, it has a complex relationship with space cooling energy demand rather than straight forward unlike other factors. There are multiple properties of buildings play a role like the roof, doors, floors, ceilings, doors, windows, walls etc. These all have an enormous impact on the need for space cooling. All these properties combined determinates the thermal mass of the building envelope which creates a natural barrier between indoor and exterior temperature (IEA,2018). For example, If the building has more window areas, it increases the home's solar gain and makes it warmer.

This indicates the potential possibilities of effecting cooling demand and supply by shaping and adjusting designing of the building accordingly to standards. These settings crucial that how they are combined might form path dependency and lock-in (Khosla et al., 2020).

2.4 Policies and measurements

In order to shift to the trend of the cold crunch that has been alarming us, authorized organizations suggested some key policy measurements after their in-depth analysis. The international energy agency is one of the most accepted authorities in this manner and has introduced two central policies to governments all around the globe in the direction of controlling and easing expected outcomes. These policies are scaling up the efficiency standards of air conditioning systems and redesigning building infrastructure as well as setting the building energy codes for new buildings to limit the need for cooling in the first place.

The core aim of these two policies is to eliminate the cooling demand as much as possible while meeting the demand with more efficient technologies to reduce energy needs. According to the International energy agency's analysis, these policies have shown promising results for the long-term future by reducing the trajectory of cooling energy demand permanently to the extent that could be managed.

However, the remaining questions are how these measurements can be implemented in the real world, to what extent they are feasible, and also how much effort from the necessary authorities like technology manufacturers, builders, and local and national governments will be willing to put into making this happen?

2.5 Conceptual Model

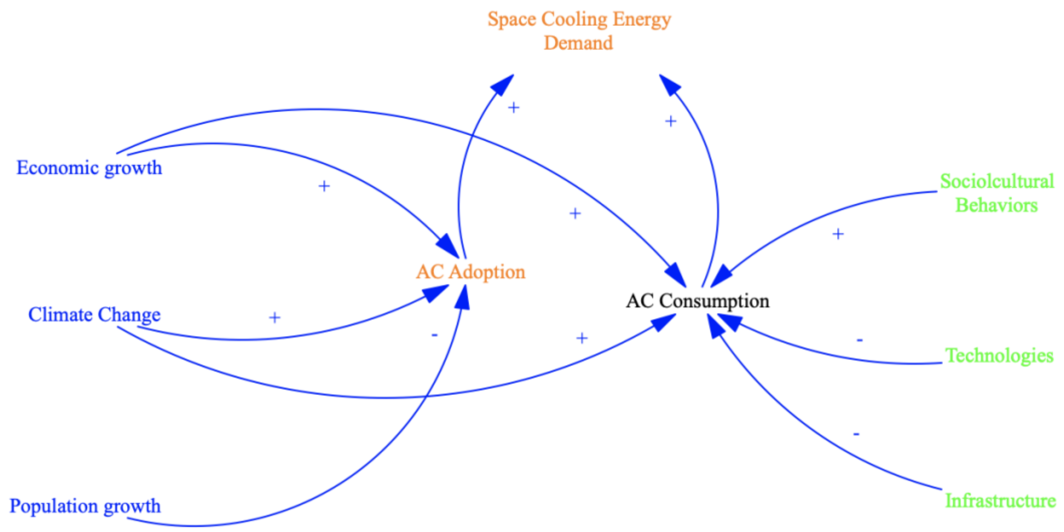


Figure 1:Conceptual Model

The conceptual model has been formed with the combination of the core concepts mentioned above from the literature, and the base model to represent the relationship and the nature of the phenomenon of cooling demand and energy consumption. The conceptual model is including causal relationship diagram. In the model, green variables represent the lever points of the system the blue variables are the external major drivers of the system, and the orange variables are performance indicators. Overall, the combination of average AC consumption of households depends on several factors. Economic growth, climate change, and sociocultural behaviors have a positive relation which means they are in the same direction when one variable increases it boosts the other one. On the contrary, technologies and infrastructure have a negative relationship. For instance, as the technologies of cooling appliances evolve the consumption decreases due to efficiency. Meanwhile, the number of people adopting AC in relation to external major drivers of the system. Economic growth and climate change drive up the adoption as they increase while population growth has a negative relation. The overall relations represented in the conceptual model are detailly examined in this paper to develop the model that would capture these dynamics.

3. Methodology

The objective of this research is to forecast how the major drivers of the system namely, economic growth, population, and climate change would drive AC ownership and space cooling demand in Delhi, India. Moreover, assessing the effectiveness of the suggested policies on space cooling demand, and what the behavior of the system align with the Sustainable development goals 3 and 7. The research design choices have been chosen accordingly to achieve these objectives in mind.

The Methodology section below will explain how the research has been conducted and why and how specific choices are serving to achieve the objectives.

3.1 Research Design.

First and foremost, the research paradigm has been adopted for this research is positivism. The main idea behind positivism is to construct explanatory associations or causal relationships that ultimately lead to the prediction and control of the phenomena in question (Sciarra D., 1999). The role of the researcher in this type of research is limited with only data collection and interpretation in an objective way of findings. This idea aligns with the research focus since our findings are quantitative, and they are not open to interpretation, and they represent one true reality.

The selected methodology for this research is the system dynamics methodology. System dynamics provide a holistic view of highly complex problems and the phenomenon at hand has many variables and layers. Most people define complexity with regard to the number of variables in the system while dynamic complexity and dysfunctionality can emerge from simple systems (Stermann,2000). Due to the combination of lack of deepness in our mental models and the complexity of real-world problems, we fall far short of gaining an understanding of what truly drives systems and how they function. That is why there are common mistakes and why we are often surprised by unexpected outcomes. While assuming decisions that have been taken are supposed to control the system actually have driven the system in an unwanted direction. However, a system thinking approach helps to open up a window to see the system and its structure from different perspectives which in a way contributes to understanding what the system is. That is why this research chose a system dynamics approach for investigating the cold crunch problem.

The system dynamics methodology substantially differs in the research design they conduct. The first split point is whether research is qualitative or quantitative. The quantitative research approach is suitable for our objective. Because the quantitative simulation model will help us to test the policy actions' effectiveness on the trajectory of space cooling energy demand under different plausible future scenarios and also will help us to find which factors have more influence in driving system behavior. The practical way to understand the complexity of the model without exceeding our mental models is to test it (Stermann,2000). The other distinction point is about the use of simulation modeling in general. They can be used for predictions, proof, prescription, discovery, explanation, and critique. This research is used a simulation model to explain where empirical confirmation of relationships in simulation output provides indirect support for unobserved processes and predicts where models result in which behavior under which conditions and what outcomes are produced (Harrison et al. 2007) These properties of methodology will allow us to reach the objective in mind.

The particular research strategy which is applicable for this study is the case study. Because case studies are adequate when research focuses on contemporary events in its real-life context, where the researcher has little or no control over the events (Yin, 2014). The sample of Delhi, India has been chosen for a case study to be analyzed. What makes Delhi, India a significant sample is that the macro drivers mentioned are scoring high. In other words, Delhi is the most urbanized city where the climate is hot and humid with a comparably low AC ownership ratio of households. These properties of the chosen sample not only increase the significance of the research but also help to understand the dynamics of the system better. As mentioned earlier this paper aims to bring a bottom-up perspective to literature which means setting the sample size of the model on a smaller scale with the motivation of enhancing the forecast of cooling space demand and ownership. The adequate and considerably smallest scale for this problem is cities which is why we have chosen Delhi, India for further analysis.

This study has followed the data collection methods of secondary data. Hakim (1982) defines secondary analysis as “any further analysis of an existing dataset which presents interpretations, conclusions or knowledge additional to, or different from, those presented in the first report on the inquiry as a whole and its main results” (p. 1). This technique is allowed to investigate what is already known and find out what remains to be learned. After reviewing secondary sources, the model has been developed by finding the connections between the variables and also formulating effects on variables. Primarily sources for this analysis are the International Energy Agency’s ``The Future of Cooling`` report, McNeil and Letschert (2008), and Khosla et al. (2021).

Moreover, The System dynamics depend heavily upon quantitative data to generate models. Therefore, in order to be able to quantify the model the necessary data is collected from reliable secondary data sources. These are mainly Indian national human development surveys (IHDS), OECD data sources, United Nations data sources and in addition several research paper in the literature. These historical data were analyzed for discovering the trend for specific variables in the model to forecast the future. All the details about which data sources were used for which variables and which trends were obtained from historical data analysis can be found in appendix D.

3.2 Research Ethics

Every researcher has to keep in mind scientific integrity and research ethics in order to have solid and suitable research. These ethics change according to pursued research design methods and this research methodology does not include any direct interaction with humans. Therefore, this really decreases the ethics that has to follow. One of the important ethical principles of the pursued system dynamics methodology is transparency. The developed model has to be transparent enough that if the reader would like to replicate the same results, he/she can be able to with all provided information. With this idea in mind, the developed model with detailed formulation, data sources, assumptions, and necessary steps that are taken is provided with full transparency in this research. Details information’s can be seen in appendix B and C.

Furthermore, the necessary assumptions that are made and choices are already ethical decisions, due to their interpretations of problem components and impacts on the upcoming research (Pruyt & Kwakkel, 2007). The assumptions that are being made in this research are explained in detail by presenting the reasons to come to those assumptions. This helps let the reader critically evaluate the reasoning and develop their perspective.

As far as conducting research, a researcher has an ethical responsibility when writing the research in a way that is usable to as wide an audience as possible (Liebenberg, 2016). With respect to this, the research paper will be written by critically reflecting on how understandable and open it is for readers.

4. Model Description

This section will firstly explain the important steps that has been taken to build the model and this will follow by model approach which will give the insights of the key concepts, how they are related, formulated and which assumptions are made under what conditions. Lastly, section is about validity of the model.

4.1 Model Boundaries

One of the first steps in building a system dynamic model is to set the boundaries of the model with respect to its purpose. The concept of boundary judgment relates to the assumptions about what is inside the range of concern and what is outside. (Flood and

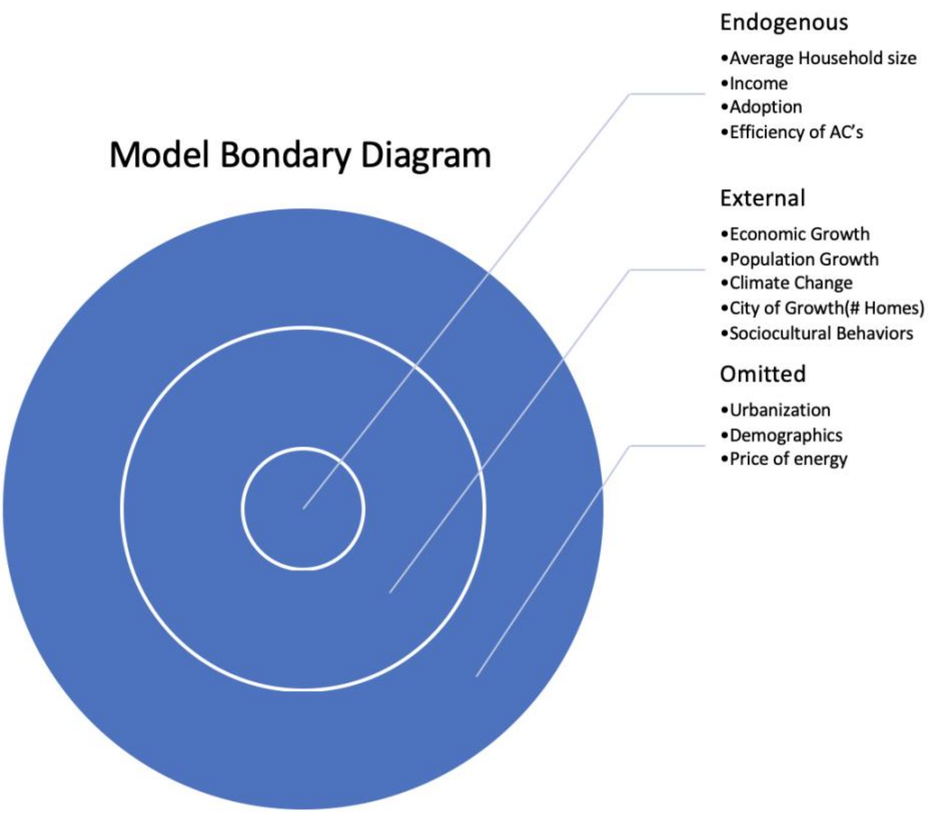


Figure 2: Model Boundary Diagram

Jackson, 1991)

This step is very important because real-world problems have high complexity with many variables integrated into each other and sometimes modeling, and capturing all dynamics are nearly impossible. Therefore, the choice of the modeler with regards to the system of concern and purpose of the model determines the model boundary.

With this idea in mind, the cold crunch has many dynamics in relation to each other; however, according to analysis from the literature review and with the objective on reach which is testing suggested policies. Furthermore, the boundary of the model has been chosen with the boundary adequacy in mind. This means that potentially important feedbacks serving the purpose at hand is included which helps to improve the model validity. The following model boundary chart with variables in figure X have been chosen to reflect significant dynamics in the system.

4.2 Modelling Approach & Assumptions

This section will cover the model's important variables and dynamics, and why they have been chosen under which assumptions.

4.2.1 Key Concepts & Variables:

4.2.1.1 Performance Indicator Variables:

As stated in the introduction, the cold crunch is tidily related to two sustainable development goals: human health and well-being (SDG 3) and affordable clean energy (SDG 7). The ultimate goal is to provide all the people who are under thermal stress cooling appliances with affordable energy. To indicate the performance of these measurements our model has two performance indicator variables. The first one is AC ownership which represents the access to the cooling appliances of residential households. This has a direct relationship with SDG3 because people who can access AC in their homes can break away from heat stress. However, the second performance indicator variable space cooling energy demand does not have a direct relation with SDG 7. This is because the supply side of energy has many mechanisms that shape its price and cleanness. However, space cooling energy demand has a major role in this relationship. Currently, energy use for space cooling is growing faster than for any other end use in buildings (Economist Intelligence Unit, 2019) which might be one of the significant obstacles on the road toward reaching affordable and clean energy (SDG7) which creates a need to be considered and analyzed. Therefore, space cooling energy demand variable associated as indicator of SDG7 in the boarder of this model.

Due to the integrated relationship between the two goals, the performance of the model is greater when AC ownership has a high ratio with comparably less space cooling energy demand. Also, it is important to state that how soon ac ownership reaches a high ratio is better due to the fact that already people are in Delhi, India under thermal stress.

4.2.1.2 Adaptation:

Many external factors are shaping households' purchase decisions on air conditioners and capturing all the dynamics behind this behavior is a relatively challenging task. Therefore, we try to choose factors that have a major effect so that they would reflect as closely real-life conditions as possible. The major two effects on the adaptation of Air conditioners are climate which defines how much a person thinks he/she is in need of technology whereas the affordability factor determines how much that need is met. Empirical studies on calculating cooling demand & energy have developed an approach to calculate these effects to come up with overall market penetration.

The saturation model by McNeil and Letschert (2008) is taking these two parameters where the Climate Effect is the function of CDD and Affordability is the function of household income.

$$\text{Market Saturation} = \text{Affordability (Income)} \times \text{Climate Impact (CDD)} \qquad (1)$$

More detail about these functions lies in empirical studies techniques with historical data. McNeil and Letschert (2008) used a data fit approach with AC market data from China which was used for specifying affordability functions. The data from China is applicable to other countries because this phenomenon has already been observed in China with 20 million units of increase in the AC market between 2000 to 2005.

The affordability function takes income parameters for representing the estimate of household income. It is calculated by annual per capita GDP divided by twelve and multiplied by the average number of people living in households. This method helps to simplify the distribution of wealth and allows a consistent methodology for using data available for a wide range of countries (McNeil and Letschert,2008).

Availability function defined with mathematical expression which is the basic term for the logistic S- curve.

$$\text{Affordability} = 1/(1+\gamma \exp(\beta \times \text{Inc})) \qquad (2)$$

where γ and β are regression analysis coefficients to help to fit historical data with equations. In order to clarify this equation to something meaningful for everyone, we choose to divide coefficients and represented in the model as follows;

- Threshold: There is a certain amount of income value when it goes beyond this threshold ownership starts to increase rapidly. This value was found to be 1000.
- Ac-Income sensitivity: The sensitivity of income divided by the threshold with respect to AC ownership rate which is -1.055.
- Regression coefficient: Linear regression analysis coefficient relation to historical data which is 4.838.

All above values is from McNeil and Letschert(2008) methodology. After this modification formulation look like follows

Affordability= 1/ (1 + e^Regression Coefficient) *e^ (AC-Income sensitivity * Income / Threshold) (3)

The Climate Impact function is rather straightforward than affordability function. McNeil and Letschert (2008) has used the historical data from United States provided by U.S Energy Information Administration's Residential Energy Consumption Survey (RECS) in 2001. The results of linear regression by using formula 3 with CDD compared to RECS data was very similar with high R2 value 0.93. This implies the accuracy of the given formula.

Climate Effect = 1- 0.949 x e ^-0.00187* CDD (4)

This method has been using in other research's in this field and that is why we also take this method as indicator variable for adaptation rate which determines the amount of households purchase air conditioner for first time in any given time span. This will help our model to be more accurate with respect to representing real life.

4.2.1.3 Income:

Income of the households are dependent on external factors of country and varies in different socio-economical levels. As it described in the last section affordability function

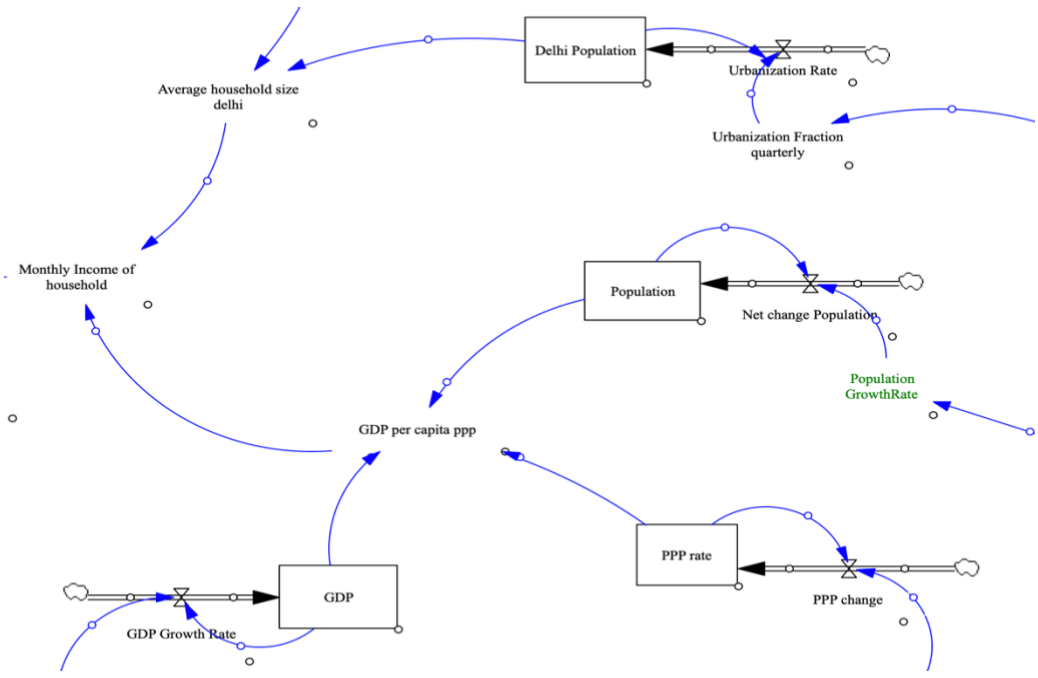


Figure 3 Model part: Structure of Income

takes into account of Income households. In order to generalize and calculate the variable, the most accepted measurements are GDP per capita. However, every country has different currencies and economic dynamics to eliminate this effect GDP per capita is adjusted with the purchasing power parity (PPP). This helps to take into consideration of the differences in the cost of living in developing countries. These external factors create the dynamics characteristic of change in the Income which as result in the affordability of AC ownership. This point outs the fact that Income variable has to be endogenous variable in the model. However, in the literature many studies have been calculated income by adjusting external values to constant value at certain time. This methodology disallowing to capture the dynamics of income variable. Therefore, the 4 external variable which are PPP, GDP and population of India taken as variables change over time. The trends of change of these variables have been calculated by looking at the last 20 years historical data. Moreover, to precisely calculate the income with GDP per capita adjusted with purchasing power parity has to multiple with the average household size. In order to be more accurate average household size of Delhi, India also calculated as auxiliary variable in the model. The overall formulation of income variable as follows;

Income= GDP per capita (ppp) *Average household size Delhi (5)

GDP per capita (ppp)= GDP (INR) * PPP/ Population (6)

Average household size Delhi= Population of Delhi/ # of residential homes (7)

4.2.1.4 AC Consumption:

The consumption and behavior are locked into a vicious circle and vary by individual. More aggregate level of AC consumption is tidily related to which conditions users feel in thermal comfort and this is strongly affected by the climate they used to live in. In other words, the northern people are less tolerant of heat while southern people are more likely to tolerate vice versa. This points out the fact that behavioral differences need to take into consideration when the AC consumption calculating. The empirical models have a shallow perspective to this point. The general empirical way of calculating AC consumption is to take CDD based on 18 °C or 21°C. This approach lefts many key elements of individual behavior aspects. To capture the behavior aspect, this research has taken a different approach to calculating AC consumption.

First and foremost, the individual behavioral patterns of using AC are strongly influenced by the seasonal temperatures while CDD is defined as the number of degrees that the average day in each year's temperature is above an arbitrarily defined comfort temperature. Also, the temperature base for households is differ as much as the number of hours used. Therefore, to be able to capture these dynamics this research has taken the last 20 years' average temperature in Delhi, India as a distribution of air temperature by months with the added effect of climate change. Furthermore, the average humidity levels of each season have been used with this distribution to calculate the ambient temperature. In this way, consumption differences in each season are aimed to be represented.

Secondly, when it comes to using CDD for cooling consumption, it is assumed that households are using their AC whenever the degree is above a certain point which leads to ignoring the lifestyles of persons. In other words, there is a certain amount of time in a day that most people spend their times outside of their houses working. For that reason, residential AC usage has certain usage times depending on the lifestyles of households. To capture this element, this study has looked at the survey that has been conducted in Delhi, India with households that have AC. The survey Khosla (2021) has shown that households that are using AC for 1-2 hours are % 17.9, for 3-4 hours are % 27.3, for 5-6 hours are % 29.6, for 7-8 hours are 10.8 and for above 8 hours are % 14.3. According to these findings, Khosla (2021) reported that the average number of hours of AC usage is 5.4 h in their sample. However, The National India Cooling Action Plan estimates cooling demand by considering that everyone who owns an AC runs it for over 8 hours a day for 6 months of the year (MoEFCC,2019). This shows the overestimation of previous studies. For the sake of accuracy and to represent the behavioral effect on AC consumption this research has taken the AC usage as 5.5 hours in a day when the desired temperature is above the ambient temperature.

Lastly, the set temperature of AC is also an important factor affecting AC consumption. As thermal comfort differentiates among countries it also differentiates with individual preferences. The same survey from Khosla (2021) also shows the distribution of preferences among households. The weighted average of the results indicated that 23 C temperature is desired room temperature for households in Delhi, India. This sets the desired temperature value for this study.

4.2.1.5 Space Cooling Energy Demand:

The AC consumption of the households is the starting point for calculating the space cooling energy demand. However, there are several important factors that play a role in determining the final energy needs to satisfy the given consumption. These are the lever points of the system that suggested policies focus on for change towards a sustainable future. The first one is the Estimated Energy Requirement (EER) level of AC which is simply representing how much input of energy needs to provide the output cooling energy. As the EER level goes up the efficiency of cooling appliances increases which leads to less energy consumption. The second one is the building's isolation condition which significantly has the effect of conserving cold air by being a barrier to the outside temperature. If the building is isolated poorly, hot air on the outside can penetrate the inside and lead to an increase in the room temperature which results in more cooling capacity need for reaching or sustaining the desired temperature in the room. The building isolation is dependent on many factors such as the basic materials that have been used for walls, the thickness of the wall, the window size of the room, roof size, and material, the location floor of a particular apartment, etc. Including all these factors are out of the reach for this study. That is why this study follows the approach of taking one coefficient which represents all these factors for the sake of simplicity.

In order to capture all these factors mentioned above, the basic physics principle of heat conduction from Joseph Fourier is adopted for calculating the required energy need. The basic principle behind this mathematical equation is that to change in temperature, the required energy depends on the volume of the area, temperature differences, and thermal conductivity of the material. The formulation is as follows

$$Q= V* DT*K \tag{8}$$

For this study, V represents the volume of the average living room size in Delhi, India, the DT is the difference between ambient temperature and AC set temperature, and K is the building isolation coefficient. Overall, Q represents the output energy need with respect to the EER level of AC. The input of energy need can be calculated.

$$EER= \text{Output energy pulled out / Input Energy (Watt).} \tag{9}$$

4.2.2 Assumptions:

One of the biggest challenges of modeling real-life problems is to find the parameter values when it comes to quantifying. There are some variables that finding the data and analyzing them to reflect their value is beyond the scope of modeling. Therefore, necessary assumptions need to be made for quantification purposes. This study is also faced with this challenge which is why the following assumptions were made for the sake of simplicity.

- The air conditioners differ with regard to their types, size, and technologies. Amongst the different types of air conditioners, this study has assumed that every household uses one type of AC, split system ACs. This type has been chosen because it is more commonly used in the residential sector, and it is relatively easy to install houses. Also, the EER scale has been taken according to the split-system ACs.
- ACs like many other technologies have a certain lifetime. It is stated that 15-20 years is the lifetime of AC. This has been accepted as 15 years in this study and after 15 years, it is accepted that once the households have to retire the AC, they immediately get a new one due to the fact that they are already above the threshold of affording.
- The building isolation standards have been separated into three categories which are
    - Well isolated construction (double Walls, Ceiling Insulation Material, Wall and Floor, Double glazed windows, and Insulated Doors) with the value of K equal to 0.9.
    - Discreetly isolated (double walls, ceiling insulating material, few windows with single glazing) with the value of K equal to 1.5.
    - Little isolated construction (simple walls with glazed parts and uninsulated roofs) with the value of K equal to 2.5.
- The purchase and usage behavior of ACs are assumed to be constant throughout the simulation time and they are set according to the survey conducted in Delhi, India by Khosla (2021).

As much as these assumptions are helping to study for quantification it is important to remember that they also set some limitations which will further discuss in the later of the document.

4.3 Model Validation

The reliability of the simulation models and results highly depend on the verification and validation of the model. The system dynamics models are representative of real-life problems and to capture real-life problems there are many methods that can be used to limit biases and boost their validity. However, all models caught up a problem of bounded to individuals' mental models which set the limitations of representations of the real world. Therefore, no models can ever fully be verified the developed tests can only prove the model is right with respect to its purpose (Stermann,2000). With this idea in mind, the model is tested according to the developed test of Senge and Forrester (1980). The applicable tests have been applied and the results of these tests indicated the model is credible and findings can be found in appendix E.

5. Model Analysis

5.1 Model set-up

The developed model for this study is aiming to reflect the real-life behavior of the Ac adaptation and space cooling energy demand between 2000-2050 years. The time horizon for this model can be divided into two. The first interval between 2000-2020 is representing the historical behavior with respect to historic data and the second interval between 2020-2050 is for predicting the future with the estimated trends from the first interval. With that idea in mind, the initial values of variables and the time horizon have been set to simulate the model. The model simulated with different scenarios and policy analyses from 2020 until 2050. The 30 years into the future is convenient enough to get an overview of the near-future impacts of the cold crunch.

Time steps are calculated quarterly for capturing seasonal effects. The 0^{th} quarter representing the first quarter of year 2000 and 200^{th} quarter in the time line representing the fourth quarter of year 2050.

The all-simulation settings detailly provided in the appendix C.

5.2 Model Simulation Results

The model is simulated with different scenarios to capture plausible future scenarios and implemented with different policies to test their effectiveness. The scenarios and policies are activated from 2020 onwards. The table 1 in below shows exactly which values belong to which scenarios. Each of the scenario results is discussed in the following sub-sections.

Table 1 Scenarios & Variable's Values

Scenarios / Values	GDP growth (annually)	Population Growth (annually)	Climate Change (Overall change in °C until 2050)	EER level	Building Isolation Coefficient
Base	0.13	0.0132	+1.3 °C	3.15	1.5
GDP (High, Low)	(0.15, 0.9)*	0.0132	+1.3 °C	3.15	1.5
Population (High, Low)	0.13	(0.008682, 0.002378)*	+1.3 °C	3.15	1.5
Climate Change (High, Low)	0.13	0.0132	(+2 °C, +1.2 °C)*	3.15	1.5

5.2.1 Base Run

The base run of this model is to represent the case which all values are set according to the trends that have come to pass in 20 years. In other words, the dynamics of the system is following the historical trends. Therefore, this run provides the reference behavior for other scenarios in terms of comparison.

The base run results are shown in figure 4. The AC ownership is following the S-curve behavior also known as logistic growth which indicates market change over the time period until 2050 which is the 200th quarter. The important essence of the S curve behavior is that once the average income of the households reaches to tipping point which in this case is the threshold of the AC-income ratio, the behavior goes into the phase of acceleration sharply. In this model, the tipping point has been reached approximately at between the 55-60th quarter which corresponds to 2014. The next phase of maturing starts when it hits to inflection point which in this case is roughly around the 95-100th quarter which corresponds to 2024. In the maturing phase, the AC ownership ratio rate of growth decelerates. The last phase of this behavior is saturation where growth greatly slows and stops. In the model, the model this phase has reached around the 140th quarter which corresponds to 2035. The change in the number of homes with AC and without AC can also be seen in the graph in figure 7.A small note is that the total number of houses stately increasing as the construction of new houses continues.

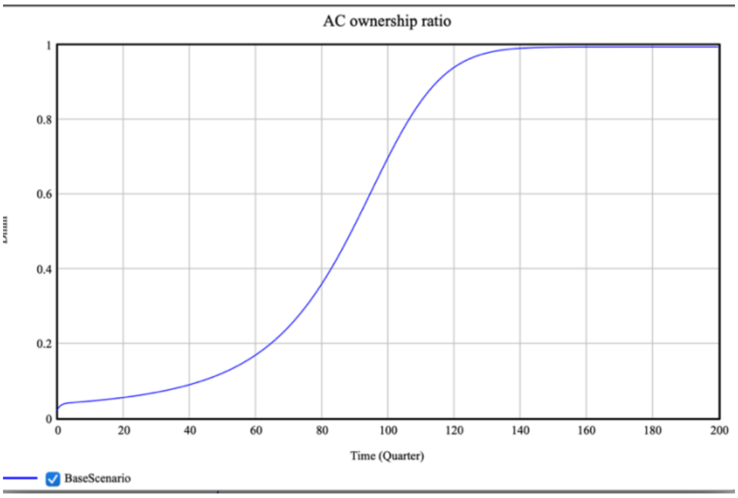


Figure 4: Baseline- AC Ownership Ratio

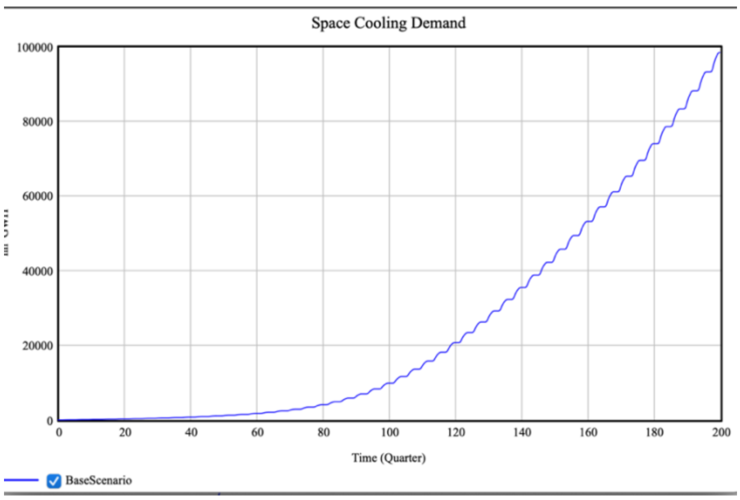


Figure 5: Baseline Space Cooling Demand

This AC ownership behavior is strongly affecting the shape of the space cooling energy demand. As it can be seen in figure 5, the behavior of the space cooling energy demand is in exponential growth. The main reason is for that the rapid increase in the number of houses adapting AC over time. The other factor that is impacting space cooling energy demand is the average consumption of electricity per season per household but the increase in the change is rather slow around %18 over 50 years. This is mainly due to climate change which results in more consumption. The combination of these effects creates the exponential growth of energy consumption over the years. Overall, the final space cooling electricity demand is reaching around 98.380 GWh by 2050.

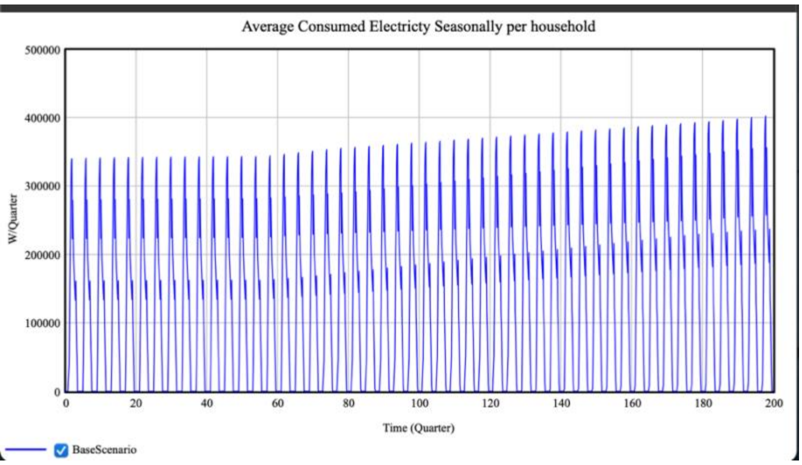


Figure 6: Baseline- Average Consumed Electricity Seasonally per household

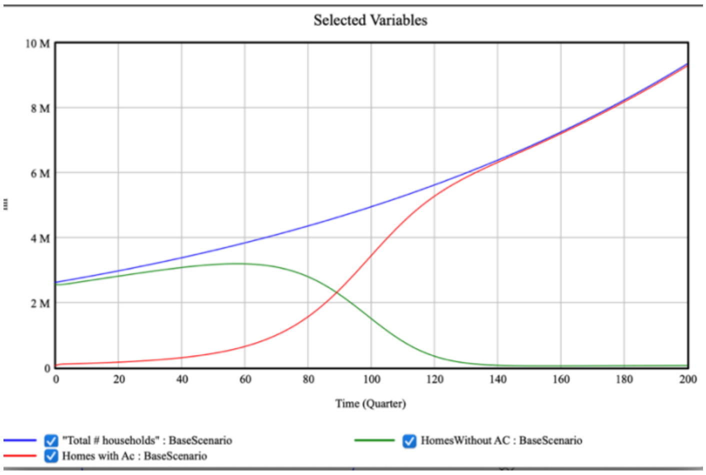


Figure 7: Baseline- Home Stock flow change in time

5.2.2 Scenario: GDP

The economic growth of a country is one of the major drivers in the system that is determining affordability. The economic growth of developing countries is the key starting point of the cold crunch problem and the pace of adapting goods and services depends on how fast their economy grows. Gross domestic product is one of the elements that is reflecting the economic scale of the country in the model and the annual increase rate for the future is dependent on many factors which makes it nearly impossible to forecast how might change. Therefore, different values of GDP growth rate have been taken as scenario analysis. The historical data of India's gross domestic product in local currency units between 2000-2020 from OECD data source has been analyzed and the trend in 20 years period has calculated around %13 yearly growth rate. This %13 growth rate is accepted as a base scenario for this research which also generates the reference mode behavior of the system. In order to capture other possibilities, two different growth rates have been taken. The one representing low economic growth between 2020-2050 is a 9% annual growth rate, and the one representing high economic growth for the same time period is a 15% annual growth rate. In the range of these high and low values, the simulation results are representing how the pace of adoption might change in near future.

The results of GDP scenarios can be seen in figure 8 and 9. One of the general takeaways from these analyses is that as the GDP increases the AC ownership ratio speeds up to reach saturation point and also this mechanism works in both ways. Meaning that as the GDP growth decreases, it slows downs the adaptation of AC. This is mainly due to the driving force of GDP which helps to reach the threshold of AC affordability for average households regardless of their social-economic level.

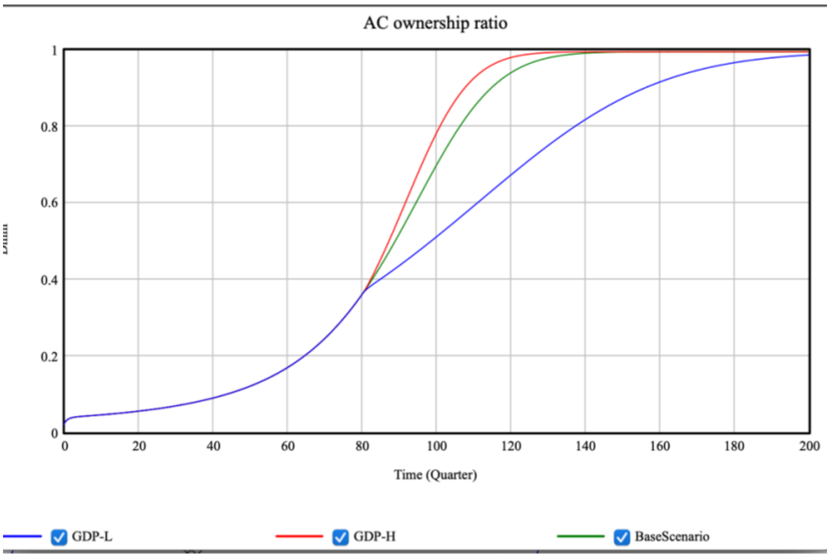


Figure 8: GDP Scenario- AC ownership Ratio

Moreover, the sensitivity of GDP to a low growth rate is higher compared to a high growth rate. This means the change in the pace is much more when the GDP grows slowly rather than the GDP growing fastly. This arises from the fact that there is a certain limit to the impact that GDP creates on the adaptation as soon as that tipping point passed with high GDP growth the effect is decreasing. This behavior reflects the realness of how the social-economic levels of households in any given country change. Because when the economy of the country enhances the distribution of added value is not equally shared with different social economic levels.

The adaptation rate reaches a higher peak point as well as a lower bottom point in the higher GDP growth scenario and also with the high pace of transition between the stages. This behavior is more in fast change which might make it hard to control. However, the low GDP growth scenario shows a different behavior than the high and baseline scenarios. It is more in balancing and stable change which is more likely to predict and easy to control towards sustainable development goals. One important point in all three of the scenarios is that they are all in the crucial phase of change which points out the need for enforcement to shape the behavior in a desired way.

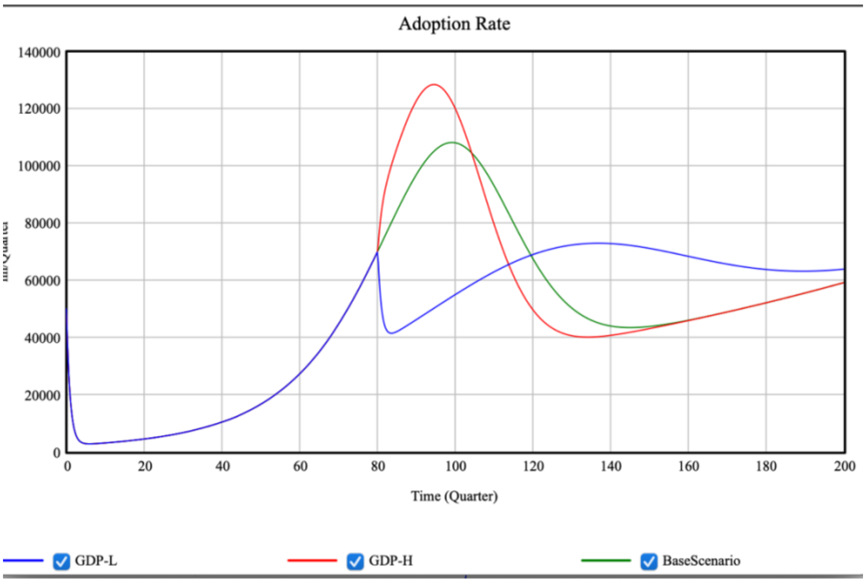


Figure 9: GDP Scenario - Adoption Rate

These changes in the adaptation pace also affect the space cooling energy demand because the early adaptation leads to more usage time. Figure 10 shows the differences, the high GDP scenario is in %1.6 increase compared to the baseline scenario in 2050 whereas the low GDP scenario is in % 11.3 decrease. This indicates that more stable adaptation behavior is helping to ease up energy demand.

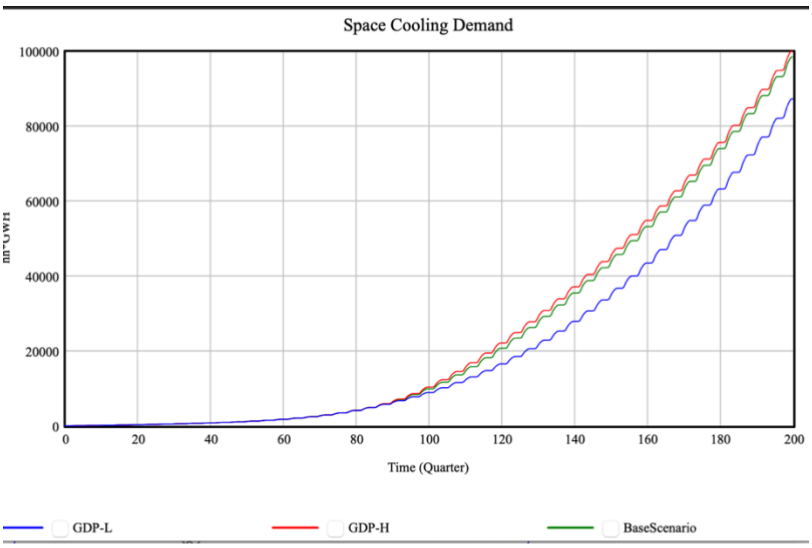


Figure 10: GDP Scenario- Space Cooling Demand

5.2.3 Scenario: Population

The second major driver of the cold crunch is the population. In this research, the population has been taken as changing level which affects the distribution of economic wealth. What it means is that it determines how much money would be per capita which set an average income with the combination of average household size. The historical data from the United Nation database showed a trend of % 1.32 growth annually between 2000-2020. This value has been accepted as a baseline scenario and for other scenarios prospects of the United Nations have been set between 2020-2050. United Nations have many prospects under different conditions for this research low fertility rate and high fertility rate taken for scenarios. The low fertility rate has around % 0.23 annual growth rate and the high fertility rate has around % 0.86 annual growth rate which both are under the baseline scenario.

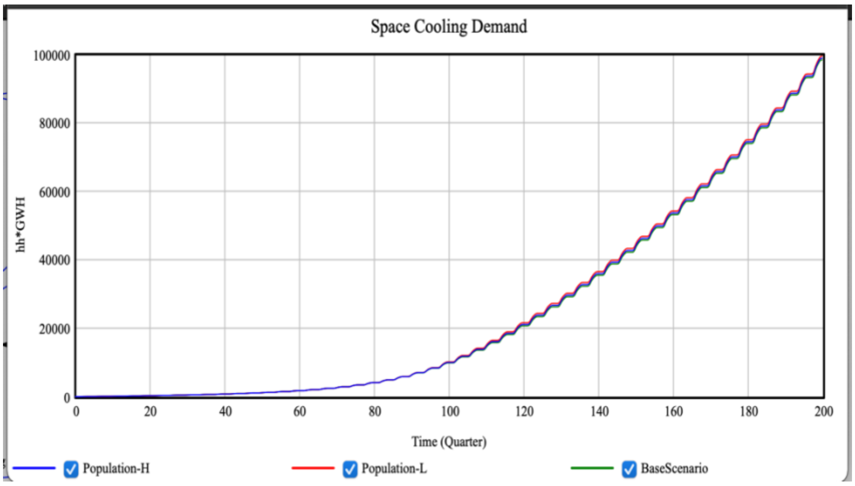


Figure 11: Population Scenario- Space Cooling Demand

The space cooling energy demand and AC ownership ratio graphs of these scenarios can be seen in figure 11 and 12.As it can be understood easily from the graphs, the population has little effect. The less population sooner it reaches the saturation point which creates a little difference in energy consumption as well. Compare to the reference baseline scenario, the low population scenario has % 1 more energy consumption in 2050 whereas the high population scenario has %0.5 more consumption in 2050. These results point out that the population has a straightforward relationship with AC ownership and space cooling energy demand and its impact is relatively little.

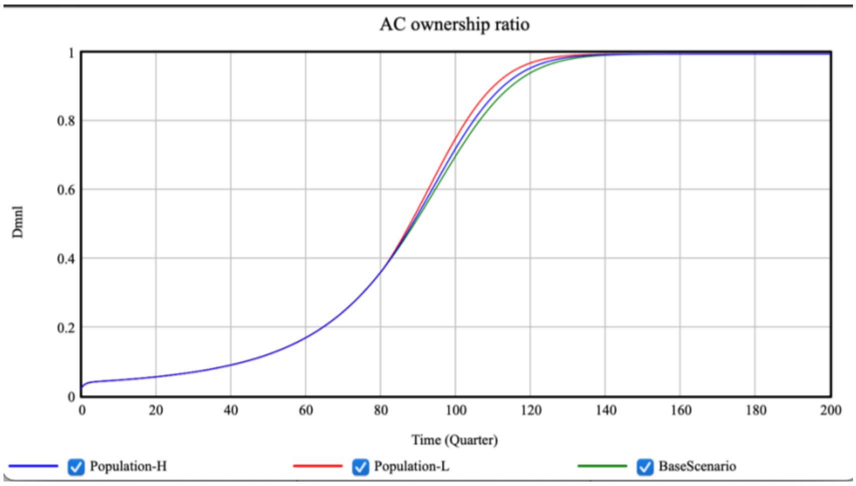


Figure 12: Population Scenarios- AC ownership ratio

5.2.4 Scenario: Climate Change

In the model climate change is only affecting the consumption of per household via increased temperatures causing more energy to cool down to desired temperature. The climate change has also affect to adopting behavior of ACs.However in the case of India, Delhi it reached already to the maximum point which states the need for ACs in Delhi is crucial, so that is why climate change does not affect adaptation of AC in the model. The scenarios of different climate change values have been taken from the analysis of G20 climate risk atlas. The temperature projectors showing that from 2014 until 2050 the highest expected temperature rise is + 2°C, the medium temperature rise is + 1.3 °C and the lowest temperature rise is +1.2 °C. The model accepted medium as baseline scenario and others accordingly.

The space cooling energy demand on different scenario settings can be seen in figure 13. As expected, higher temperatures causing more consumption with % 9 increase at the 2050 whereas the lower temperature scenario has % 1.2 less consumption at the 2050. As the time goes by the difference is increasing as it can be seen in the graph. This also means that it might create more energy differences in long term period as the temperature continues to rise incrementally. In conclusion, households Ac consumption directly related with the climate change effect.

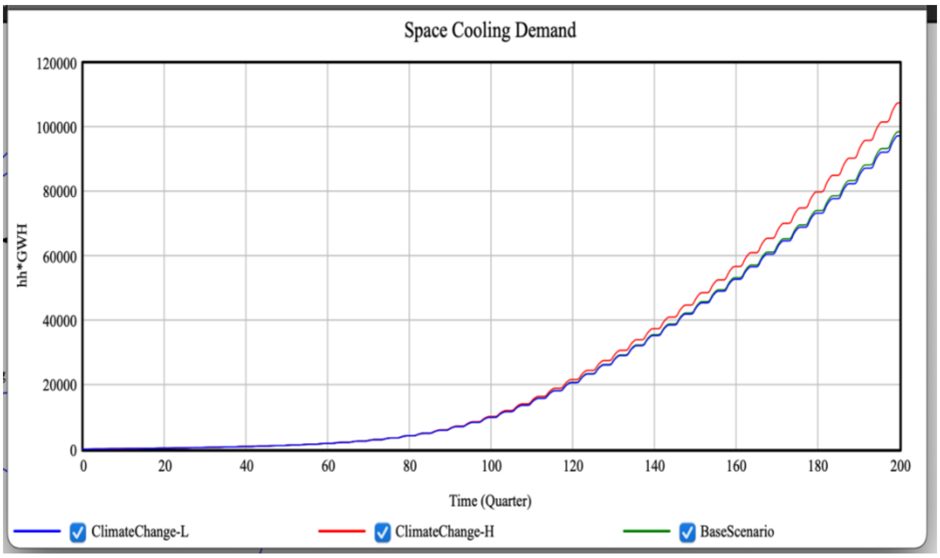


Figure 13: Climate Scenarios- Space Cooling Demand

5.2.5 Policy Analysis: EER Level

The International Energy Agency has suggested two policies to the authorities in order to deal with the arising problem of the cold crunch. One of them is the implementation of rules and regulations on the efficiency of AC technologies. As mentioned above the measurement to reflect AC efficiency is EER level. It found out that the general buying behavior of households is more to the average efficient technologies available on the market at that moment and increasing the standards of the market is aimed to increase the overall efficiency. The EER level of the AC's initially considered as 3.15 with respect to the data from the Bureau of Energy Efficiency Minister of Power and accepted as a baseline scenario without any change. The EER+ scenario represents the recently introduced policy of increasing every star level by 0.4 in 2018. The second scenario is aimed to capture the most extreme case which is implementing a gradual increase of 0.4 points to every star level of EER over the 5 years period. This assumption has been made to measure the maximum impact of efficiency.

	2000-2018	**2018-2050**
Baseline	3.15	+ 0
EER+	3.15	+ 0.4
EER+++	3.15	+ 0.4 for every 5 years period

It is already mentioned in the key concepts that policies are only affecting the consumption of ACs, not the adoption phases. However, the important dynamic here is that the speed of change in the overall average EER level of ACs not just depends on the

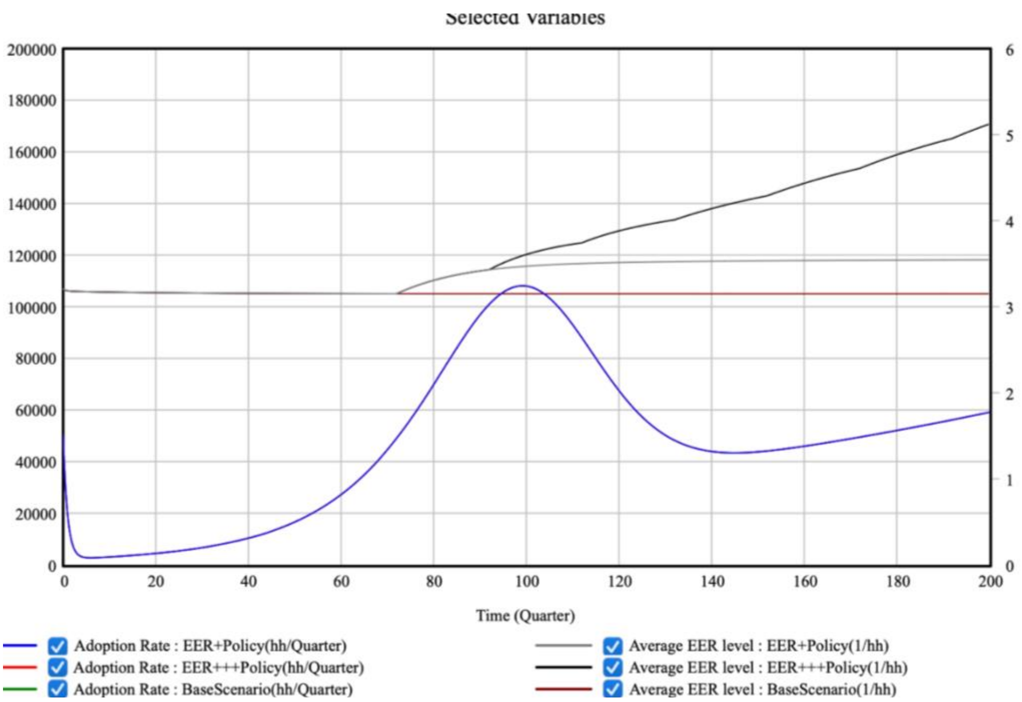


Figure 14: Policy Scenarios- Adoption Rate & Average EER level

market's EER level standards but also depends on the amount of adaptation that happened in that given time. This relation can be seen in figure 14, the first jump on the average EER level at the EER+++ policy scenario takes a concave down behavior which by time evolves into a more linear change which is more rapid than the concave curve, and then when the adoption decreases it again slows down.

The effectiveness of policy EER+ compared to baseline is that the space cooling energy demand at the 2050 is decreased around by % 10 percent whereas in the EER+++ policy it is decreased around by %25 percent. It does not change the behavior, it is still exponential growth for all three scenarios.

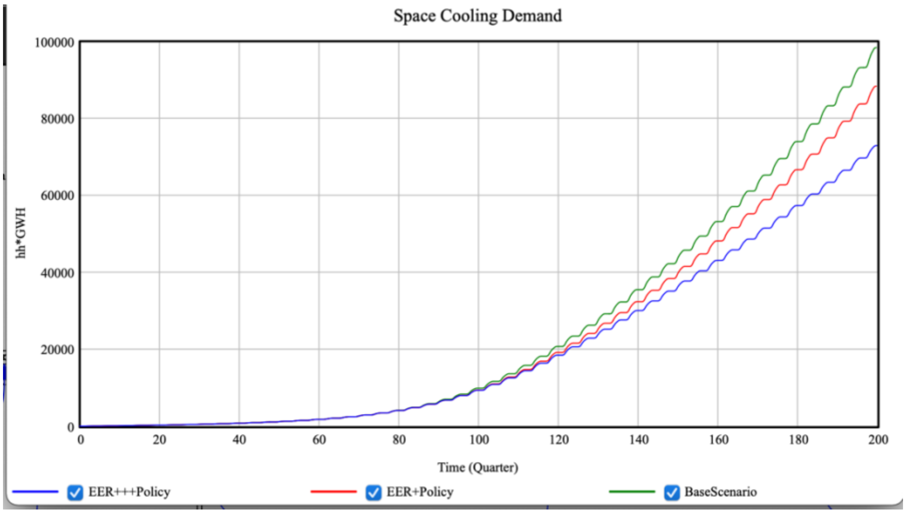


Figure 14: Policy Analysis- Space Cooling Demand

5.2.6 Policy Analysis: Isolation

The second policy suggested by the International Energy Agency is that designs the buildings in a way that would decrease the cooling needs indoors in the first place. The policy has been tried to reflect the building isolation coefficient in the model under some assumptions that have been made and explained earlier. The assumption is that the average Delhi household has a discreetly isolated home and therefore the baseline value of the building isolation coefficient is 1.5. There are few actions that are being taken to apply this policy suggestion by the Indian authorities however these are rather abstract and out of the scope of the model. Therefore, scenarios developed by firstly considering that the condition of the buildings only can get better which means that the average building isolation coefficient might only decrease in future scenarios. The policy scenario called Isolation + is assumed that with certain actions by the government, the average building isolation coefficient decreases to 1.2 starting on 2020 until 2050. The other policy scenario called isolation ++ is for capturing more serious actions taken by the government that would lead to the average building to a well-isolated construction. The assumption made accordingly to this indicates the decrease in the building isolation coefficient to 0.9 in the same time period 2020-2050. These changes are shown in figure 15.

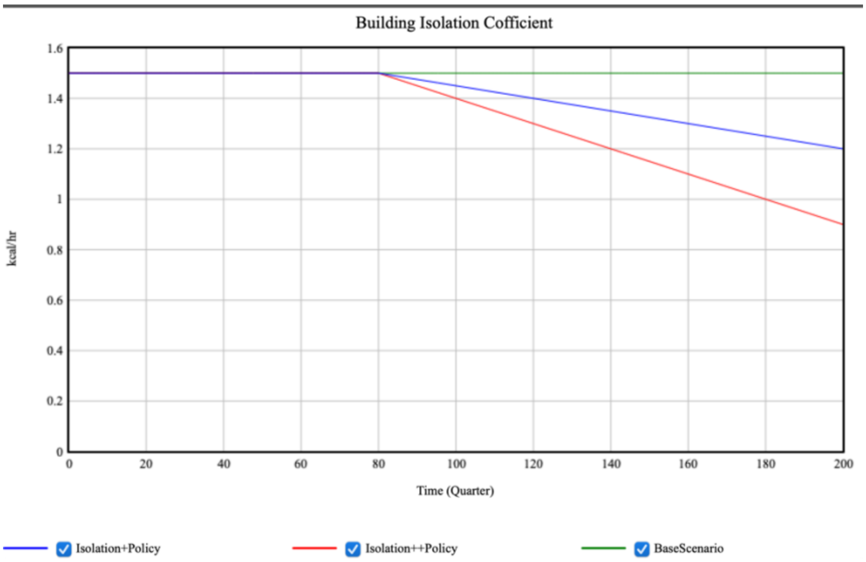


Figure 15: Policy Scenarios- Building Isolation Coefficient

The results of the analyzing policies have shown that total space cooling energy demand decreased by around % 11 in the Isolation+ policy scenario and around % 23 in the Isolation++ policy scenario. These results are more or less the same as the EER policy analysis. Both policies have a significant influence on decreasing energy consumption.

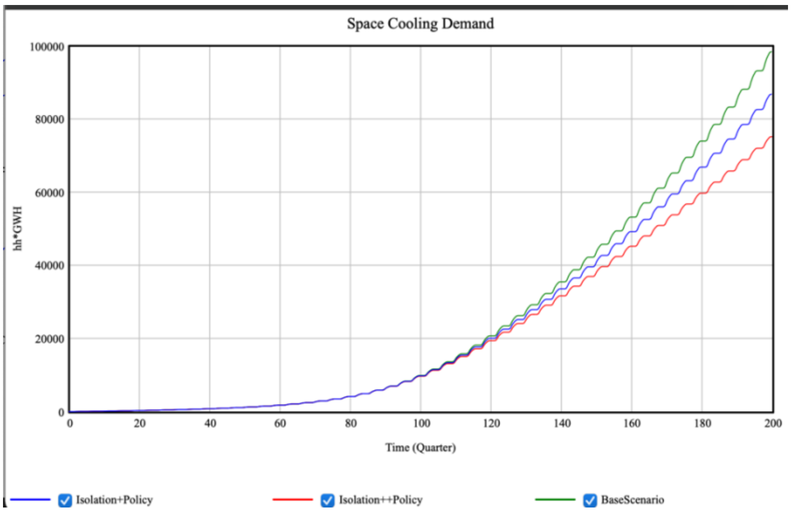


Figure 15: Policy Scenarios- Space Cooling Demand

5.2.7 What İf cases

After the policy and system driver's scenario analysis above, it found which variables influence the system in what way. However, these analyses only take into consideration of a change in one variable at that time which does not capture real-life because all these variables can change simultaneously. Therefore, the combinations of these variables have been taken as what-if cases. There are many combinations of these variables due to that, this research only took the values that would create best case scenario and worst-case scenario. The best-case scenario represents the slow transition pace of AC ownership and settings that would require less consumption which makes it easy to control towards a common sustainable goal whereas the worst-case scenario adaptation of AC is rather faster and consumption needs are more. Specific values of each scenario can be seen in table 2. Moreover, the combination of the policies has been tested in these scenarios settings to further understood the effectiveness of the policies.

Table 2 : What İf Scenarios and Values of External Variables

	GDP growth	Population Growth	Climate Change
Best Case Scenario	%9	%0.2	+1.2 °C
Worst Case Scenario	%15	% 1.3	+ 2 °C

The results of the scenario simulations can be seen in figure 17. The behavior of the space cooling energy demand is the same as it was exponential at the baseline for both cases. The end energy consumption of space cooling in 2050 is % 12.4 less in the best-case scenario and % 11.5 more in the worst-case scenario relatively to baseline. The difference is significant enough to take into account by the necessary authorities. Therefore, these cases were also tested with a combination of policies. The combined policy+ stands for applying both EER+ and Isolation + and combined policy++ stands for applying both EER++ and Isolation++. The end results of these tests are represented in table X. The combined policy + is decreasing the space cooling energy demand by approximately %20 for both best case and worst-case scenarios while the combined policy ++ is decreasing it by %42-43. The effectiveness of

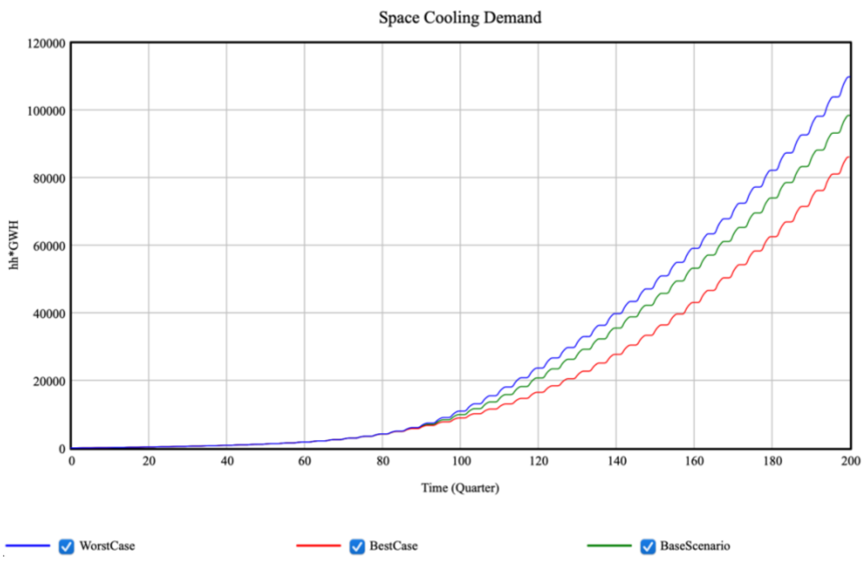


Figure 17: What if Scenarios- Space Cooling Demand

policies is the same in the different scenarios however, the differences in the space cooling energy demand amongst scenarios are quite significant. The worst-case scenario combined policy + has a % 27 more than the best-case combined policy +. While this difference is %30 between worst-case combined policy ++ and best-case combined policy ++. There are two takeaway points from these results. The first one is when the policy actions get tough, the effectiveness increase slightly in the best-case scenario. The second point is that these differences are considerably high which might lead to whether meet sustainable goals or not.

Table 3 Comparison of Space Cooling Demand in Scenarios

Scenario	Space Cooling Demand (GWH in 2050)
Base Scenario	98378,5
Best-case	86097,2
BestCase-CombinedPolicy+	68076,2
BestCase-CombinedPolicy++	48480,4
Worst-case	109772
WorstCase-CombinedPolicy+	86942,8
WorstCase-CombinedPolicy++	63459,1

6. Conclusion

This chapter will conclude the study by summarizing the key research findings in relation to the research aim and questions, as well as the value and contribution thereof. It will also review the limitations of the study and propose opportunities for further research.

First and foremost, the findings clearly indicate that the behavior of the AC adoption is the same in all scenarios which follow an S-curve shape. This behavior of AC adoption is also addressed in the literature in the same way. The reason behind this is the external drivers which are economic growth, and climate, steering the system in that direction. Currently, according to the outcomes of this research, the trend in Delhi, India is in the acceleration phase with the reliability of the past 20 years' data. This points out the importance of the problem and also the necessity to take action soon toward the state that can be controllable by the Indian government and Delhi authorities. Otherwise, it might create unwanted consequences such as a lack of energy infrastructure, the high price of electricity, driving up emissions, etc.

Secondly, findings illustrate that due to the embedded nature of the relationship between AC adoption and space cooling energy demand, the logistic growth in AC adoption produces exponential growth in energy consumption. While households' AC usage depends on many factors like lifestyle, geographical settings, sociocultural behaviors, technologies, and infrastructure which vary regionally, the high and relatively fast adoption of AC causes exponential behavior. The differences in the AC usage only decrease the end result of energy consumption, it does not change the shape of behavior. Yet these differences have promising potential to keep the space cooling energy consumption at a certain limit that can be controlled by authorities without causing undesirable consequences.

The behaviors of AC ownership and space cooling energy demand are on a locked-in path that can be only eased down or sped up via the external factors and lever points of the system. The complex nature of the system and the interchanges of factors across the different countries makes it difficult to judge which factors influence to what extent. Therefore, this research was conducted in a bottom-up approach to narrow down the scope with the aim to assess how major drivers have an impact on regional systems. Delhi, India has a crucial place in the cold crunch problem because major drivers create a suitable environment to feed the cold crunch trend. One of the best-known factors climates has been already at the maximum level which shows that everybody is suffering from the need for cooling appliances in the region however affordability of households is the key factor to meet with this need. The affordability of household's changes depending on external factors that are GDP, and population. In order to find how these factors, have a role in the system scenario analysis has been conducted. What these analyses show us is that GDP is the most effective factor that boosts the adoption of AC which leads to speeding up the transition of different phases in the S curve. In other words, more GDP growth means AC ownership will achieve saturation point sooner and vice versa. One important point to mention is that there is a certain threshold point when it passes that point the boosting effect slightly decreases. The population on the other hand has an opposite effect when the growth of the population decreases the AC ownership ratio increases. However, the impact is very weak relative to GDP. Last but not least climate change has a direct effect on the consumption side of the system. Because it is already mentioned that the climate effect on AC adoption is at the maximum level so the increase in the temperature has no effect on AC adoption. Where it is affecting the difference between the desired temperature of households and the outside temperature which results in more energy consumption. In the spec of near future, rising temperatures have a relatively small effect with differentiates %10 on the space cooling energy demand in different scenarios while this is more than population growth effect which is % 2. These outcomes conclude the first research question in mind.

The system has several lever points that are affecting the energy consumption part. They are namely sociocultural behaviors, technologies, and infrastructure design. The suggested policies by the International Energy Agency cover two of them. One is setting high standards for the efficiency of ACs and the other is improving the conditions of buildings in a way that leads to less heat loss. These policies have been tested in the model to see their effectiveness compared to a baseline that would not include any policy actions. The developed policies are according to actions that the Indian government is recently introduced. However, in order to fit these actions into our model, there have been some assumptions made. The important ones are that the first policy scenario developed according to what has already been introduced and no further policies until 2050. The second one is that in the future we assumed that these policies increase gradually over years with the same trend. The results of the simulations indicate that both policies have shown more or less the same effectiveness in decreasing the space cooling energy demand by %10 compared to baseline in the first policy scenarios (EER+, Isolation+). This value is %25 percent for the second policy scenarios of both policies (EER+++, Isolation++). Even though the effectiveness of the two policies seems the same in the model, increasing the efficiency standards of the air conditioners is more applicable and feasible when it comes to implementation in real-life conditions. Because designing new buildings as well as increasing the present ones to fully into a well-isolated state requires quite a challenging process and high costs. While increasing the efficiency of AC options in the market is rather straightforward and easy. The significant takeaway point from policies analysis is that due to AC adoption being in the acceleration phase in Delhi, India, actions that are taken soon have more effectiveness overall.

Moreover, the combined policies are tested in the worst case and the best-case scenarios that consist of the certain values of macro drivers. The first combined policy scenarios which were EER+ and Isolation + decrease the space cooling energy demand by approximately %20 for both best-case and worst-case scenarios while the combined policy ++

(EER+++ and Isolation ++) is decreasing it by %42-43. These percentages indicate highly promising impacts that would sustain the system at the desired level without causing unwanted consequences.

The cold crunch problem is linked to all 17 sustainable development goals (Khosla et al., 2020). Where AC ownership is strongly related to SDG 3 good health and well-being and also space cooling energy demand is actively interconnected with SDG 7 affordable clean energy. The behaviors of performance indicator variables indicate that AC ownership is rising fast to a level that would satisfy the need to sustain the thermal comfort of individuals until around 2035. This relationship is consistent with the SDG 3 and rather straightforward. However, the exponential growth on the space cooling energy demand putting strain on providing affordable and clean energy. The one of the challenges of meeting this growing cooling energy demand is the electricity demand on peak times (IEA,2018). Therefore, exponential behavior of the space cooling energy demand would create more and more extreme peaks overtime which points out the needs to take into account from necessary authorities in order to create a pathway to reach SDG3. There are more dynamics that is playing role in this relationship such as the supply part. Even though the amount of space cooling energy demand increases incrementally, if the necessary measures and actions are taken in the supply chain. Energy provides might still give affordable and clean energy to consumers. However, these dynamics are way out of the scope of this research.

The mentioned insights from the research results above with respect to research aim, contribute to the existing literature as well as challenge some points. First of all, there is a paucity of literature that investigates the cold crunch problem on the small scale. It is more on broad borders while there are many findings that are underlying the importance of how the drivers and lever points variable changes region to region. This point motivated the research to pursue the bottom-up perspective for sake of accuracy. I strongly believe that this perspective brought in-depth analysis which contributes to the understanding of the problem in more detail and also offers a potential to improve more. Secondly, the cold crunch problem as in its nature involves high complexity and complicated relationships which are affecting each other simultaneously. Therefore, the system dynamics methodology is ideal to capture the cold crunch problem. This system dynamic model might be a starting point to improve the understanding more about the problem. The literature review shows that trend of AC ownership is underestimated compared to this research findings. For instance, according to Akpinar-Ferrand and Singh’s (2010) research, it is expected that residential AC ownership is going to reach a saturation point by 2070 in India. In contrast, according to this research results show that saturation point is going to be reached by 2035 in the Delhi baseline scenario which is a way earlier than expected. This challenges existing literature to develop more recent accurate trajectories for the future with keeping in mind that the problem at hand is one of the crucial topics that might create obstacles on a road to a sustainable future.

7. Limitations & Future Research

Like all many research papers, this research has its limitations that set the results of research on what can be reflected with it and what cannot be. These limitations help us comprehend the research and its relevance. So, it can be understood from this that it is significant for the researcher to be aware of the limitations of its research design. The followed methodology in this research is System dynamics. While developing the system dynamics model, there are factors taken into account considered as inside of the border system as well as factors that are ignored. Each of these factors creates some limitations with respect to reflecting on real life. Furthermore, the assumptions that are made in order to quantify the model also represent the limitations of research. All these limitations offer suggestions for further study to deepen our grasp of the subject. In this section, a few important ones are discussed.

First of all, the omitted dynamics that are ignored in the model limit the realness of the problem. The pricing of the unit cost of electricity changes over time depending on many factors such as supply and demand, investment politics, etc. while this has a strong influence on the consumption of AC for each household corresponding to their income. This is one of the cause-effect relationships that are not represented in the model. However, the importance of this dynamic in the system is acknowledged by the literature which encourages future research to improve the model by involving the dynamic of price and consumption.

Secondly, the model tries to capture sociocultural behavior patterns of individuals in that region, and this is based on assumptions from secondary data. However, these types of intangibles, subjective factors are only implemented with limitations. Because it is nearly impossible to capture individuals' behavior patterns that are changing constantly with respect to the relation with several factors. In this research, this complicated relationship is out of the scope and therefore is just simplified with the assumption of behavioral patterns are the same throughout the years. This significantly limits the understanding of how behavioral-dependent consumption influences the dynamics in the system. Also, the sociocultural behavior mechanism is considered a lever point in the literature which points out that there is promising potential for implementations towards to aimed goal. Therefore, I strongly believe that it is valuable to examine and model sociocultural behaviors for future research.

Last but not least, like many research one of the big limitations of this research was the time and data availability. The scope and highly complex nature of the cold crunch problem with the combination of limited time and data lead to having an abstract view of the problem rather than an in-depth analysis. Also, secondary data and the assumptions on quantifying chop off accuracy and validity of the results. These limitations can be improved with the help of relevant authorities by collecting data and getting guidance on some specific technical points about the problem. For the upcoming research, it is important to have collaborative research with available data and time.

8. References

Akpinar-Ferrand, E., & Singh, A. (2010). Modeling increased demand of energy for air conditioners and consequent CO2 emissions to minimize health risks due to climate change in India. *Environmental Science & Policy*, *13*(8), 702–712. https://doi.org/10.1016/j.envsci.2010.09.009

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, *12*(3), 183–210. https://doi.org/3.0.co;2-4">10.1002/(sici)1099-1727(199623)12:3<183::aid-sdr103>3.0.co;2-4

Biardeau, L. T., Davis, L. W., Gertler, P., & Wolfram, C. (2019). Heat exposure and global air conditioning. *Nature Sustainability*, *3*(1), 25–28. https://doi.org/10.1038/s41893-019-0441-9

Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M. L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O. Y., Geels, F. W., Grubler, A., Hepburn, C., Hertwich, E. G., Khosla, R., Mattauch, L., Minx, J. C., Ramakrishnan, A., Rao, N. D., Steinberger, J. K., Tavoni, M., Ürge-Vorsatz, D., & Weber, E. U. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, *8*(4), 260–263. https://doi.org/10.1038/s41558-018-0121-1

Flood, R.L., Jackson, M.C. Total systems intervention: A practical face to critical systems thinking. Systems Practice 4, 197–213 (1991). https://doi.org/10.1007/BF01059565

Hakim, C. (1982). Secondary analysis in social research: A guide to data sources and method examples. London, UK: George Allen & Uwin

Harrison, J. R., Lin, Z., Carroll, G. R., & Carley, K. M. (2007). Simulation modeling in organizational and management research. *Academy of Management Review*, *32*(4), 1229–1245. https://doi.org/10.5465/amr.2007.26586485

Hollweck, T. (2016). Robert K. Yin. (2014). Case Study Research Design and Methods (5th ed.). Thousand Oaks, CA: Sage. 282 pages. *The Canadian Journal of Program Evaluation*, *30*(1). https://doi.org/10.3138/cjpe.30.1.108

IEA (2021), Cooling, IEA, Paris https://www.iea.org/reports/cooling

International Energy Agency (IEA), The Future of Cooling, 2018. https://www. iea.org/.

International Herald Tribune, 2007. Cool rooms in Asia warming the planet. February 22, 2007.

Khosla, R., Agarwal, A., Sircar, N., Chatterjee, D. (2021). The what, why, and how of changing cooling energy consumption in India's urban households. Environmental Research Letters, 16(4). https://doi.org/10.1088/1748-9326/abecbc

Khosla, R., Miranda, N. D., Trotter, P. A., Mazzone, A., Renaldi, R., McElroy, C., Cohen, F., Jani, A., Perera-Salazar, R., & McCulloch, M. (2020). Cooling for sustainable development. *Nature Sustainability*, *2020*(a). https://doi.org/10.1038/s41893-020-00627-w

Liebenberg, L. (2016). Writing to Learn. *International Journal of Qualitative Methods*, *15*(1), 160940691667615. https://doi.org/10.1177/1609406916676150

Manu, S., Shukla, Y., Rawal, R., Thomas, L. E., & de Dear, R. (2016). Corrigendum to "Field studies of thermal comfort across multiple climate zones for the subcontinent: India model for adaptive comfort (IMAC)" [Building and Environment 98 (2016) 55–70]. *Building and Environment*, *106*, 422–426. https://doi.org/10.1016/j.buildenv.2016.07.015

Mastrucci, A., Byers, E., Pachauri, S., & Rao, N. D. (2019). Improving the SDG energy poverty targets: Residential cooling needs in the Global South. *Energy and Buildings*, *186*(186), 405–415. https://doi.org/10.1016/j.enbuild.2019.01.015

Mcgregor, G. R., Bessemoulin, P., Ebi, K. L., B Menne, World Meteorological Organization, & World Health Organization. (2015). *Heatwaves and health : guidance on warning-system development*. World Meteorological Organization.

McNeil, M., & Letschert, V. (2008). Future Air Conditioning Energy Consumption in Developing Countries and what can be done about it: The Potential of Efficiency in the Residential Sector. Lawrence Berkeley National Laboratory. Retrieved from https://escholarship.org/uc/item/64f9r6wr

McNicoll, G. (2005). United Nations, Department of Economic and Social Affairs: World Economic and Social Survey 2004: International Migration. *Population and Development Review*, *31*(1), 183–185. https://link.gale.com/apps/doc/A132710943/AONE?u=anon~9d35a128&sid=googleScholar&xid=9ceede86

Pavanello, F., De Cian, E., Davide, M., Mistry, M., Cruz, T., Bezerra, P., Jagu, D., Renner, S., Schaeffer, R., & Lucena, A. F. P. (2021). Air-conditioning and the adaptation cooling deficit in emerging economies. *Nature Communications*, *12*(1), 6460. https://doi.org/10.1038/s41467-021-26592-2

Pruyt, E., & Kwakkel, J. (2007). Combining system dynamics and ethics: Towards more science. 25th international conference of the system dynamics society.

Santamouris, M. (2016). Cooling the buildings – past, present and future. *Energy and Buildings*, *128*, 617–638. https://doi.org/10.1016/j.enbuild.2016.07.034

Sciarra D. The role of the qualitative researcher. In: Kopala M, Suzuki LA, eds. Using Qualitative Methods in Psychology. Thousand Oaks, CA: Sage; 1999;37-48

Senge, P. M., Forrester, J. W. (1980). Tests for building confidence in system dynamics models. *TIMS studies in management sciences*. 14, 209-228.

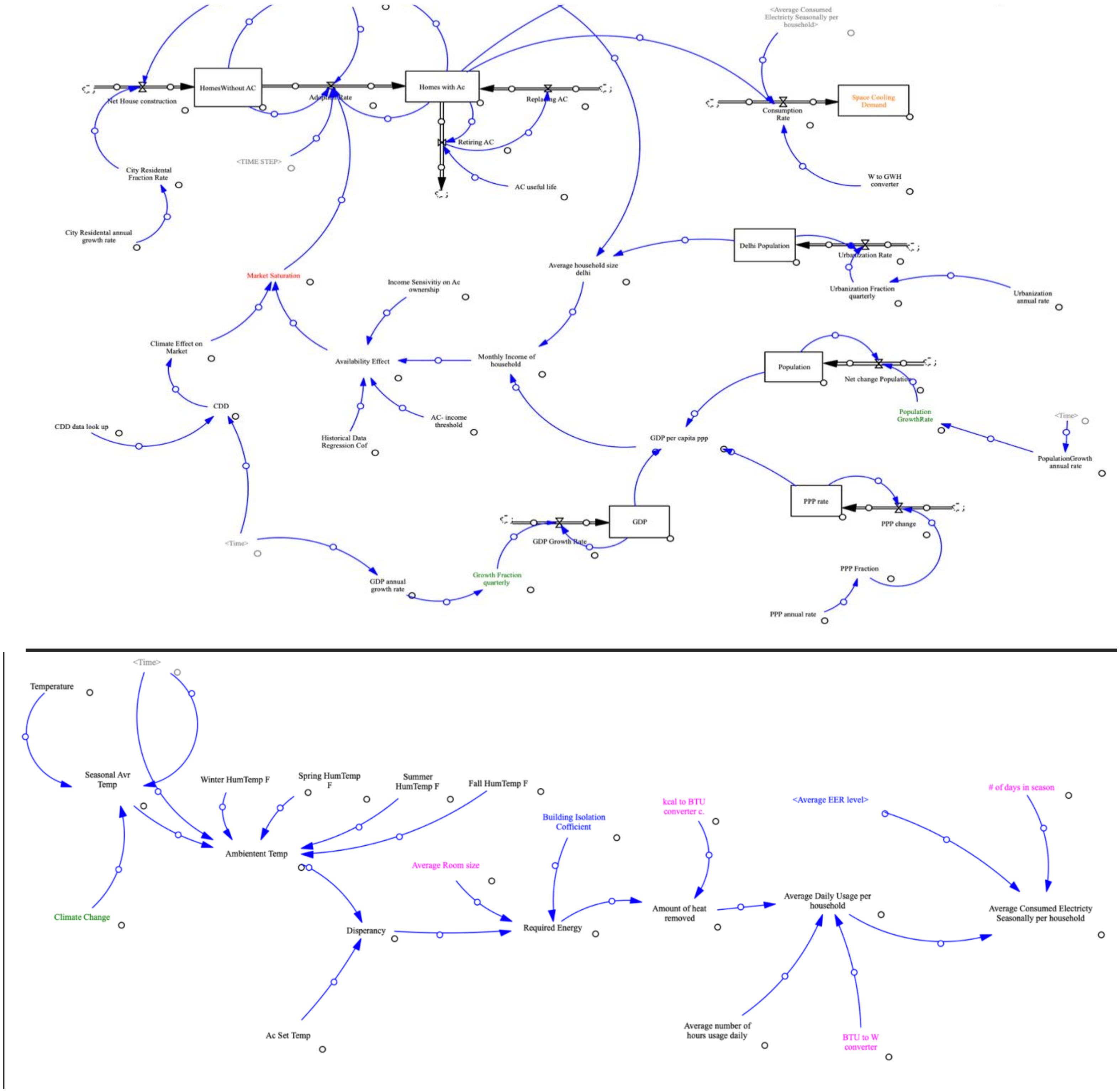
Sivak, M. (2009). Potential energy demand for cooling in the 50 largest metropolitan areas of the world: Implications for developing countries. *Energy Policy*, *37*(4), 1382–1384. https://doi.org/10.1016/j.enpol.2008.11.031

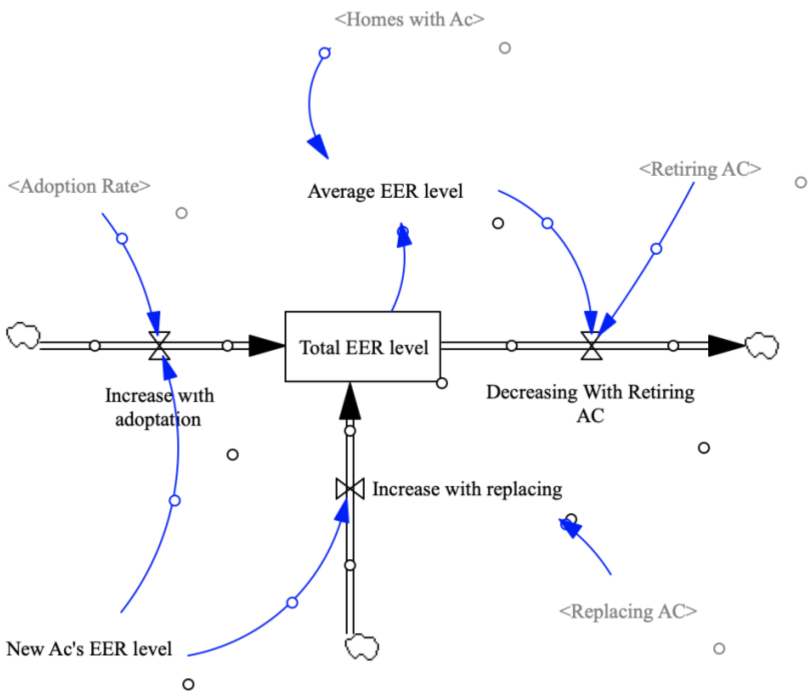
Stephenson, J., Barton, B., Carrington, G., Gnoth, D., Rob Lawson, Thorsnes, P. (2010)Energy cultures: A framework for understanding energy behaviours,*Energy Policy*, 38(10), 6120-6129.https://doi.org/10.1016/j.enpol.2010.05.069.

Sterman, J. D. (2000). *Business dynamics : systems thinking and modeling for a complex world*. Irwin.

Appendix A: Model Overview

Figure 17: The Full Model Overview





Appendix B: Model Documentations

Table 4: Model Documentations

(01) "# of days in season"= 90
Units: days/Quarter
(02) Ac Set Temp=23
Units: Dmnl
(03) "AC- income threshold"=1000
Units: $/Quarter
(04) AC ownership ratio=Homes with Ac/"Total # households"
Units: Dmnl
(05) AC useful life=60
Units: Quarter
(06) Adoption Rate=
MIN(("Total # households"*Market Saturation)-Homes with Ac,HomesWithout AC /TIME STEP)
Units: hh/Quarter
(07) Ambientent Temp=

IF THEN ELSE(MODULO(Time,4)=1,Winter HumTemp F(Seasonal Avr Temp),IF THEN ELSE(MODULO(Time,4)=2 ,Spring HumTemp F(Seasonal Avr Temp),IF THEN ELSE(MODULO(Time,4)=3,Summer HumTemp F(Seasonal Avr Temp),Fall HumTemp F(Seasonal Avr Temp))))

Units: Dmnl

(08) Amount of heat removed=

"kcal to BTU converter c."*Required Energy

Units: BTU/hr/hh

(09) Availability Effect=

1/(1+(EXP(Historical Data Regression Cof)*EXP((Income Sensivitiy on Ac ownership
*Monthly Income of household)/"AC- income threshold")))

Units: 1/Quarter

(10) Average Consumed Electricty Seasonally per household=

(Average Daily Usage per household/Average EER level)*"# of days in season"

Units: W/Quarter

(11) Average Daily Usage per household=

Amount of heat removed*BTU to W converter*Average number of hours usage daily

Units: W/(hh*days)

(12) Average EER level=

Total EER level/Homes with Ac

Units: 1/hh

(13) Average household size delhi=

Delhi Population/"Total # households"

Units: person/hh

(14) Average number of hours usage daily= 5.5

Units: hr/days

(15) Average Room size= 76

Units: 1/hh

(16) BTU to W converter= 0.29308

Units: W/BTU

(17) **Building Isolation Coefficient= 1.5**

Units: kcal/hr

(18) CDD= CDD data look up(Time)

Units: Dmnl

(19) CDD data look up=

[(0,0)-(400,5000)],(0,3418),(4,3520),(8,3471),(12,3466),(16,3477),(20,3557),(24,3510),(28,3407),(32,3407),(36,3668),(40,3783),(44,3462),(48,3490),(52,3562),(56,3721),(60,3846),(64,3813),(68,3687),(72,3751),(76,3692),(80,3647),(120,4080),(160,4213),(200,4345),(400,4800))

Units: Dmnl

(20) City Residental annual growth rate= 0.025705

Units: Dmnl

(21) City Residental Fraction Rate= ((1+City Residental annual growth rate)^0.25-1)

Units: 1/Quarter

(22) Climate Change= RAMP (0.008333,56,200)

Units: Dmnl

(23) Climate Effect on Market= 1-0.949*EXP(-0.00187*CDD)

Units: Dmnl

(24) Consumption Rate=

(Average Consumed Electricity Seasonally per household*Homes with Ac)/W to GWH converter

Units: hh*GWH/Quarter

(25) Decreasing With Retiring AC= Average EER level*Retiring AC

Units: 1/Quarter

(26) Delhi Population= INTEG (Urbanization Rate, 1.35629e+07)

Units: person

(27) Disperancy= MAX(Ambientent Temp-Ac Set Temp,0)

Units: Dmnl

(28) Fall HumTemp F=

[(10,0)-(39,60)],(10,10),(22,22),(23,23),(24,24),(25,25),(26,26),(27,28),(28,29),(29,31),(30,33),(31,35),(32,37),(33,40),(34,42),(35,45),(36,48),(37,51),(38,55),(39,59))

Units: Dmnl

(29) FINAL TIME = 200

Units: Quarter

The final time for the simulation.

(30) GDP= INTEG (GDP Growth Rate, 2.13989e+13)

Units: INR/Quarter

(31) GDP annual growth rate=

IF THEN ELSE(Time<=80,0.13,0.09)
Units: Dmnl
(32) GDP Growth Rate=
GDP*Growth Fraction quarterly
Units: INR/Quarter/Quarter
(33) GDP per capita ppp=
GDP/(PPP rate*Population)
Units: $/Quarter/person
(34) Growth Fraction quarterly=
((1+GDP annual growth rate)^0.25-1)
Units: 1/Quarter
(35) Historical Data Regression Cof= 4.152
Units: Dmnl
(36) Homes with Ac= INTEG ((Adoption Rate+(Replacing AC-Retiring AC)), 52702**)**
Units: hh
(37**) HomesWithout AC=** INTEG (Net House construction-Adoption Rate, 2.66488e+06-100000)
Units: hh
(38) Income Sensivitiy on Ac ownership= -1.055
Units: hh
(39) Increase with replacing=
New Ac's EER level*Replacing AC
Units: 1/Quarter
(40) Increase wıth adoptation=
Adoption Rate*New Ac's EER level
Units: 1/Quarter
(41) INITIAL TIME = 0
Units: Quarter
The initial time for the simulation.
(42) "kcal to BTU converter c."= 3.96567
Units: BTU/kcal
(43) Market Saturation=
Availability Effect*Climate Effect on Market
Units: 1/Quarter
(44) Monthly Income of household=

(GDP per capita ppp*Average household size delhi)/12
Units: $/hh/Quarter
(45) Net change Population=
Population*PopulationGrowthRate
Units: person/Quarter
(46) Net House construction=
"Total # households"*City Residental Fraction Rate
Units: hh/Quarter
(47) New Ac's EER level= 3.15
Units: W/W/hh
(48) Population= INTEG (Net change Population, 1.05658e+09)
Units: person
(49) PopulationGrowth annual rate=
IF THEN ELSE(Time<=80,0.0132,0.0132)
Units: Dmnl
(50) PopulationGrowthRate=
(1+PopulationGrowth annual rate)^0.25-1
Units: 1/Quarter
(51) PPP annual rate= 0.04
Units: Dmnl
(52) PPP change= PPP rate*PPP Fraction
Units: INR/$/Quarter
(53) PPP Fraction=
((1+PPP annual rate)^0.25-1)
Units: 1/Quarter
(54) PPP rate= INTEG (PPP change, 9.664)
Units: INR/$
(55) Replacing AC= Retiring AC
Units: hh/Quarter
(56) Required Energy=
(Average Room size*Building Isolation Cofficient*Disperancy)
Units: kcal/hr/hh
(57) Retiring AC=
Homes with Ac/AC useful life
Units: hh/Quarter

(58) SAVEPER =
TIME STEP Units: Quarter [0,?]
The frequency with which output is stored.

(59) Seasonal Avr Temp=
Temperature(MODULO(Time,4))+Climate Change
Units: Dmnl

(60) Space Cooling Demand= INTEG (Consumption Rate, 0)
Units: hh*GWH

(**61) Spring HumTemp F=**
[(27,0)-(43,60)],(27,27),(28,28),(29,29),(30,30),(31,31),(32,32),(33,34),
(34,35),(35,37),(36,39),(37,41),(38,43),(39,46),(40,48),(41,51),(42,54),(43
,57))
Units: Dmnl

(62) Summer HumTemp F=
[(27,0)-(36,60)],(27,29),(28,31),(29,34),(30,36),(31,39),(32,42),(33,46),
(34,49),(35,53),(36,58))
Units: Dmnl

(63) Temperature=
[(0,0)-(4,40)],(0,13.4),(0.33,13.4),(0.66,16.8),(1,22.4),(1.33,29.1),(1.66
,32.7),(2,32.9),(2.33,29.9),(2.66,28.8),(3,27.9),(3.33,25.5),(3.66,20.5),(
4,15.3))
Units: Dmnl

(64) TIME STEP = 0.125
Units: Quarter [0,?]
The time step for the simulation.

(65) "Total # households"=
ACTIVE INITIAL (Homes with Ac+HomesWithout AC,
Homes with Ac+HomesWithout AC)
Units: hh

(66) Total EER level=
INTEG (Increase with replacing+Increase wıth adoptation-Decreasing With Retiring AC,53656*3.15)

Units: W/W

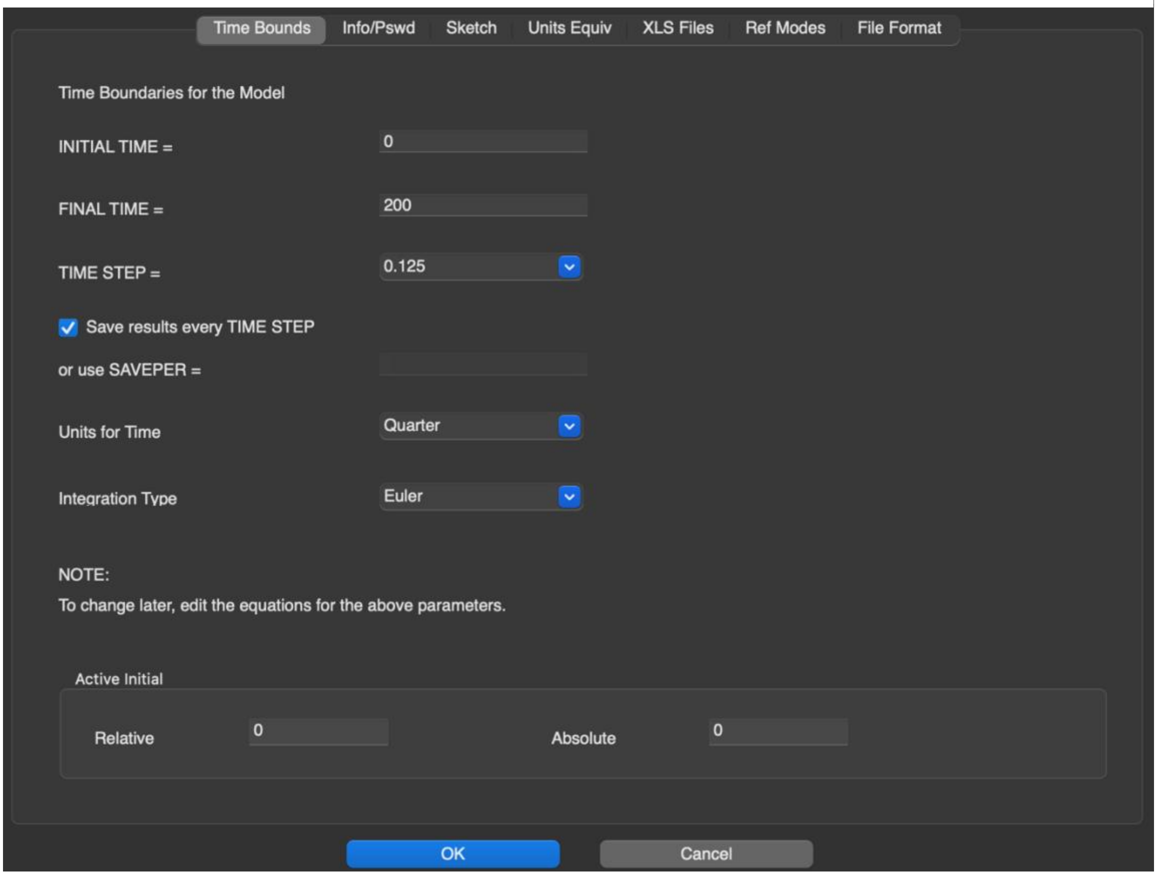
(67) Urbanization annual rate= 0.0212081
Units: Dmnl

(68) Urbanization Fraction quarterly=

((1+Urbanization annual rate)^0.25-1)
Units: 1/Quarter
(69) Urbanization Rate=
Delhi Population*Urbanization Fraction quarterly
Units: person/Quarter
(70) W to GWH converter= 1e+09
Units: W/GWH
(71) Winter HumTemp F=
[(0,0)-(30,30)],(0,0),(25,25),(30,30))
Units: Dmnl

Appendix C: Simulation Settings

Figure18: Model Settings



Appendix D: Data Sources & Analysis

Table 5: Data Sources & Analysis

Data Source	Time Period	Corresponding Variable	Initial Value (2000)	Change*	Annual Trends
Census	2001*,2011*	Population of Delhi	1.35629e+07	Growth	0.021208
Census	2001*,2011*	Residental # of Household Delhi	2664883	Growth	0,25705
OECD Data (India)	2000-2020	GDP(LCU)	21398856906300	Growth	0.13
OECD Data (India)	2000-2020	PPP	9.664	Growth	0.04
United Nations World Population Prospeects 2022	2000-2020	Population(India	1 056 576 0000	Growth	0.01326
Climate-data.org	1991-2021	Temperature (Delhi)	Seosonal Average	Climate Change	-
IEA Weather for Energy Tracker	2000-2020	CDD(Delhi 18°C,humdity)	3418	-	-

Appendix E: Validation Tests

Table 6 Validation Tests

Tests	Explanation of Validity
Boundary Adequacy	The important variables of the problem at hand are addressed endogenously which are adoption, income, and EER level of AC. The boundary chart is already provided in the model description section. The adequacy of necessary boundaries what to include what to exclude have been chosen according to the aim of the research. These choices set credible grounds for this research.
Structure confirmation	The structure of the model is based on articles and the International Energy Agency report on the Future of Cooling. The developed relationships between variables come from literature. The level of aggregation of the model is in line with the purpose of the study, however, the behavior mechanism of the model is not depth due to the limitations of the research. The model conforms to the basic physical laws.
Dimensional Consistency	Model equations and units are checked and they are consistent. All the units have real-world meanings.

Extreme Conditions	The model passes the most reasonable direct extreme condition tests. To fit the model to extreme conditions the max, min, and 'if then else' functions are used in the equations of the model. The test results showed expected outcomes which line with realty
Integration error	A time interval- and integration tests are performed. For validation tests, the model is not sensitive to them.
Behavior reproduction	The behaviors of the performance indicator variables are the same reference behaviors of empirical studies and reports. There is no historical data that matches the scope of the model, therefore the output could not compare in order to assess correspondence in between. However, the analysis of the National Capital Regional Survey of India in 2017 contains the AC ownership ratio in Delhi which is %24 percent. The output of our model has less than %1 error corresponding with that data.