UNIVERSIDADE ESTADUAL DE CAMPINAS
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FRANK VICENTE PORRAS CARRIÓN

Assessment of the Effects of Stricter Standards in Energy Efficiency Regulation for Residential Air Conditioning in Guayaquil, Ecuador

Avaliação dos Efeitos de Padrões mais Restritivos na Regulamentação de Eficiência Energética no Uso Residencial de Ar Condicionado em Guayaquil, Equador

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Dissertation presented to the School of Mechanical Engineering of the University of Campinas in partial fulfillment of the requirements for the degree of Master in ENERGY PLANNING.

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Orientador: Prof. Dr. Arnaldo Cesar da Silva Walter
Coorientador: Prof. Dr. Guillermo Enrique Soriano Idrovo

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Resumo

No mundo, o uso de energia elétrica para resfriamento de espaços tem o mais rápido crescimento em edificações; em 2016, esse consumo foi de 2020 TWh, o que representou 18,5% do consumo total de eletricidade nesse setor, e 12% de suas emissões totais de CO_2. No Equador, o mais recente estudo sobre usos finais de energia elétrica foi publicado em 1993 pelo ex-INECEL. Esse estudo mostrou que a parcela devido a ar condicionado representou 14,3% da demanda total de eletricidade e contribuiu com 12% da demanda pico na região litoral.

Este trabalho estima a demanda elétrica de equipamentos de ar condicionado (AC) no setor residencial de Guayaquil - Equador e quantifica os benefícios potenciais do aumento do atual padrão mínimo de eficiência energética (PMEE) considerando dois cenários de crescimento econômico, tendo 2020 como ano base e 2030 como horizonte. O impacto na difusão dos aparelhos também é quantificado, principalmente em residências de renda média, que apresentam o maior potencial de crescimento no uso de equipamentos de ar-condicionado.

A estimativa mostra que a demanda devido aos sistemas de AC representou 15,4% da demanda total de eletricidade no setor residencial em 2000 (108 GWh em termos absolutos), e essa quase triplicou em 2019 (285 GWh), representando 19,5% da demanda total residencial. Com o atual padrão de eficiência energética (EER = 3.2 W/W), a demanda de eletricidade associada pode chegar a 489 GWh em 2030, representando 21,5% da demanda e 0,07 $MtCO_2eq$ em emissões relacionadas ao consumo de energia elétrica.

No contexto analisado (i.e., preços da eletricidade, nível de renda das famílias e o aumento nos custos dos equipamentos associados aos diferentes PMEE analisados, oito no total), o PMEE melhor avaliado foi 4,3 W/W. A avaliação leva em consideração tanto a perspectiva do consumidor, em termos de economia nos custos no ciclo de vida (ECCV), e a perspectiva da sociedade, avaliada em termos do valor presente líquido. Com o novo padrão, seria possível reduzir o consumo acumulado de eletricidade nos aparelhos de AC e as emissões de CO_2 relacionadas à energia elétrica em até 11% entre 2020 e 2030. Porém desde o ponto de vista do consumidor os benefícios serão pequenos em comparação ao aumento no valor de compra do equipamento. Portanto, as famílias não estarão incentivadas a trocar os equipamentos por unidades mais eficientes, a menos que haja políticas para minimizar o impacto do custo adicional.

Palavras-chave: demanda de energia, ar condicionado residencial, padrões mínimos de eficiência energética, regulamentação de eficiência energética.

Abstract

Worldwide, the energy use for space cooling has the fastest growth in buildings; in 2016, this consumption was 2020 TWh, which represented 18.5% of the total electricity consumption in this sector, and 12% of its total CO_2 emissions. In Ecuador, the latest national end-use energy study was published in 1993 by the ex-INECEL. This study showed that the share of air conditioning was 14.3% of total electricity demand and contributed with 12% of the peak demand in the coast region.

This work estimates the energy demand of air conditioning equipment (AC) in the residential sector of Guayaquil - Ecuador, and quantifies the potential benefits of increasing the current minimum energy performance standard (MEPS) considering two economic growth scenarios, having 2020 as the base year and a horizon until 2030. It also quantifies the impact in the diffusion of the appliance, especially in middle-income households, which presented the greatest growth potential in the use of air conditioning.

The results show that AC demand represented 15.4% of total residential electricity demand in 2000 (108 GWh in absolute terms), and almost tripled in 2019 (285 GWh), representing approximately 19.5% of total residential electricity demand. With the current energy efficiency standard (EER = 3.2 W/W), the associated electricity demand could reach up to 489 GWh in 2030, representing 21.5% of the total residential electricity demand and 0.07 $MtCO_2eq$ in energy-related emissions.

In the assessed context (i.e. the electricity prices, the level of households' income, and the increase in equipment costs associated with the different MEPS analyzed, eight, in total), the best-rated MEPS was 4.3 W/W. The assessment took into account both the perspective from a single household, in terms of the life-cycle cost savings (LCCS), and the society perspective, in terms of the net present value. With the new standard, it would possible to reduce the aggregate AC electricity consumption and energy-related CO_2 emissions up to 11% between 2020 and 2030. However, from the consumers' point of view, the benefits would be small compared to the increase in the equipment cost. This result would not encourage the acquisition of more efficient units, unless additional policies would stablish to reduce the upfront cost.

Key Words: energy demand, residential air conditioning, minimum energy performance standards, energy efficiency regulation.

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List of Acronyms and Abbreviations

AN	Asamblea Nacional
ANSI	American National Standards Institute
ARCONEL	Agencia de Regulación y Control de Electricidad
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCE	Banco Central del Ecuador
CELEC	Corporación Eléctrica del Ecuador
CENACE	Centro Nacional de Control de Energía de la República del Ecuador
CIBSE	Chartered Institution of Building Services Engineers
CLASP	Collaborative Labeling and Appliance Standards Program
CNEE	Consejo Nacional de Eficiencia Energética
CNEL	Corporación Nacional de Electricidad
IEA	International Energy Agency
INAMHI	Servicio Meteorológico e Hidrológico Nacional del Ecuador
INEC	Instituto Nacional de Estadisticas y Censos
INEN	Instituto Ecuatoriano de Normalización
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
MEER	Ministerio de Energía y Recursos Naturales no Renovables
MIPRO	Ministerio de Industria y Productividad
OLADE	Organización Latinoamericana de Energía
PAHO	Pan American Health Organization
SEforALL	Sustainable Energy for All
SNI	Sistema Nacional Interconectado
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

A1	High income scenario
AC	Air conditioning
AMA	Arithmetic moving average
B2	Mid income scenario
BAU	Buissness as usual scenario
CDD	Cooling degree days
CFCs	Chlorofluorocarbons
CMS	Climate maximum saturation
COP	Cofficient of performance
CP	Compressor
DMEE	Distintivo de máxima eficiencia energética
DSM	Demand side management
EER	Energy efficiency ratio
ENSO	El Niño – Southern Oscillation

EXT	Thermostatic Expansion Valves
GDP	Gross domestic product
GHG	Greenhouse gases
GNI	Gross national income
GWP	Global warming potential
HCFCs	Hydro chlorofluorocarbons
HCs	Hydrocarbons
HE	Heat exchanger
HFCs	Hydro fluorocarbons
HFOs	hydrofluoro-olefins
HI	Heat index
HVAC	Heating, ventilating and air conditioning
IDA	Index decomposition analysis
I-P	Imperial Units
LCC	Life cycle cost
LMDI	Logarithmic mean divisia index
LOEE	Ley orgánica de eficiencia energética
LOSPEE	Ley orgánica de servicio público de electricidad
MEPS	Minimum energy performance standards
Mt	Million tonnes
MVE	Monitoring, verification and enforcement
NPV	Net present value
NTE	Norma técnica ecuatoriana
ODP	Ozone depletion potential
ODS	Ozone-Depleting Substances
PLANEE	Plan nacional de eficiencia energética
PME	Plan maestro de eléctricidad
PPP	Purchasing power parity
PRTE	Projecto de reglamento técnico ecuatoriano
R	Refrigerant
RH	Relative humidity
RTE	Reglamento técnico ecuatoriano
S&L	Standard and Labelling programmes
SBU	Salário básico unificado
SEER	Seasonal energy efficiency ratio
SI	International unit system
TMY	Typical meteorological year
TXV	Thermostatic expansion valves
UAC	Unitary air conditioning
UEC	Unit energy consumption
UHI	Urban heat island
VRF	Variable refrigerant flow

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1 INTRODUCTION

This introductory chapter describes the main issues related to the use of air conditioning in the residential sector, as well as the context of the research that was conducted focusing on the city of Guayaquil, Ecuador. The scope and objectives of the research, the development line and, finally, the structure of this dissertation are presented in the following sections.

1.1 Motivation and context

In regions with hot and/or humid climate air conditioning systems are required in order to achieve thermal comfort conditions indicated by engineering standards (ANSI/ASHRAE, 2010; ISO, 2005). The associated energy consumption increases sharply as population, socioeconomic conditions, and consumer expectations of thermal comfort increase, especially in emerging economies, which are mainly located in the tropics and subtropics, and where greater impact is expected due to global warming (IEA, 2018a).

Worldwide, electricity consumption for space cooling in buildings tripled between 1990 and 2016, reaching more than 2000 Terawatt hours (TWh), which accounted for 18.5% of total electricity use in this sector (it was estimated at 13% in 1990). This has been the fastest-growing energy use in buildings, accounting for a large share of peak demand; placing further stress on the power system, especially during periods of extreme heat, and also contributing significantly to global warming through direct and indirect emissions (IEA, 2018b). The present work highlights these impacts, which are blind spots in the current Ecuadorian energy policy.

Several factors determine the energy consumption of air conditioning systems and its growth, such as local climate, economic growth and affordability, demographic issues, the technology, the existence of energy performance requirements in building codes, energy efficiency programs, and actions for demand-side management (IEA, 2018b).

The city of Guayaquil-Ecuador has a tropical climate with an annual average temperature of 27°C and average relative humidity of 77% (INAMHI, 2015). Thus, local climatic conditions justify the intense use of air conditioning systems. This study is the first of kind in Ecuador, focusing the electricity consumption analysis of residential air conditioners in Guayaquil. More specifically, an aim is the assessment of the potential benefits of increasing the minimum energy performance standard (MEPS) set out by the Ecuadorian technical regulation for Ductless Mini-Split Air Conditioners[1] (INEN, 2017).

From a regulatory point of view, the context of this dissertation is defined by the first Energy Efficiency Law[2] of Ecuador, approved in 2019 (AN, 2019), and by the draft of the new Ecuadorian technical regulation for AC units (INEN, 2019). The context is such that the MEPS for equipment sold in the country would remain the same, and there is no time period for their review; Energy efficiency ratio (EER) 3.2 W/W is the currently established standard.

1.2 Objectives and scope

The present work has two general objectives. The first is to characterize the air conditioning demand in Guayaquil, in terms of climate, household income, and energy-related greenhouse gas (GHG) emissions. The second general objective is to assess the impact of more stringent MEPS on household AC energy demand, on emissions related to the use of AC equipment and on the diffusion of AC in households. Guayaquil is the study case within the Ecuadorian context due to the representativeness of the city and the availability of information.

The first objective builds a baseline for the air conditioning demand. The second objective uses this baseline to assess the cost-benefits of more stringent MEPS in the energy efficiency regulation of Ecuador. Therefore, both objectives are complementary and seek to broaden the debate on the use of energy in air conditioning equipment within the context of Guayaquil-Ecuador.

To achieve the first general objective, the following specific actions were conducted:

- To quantify the increase in electricity consumption associated with space cooling in Guayaquil, electricity consumption was correlated with local climatic conditions.
- Estimate the electricity demand of AC units and quantify the share of air conditioning in total household electricity demand. From this, estimate the associated CO_2 emissions. For this task, models mentioned in the literature and data from surveys on consumption habits and equipment ownership were used.

[1] From now on, called AC units.
[2] This law contemplates the creation of a National Energy Efficiency Committee. One task of this committee is to create a list of high-energy consumption equipment. The level of energy efficiency of these equipment will be determined by the MEPS established in the Ecuadorian technical regulations.

- To define a baseline for the assessment of more stringent MEPS, economic growth scenarios - having 2030 as the horizon - were established. Estimates for the electricity demand of ACs are in function of household income growth.
- For setting references, indicators from countries with similar economic and climatic characteristics to Ecuador were compiled and these were compared with the results of the AC energy demand model for Guayaquil.
- AC energy consumption were stratified by households' income levels. The objective was to identify the group of families with the highest potential for diffusion of more efficient equipment, and the information was used to assess the impact of more stringent MEPS policies.

To achieve the second general objective, the following specific actions were performed:

- The impacts of adopting more stringent MEPS were assessed from both the consumer (for a single family) and societal points of view. More efficient equipment allows the reduction of electricity consumption, which can bring economic benefits to consumers and to the society. In addition, potentially there are benefits due to the lower emissions of GHG.
- The estimated AC demand was decomposed according to its drivers in order to quantify their relative contribution. These results were used to estimate the effectiveness of more stringent MEPS.

1.3 Dissertation development line

In a broader sense, there are several aspects related to the widespread use of air conditioning systems, including energy efficiency, feasibility of technological developments, environmental aspects, and especially those related to climate change, improved quality of life, productivity and people's health, and policies and regulations. This dissertation addresses some of these aspects and takes them into the Ecuadorian context. In order to have a better understanding, the work line is schematically presented in Figure 1.1. The following subsections present a further explanation of this work line.

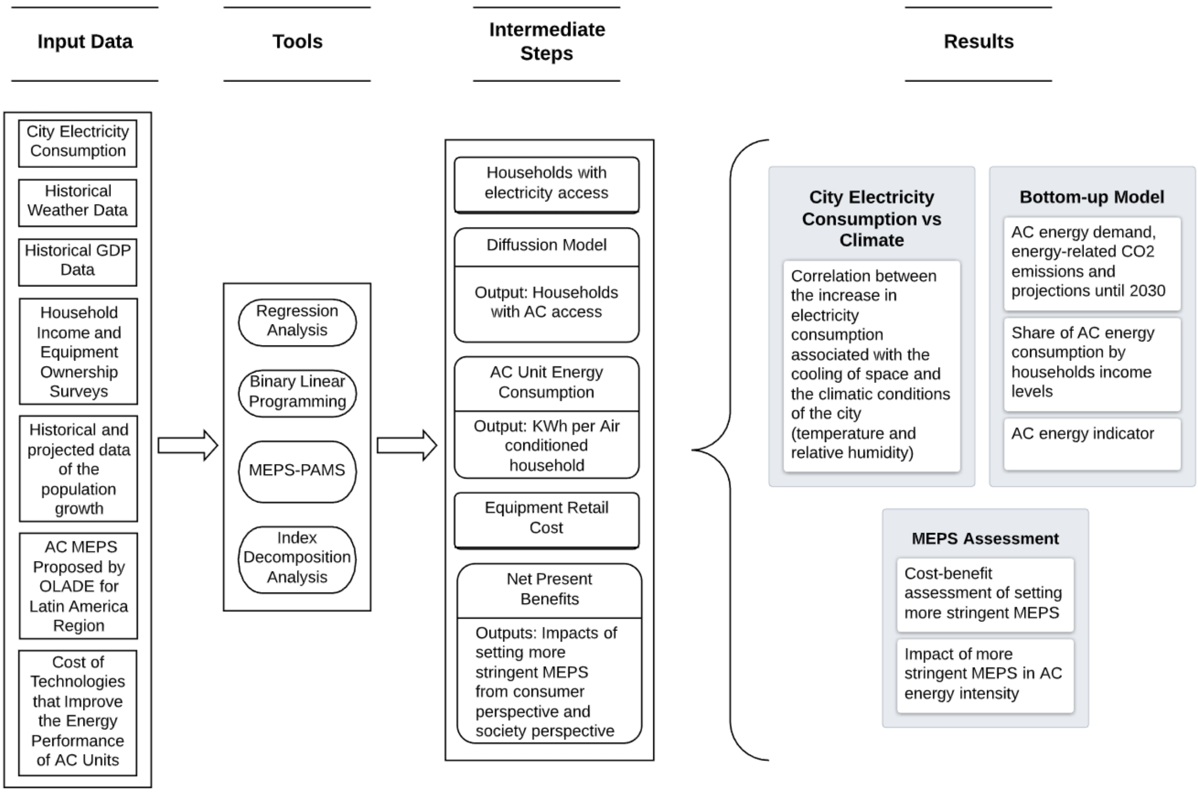


Figure 1.1: Scheme of the dissertation development line

1.3.1 Input Data

Required information (Input Data) related to the use of AC equipment was gathered from national, regional[3] and global sources. At the national level, for example, information about the electricity consumption in Guayaquil was obtained from the local electricity company (CNEL). In addition, data related to household income, AC ownership and use were gotten from the surveys performed by the National Institute of Statistics and Census (INEC).

Data on the costs of ACs[4] and on the technologies that would result in better energy performance were collected from the regulatory impact studies and reports on efficient cooling equipment conducted in the region (Costa et al., 2019; Letschert, Karali, Jannuzzi, Lamberts, & Costa, 2019; MINEN, 2017; OLADE, UNEP, & CLASP, 2015). The average efficiency of the stock of ACs and the information needed to estimate electricity demand was obtained from the literature. (IEA, 2018b; McNeil & Letschert, 2008). Chapter 4 presents more details about input data and data sources.

[3] Hereafter referred to Latin America.

[4] Some assumptions about the local AC market may create uncertainties when calculating cost-benefits of more stringent MEPS. One way to reduce them is with local market studies (Guayaquil-Ecuador), which could not be done in this dissertation.

1.3.2 Tools

As can be seen in Figure 1.1, four computational procedures or tools were used along the project.

Regression analysis was used to set correlations between the daily electricity consumption and the climate in Guayaquil for different years, also a correlation between the annual electricity consumption and household income was found. Finally, this analysis was used to set a correlation between the AC ownership and household income.

Binary Linear Programming was used to define the configuration of AC devices, minimizing equipment manufacturing costs. The procedure was applied taken into account different proposed[5] MEPS (OLADE et al., 2015). These costs were related to retail prices.

Policy Analysis Modeling System (PAMS) was used to evaluate the net present benefits related to the adoption of alternatives to the current MEPS in Ecuador. PAMS was created by the Lawrence Berkeley National Laboratory (Mcneil, Letschert, & Van Buskirk, 2007) and is based in a bottom-up approach. This tool allows policy analysts to produce a first-cut analysis, to examine the sensitivities concerning different policy parameters and assumptions, and to continually refine the analysis as more data becomes available (LBNL, 2007).

Finally, the Index Decomposition Analysis (IDA) was used to perform the decomposition of the AC demand in terms of their driving factors (i.e. Activity, Structure and Energy Intensity). The procedure was also used to assess the impact of higher standards in relation to changes in energy intensity (IEA, 2014b).

1.3.3 Intermediate Steps

The intermediate steps correspond to a set of calculations and include the assumptions made to simplify the analysis.

The estimate of the electricity demand by AC systems was done using a bottom-up model which depends on three factors. The activity factor corresponds to the households with access to electricity in Guayaquil. The structure factor involves the diffusion of AC systems in the residential sector. Finally, the intensity factor represented by the Unit Energy Consumption (UEC) of the appliance.

[5] Based on technologies and equipment currently available in the regional market.

The number of households with access to electricity is based on INEC's information about population growth and household size, as well as on CNEL's reports about the coverage of electricity service.

The diffusion of AC systems follows a logistic model and their parameters were calculated through a linear regression between AC ownership and household income. The data sets were obtained from surveys conducted by INEC.

The estimate of the UEC requires a reference[6] equipment in the local market but, due to the absence of proper data, it was chosen a common equipment in the Latin American market. How this equipment is used and the number of equipment per household (with access to air conditioning) were set based on the INEC's surveys conducted in Guayaquil. The UEC represents an energy indicator and provides insights for estimating the energy consumption in air conditioning. Therefore, is a relevant parameter in energy efficiency policies (IEA, 2014b).

Adopting more stringent MEPS could cause impacts on different stakeholders (consumers, public sectors, manufacturers and other private agents). In this dissertation the PAMS-MEPS tool was used only to assess impacts from the perspective of the consumer (single household) and the society as whole. The assessment of impacts on private sectors[7] is beyond the scope of this work, given data and resources constraints. Thus, the use of PAM-MEPS focused on the Life Cycle Cost (LCC) and Net Present Value (NPV) calculations. Chapter 4 presents details about the required inputs, intermediate calculations and outputs of this tool.

In (Costa et al., 2019; Wiel & McMahon, 2005) it can be found the guidelines and one example of a complete regulatory impact study based on PAMS-MEPS. This dissertation presents a simplified application of the methodology, based on (Mcneil, Letschert, & Buskirk, 2007; Mcneil, Letschert, & Van Buskirk, 2007) and used in (MINEN, 2017).

1.3.4 Results

The set of results varies from the specific to the general, and reflect the aims defined in this research project. The first two blocks of results presented in the scheme showed in Figure 1.1 corresponds to the correlation of daily electricity consumption in Guayaquil with local climate and to the results of the bottom-up model used for estimating parameters of AC use:

[6] It refers to an equipment usually found in the market, and the UEC is related to the energy efficiency ratio (EER) and to its cooling capacity (e.g. BTU/h). Regional studies (OLADE et al., 2015) were used to define this reference.

[7] Ecuador does not have AC industries. However, assessing impacts on importers, sellers, and other private stakeholders may be important considering the goal of implementing a successful MEPS program. (Wiel & McMahon, 2005).

the annual electricity demand for air conditioning, its share in total residential electricity demand, the stratification by household income levels, and a comparison with AC energy indicators of different countries. Projections of the AC demand in Guayaquil follow the economic scenarios considered, having 2030 as the horizon. The baseline for the MEPS assessment is based on the bottom-up model results.

The other block of the results in Figure 1.1 correspond to the assessment of more stringent MEPS either from the consumer or from the society perspectives. The impacts of more efficient AC devices on appliance diffusion, on the electricity consumption and on the energy-related CO_2 emissions are highlighted.

1.4 Structure of the dissertation

This work is organized in six chapters, including this introductory chapter.

Chapter 2 presents the literature review. Aspects addressed include how space cooling has driven energy demand in buildings and the relevance of air conditioning in electricity consumption. A second issue addressed is related to energy policies to curb the growth in energy consumption due to AC. The impacts of space cooling on health and wellness of the people, the required electrical infrastructure, energy security, and on emissions are described in the Appendix A.

Chapter 3 describes the structural characteristics of Guayaquil and Ecuador, based on geographical, demographic, climatic, and socio-economic parameters. It is also presented a summary of the national standard and labeling program. Appendix B shows information about the regulatory and legal context related to electricity consumption and energy efficiency in Ecuador.

Chapter 4 reports the methodology used in this dissertation. The tools and the intermediate steps presented in Figure 1.1 are described.

The results obtained and their discussion are presented in Chapter 5. The estimation shows that AC demand represented 15.4% of total residential electricity demand in 2000 (108 GWh) and in absolute terms, it almost tripled in 2019 (285 GWh) representing approximately 19.5% of total residential electricity demand. With the current energy efficiency standard (EER = 3.2 W/W), the associated electricity demand could reach up to 489 GWh in 2030, representing 21.5% of the total residential electricity demand and 0.07 Mt CO2eq in energy-related emissions. The results obtained from the evaluation of the different MEPS show that the best-rated MEPS is 4.3 W/W. With the new standard it would possible to reduce the aggregate AC electricity consumption and energy-related CO2 emissions up to 11% between 2020 and 2030.

Finally, Chapter 6 presents the conclusions of this research, as well as recommendations for future work on the same topic of this dissertation.

2 LITERATURE REVIEW

2.1 Drivers of space cooling demand

Nowadays the world is facing a rapid growth in space cooling demand, which can negatively impact the electrical infrastructure, environment and people (IEA, 2018b). Studying the factors that drive this demand is important to determine the actions to curve it. This section describes the main factors: Thermal comfort and climate, income and ownership, demographic factors, energy efficiency and buildings energy performance.

2.1.1 Thermal comfort and climate

Thermal comfort feeling is cognitive and involves different aspects. It is influenced by human thermoregulation, thermal exchanges with the environment, day-to-day variations of ambient temperature, age, adaptability, gender, and seasonal and circadian rhythms (ASHRAE, 2013b). The space cooling demand depends on the level of thermal comfort required by the occupants of a building or a dwelling. For millions of people around the world, the access to space cooling is an improvement in indoor environmental quality, which means better health, quality of life and productivity, and will be a key aspect of adaptation strategies in the face of global warming (ASHRAE, 2013b; PAHO, 2019; SEforALL, 2018)

Climate is statistically described in terms of the mean and variability of meteorological parameters which indicate how the atmosphere behaves over relative long periods. The difference between weather and climate is that weather consists of the short-term changes in the atmosphere (NASA, 2015; World Meteorological Organization (WMO), 2019). Climate affects the thermal comfort and is the main factor for the space cooling demand in the residential sector (Fazeli, Ruth, & Davidsdottir, 2016; IEA, 2018b).

In the residential sector, the energy demand is more sensitive to weather than in the commercial sector since the ratio between envelope and internal area is higher (a larger heat transfer surface or envelope with respect to the occupied space), which increases the importance of external weather conditions in thermal comfort. Unlike the residential sector, in commercial buildings energy use is more sensitive to internal loads (Brown, Cox, Staver, & Baer, 2016). Thus, in regions with hot and/or humid climates air conditioning systems, buildings design with better thermal performance and materials, and passive cooling are required to achieve the thermal comfort indicated by engineering standards (ANSI/ASHRAE, 2010; ISO, 2005). Of all these options AC equipment are widely used to space cooling because they reduce the temperature and humidity inside of buildings.

The traditional approach to estimating the impact of the climate on the overall demand for space cooling is by calculating cooling degree days – CDD[8] (Apadula, Bassini, Elli, & Scapin, 2012; Brown et al., 2016; IEA, 2018c; David J. Sailor, 2001). Electric companies use this approach to predict energy loads based on climate forecasts (IEA, 2018c; David J. Sailor, 2001). Compared to other methods that use average temperatures to estimate energy demand, CDD offers advantages because it captures extremes and the duration of outdoor temperature, resulting more reliable assessments (CIBSE, 2006).

Figure 2.1 presents, as an illustration, the distribution of CDD around the word; the color scale in the right side shows an annual mean (average between 2007 and 2017). It can be seen that in the tropics and subtropics the CDD are higher and, therefore, the demand for space cooling is higher. However, other factors such as humidity influence the energy consumption due to space cooling in some regions.

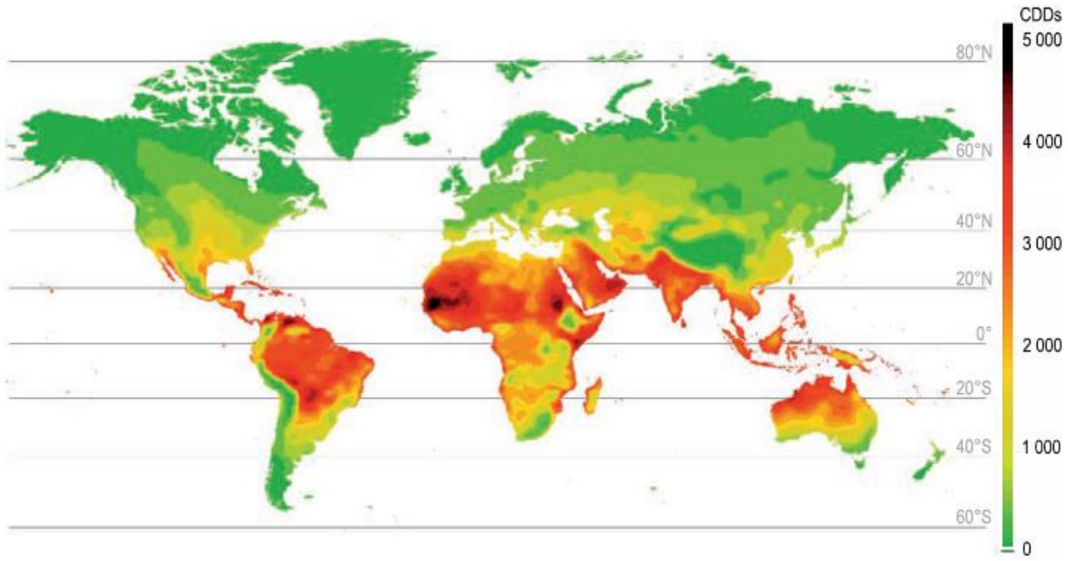


Figure 2.1: Mean annual CDD, average between 2007 and 2017
Source: (IEA, 2018b)

CDD varies throughout each cooling season and from year to year, but sudden and high increases in CDD (e.g. due to heat waves) can stimulate permanent changes in usual cooling

[8] The definition of CDD is presented in Chapter 4.

load, as purchases of AC equipment and fans increase (IEA, 2018b; D. J. Sailor & Pavlova, 2003).

The increase in the average temperature of the Earth as a result of climate change will lead to an increase in the CDDs. According to the IEA, for the year 2050 an additional 1°C rise in average temperature could lead to a 25% increase in CDD for all regions (IEA, 2018b). Figure 2.2 shows the predicted CDD increase in 2050 relative to the historical CDD values.

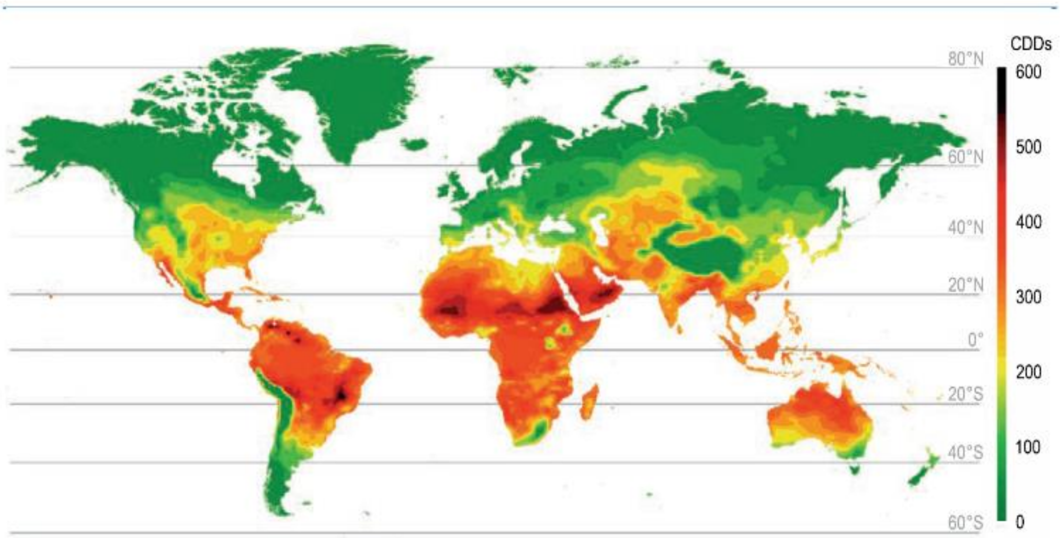


Figure 2.2: Predicted CDD rise between 2016 and 2050
Source: (IEA, 2018b)

In general, the regions with the largest expected increase in CDD are the most densely populated, with the highest population and income growth rates (proportionally). These characteristics imply higher energy consumption to meet the thermal comfort needs in these regions. Understanding how climate change can affect electricity demand will be helpful in carrying out proper energy planning in the medium and long term, to ensure electricity supply (Brown et al., 2016; Isaac & van Vuuren, 2009) and also to identify adequate adaptation strategies (Fazeli et al., 2016).

2.1.2 Income and ownership

Income and access to electricity are constraints for the ownership and use of AC in households (IEA, 2018b). The relationship between household income and AC ownership is strongly influenced by climate. This can be observed in Figure 2.3 that shows the relationship between GDP per capita (2015 PPP[9]), annual CDD and the AC ownership for several countries. The dashed lines represent ownership trajectories for clusters of countries (and regions), according to CDD. The lines suggest that AC ownership is larger in countries with hot and humid climates (with higher CDD), as long as larger is the income (IEA, 2018b).

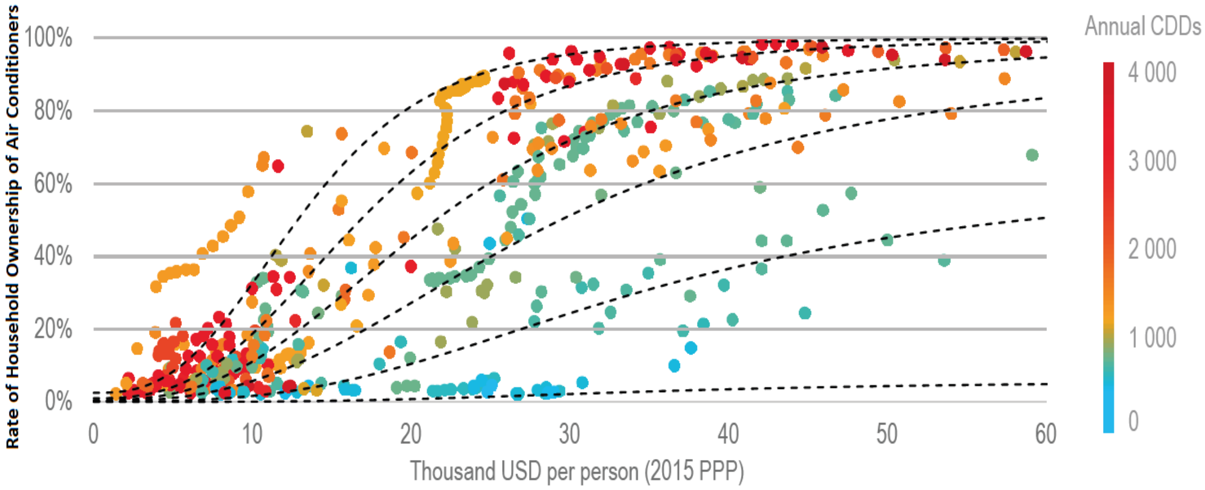


Figure 2.3: Income per-capita and share of households with AC systems
The dashed lines represent ownership trajectories for typical countries[10] according to CDD; in the left axis the ownership is as share of households, and the color scale indicates annual CDDs. **Source:** (IEA, 2018b)

Factors such as equipment purchase price and the electricity tariff also influence the energy consumption associated with space cooling. Relatively high prices of AC equipment (e.g. due to taxes and import tariffs) tend to delay the growth of electricity consumption related with space cooling. (IEA, 2018b)

[9] Purchasing Power Parity (PPP): Purchasing power of a currency refers to the expense of purchasing a particular unit of a good or basket of common goods and services. Relative cost of living and inflation rates determine purchasing power in different countries. PPP is a way of equalizing the buying power of two currencies by taking these aspects into account (OECD, 2019).
[10] The IEA has analyzed the climate-income relationship for 68 countries, using the CDD adjusted with the heat index (described in section 4.1.2).

2.1.3 Demographic factors

Population growth

Population growth is a factor that influences the space cooling demand, since a larger number of people implies a larger demand (IEA, 2018b). Especially in developing regions, some countries have the highest rates of population growth and, at the same time, have the warmest and most humid climates in the planet; therefore, the space cooling demand could be critical when increases in households income would allow the purchase of more AC units (DOE, 2016; Ürge-Vorsatz, Cabeza, Serrano, Barreneche, & Petrichenko, 2015).

Urbanization

The largest demand for space cooling is in the cities. This is due to three aspects: urban areas usually have higher temperatures than rural areas, thermal comfort needs are higher, and the income tend to be higher in cities (IEA, 2018b). The temperature difference between rural and urban areas is due to disturbances in the energy balance of Earth's surface caused by land use change (L. Zhao, Lee, Smith, & Oleson, 2014).

Human activities like air conditioning, manufacturing and transportation discharge heat into urban environments, these anthropogenic heat emissions increase the temperature in cities, warming them and further increasing the cooling needs. A study performed in Phoenix - USA metropolitan area showed that waste heat released from AC systems could increase the average air temperature during the night up to 1°C in some urban locations (Salamanca, Georgescu, Mahalov, Moustaoui, & Wang, 2014).

Another disturbance is the reduction of evaporative cooling due to the replacement of vegetation by buildings and infrastructure, which also increase the solar radiation absorbed by the surfaces and the internal temperature. Hard physical structures store more solar radiation than the vegetation, releasing it in the nights and increasing the space cooling demand even more (IEA, 2018b).

The human activity and the absorption of solar radiation by buildings and pavements cause a phenomenon called urban heat islands (UHI), which are hot spots in cities. The more densely populated a city is, the larger and more frequent these locations are. Figure 2.4 illustrates the effect of UHI, with air in urban areas between 1°C-3°C warmer than contiguous rural areas (Lawrence Berkeley National Laboratory, 2018).

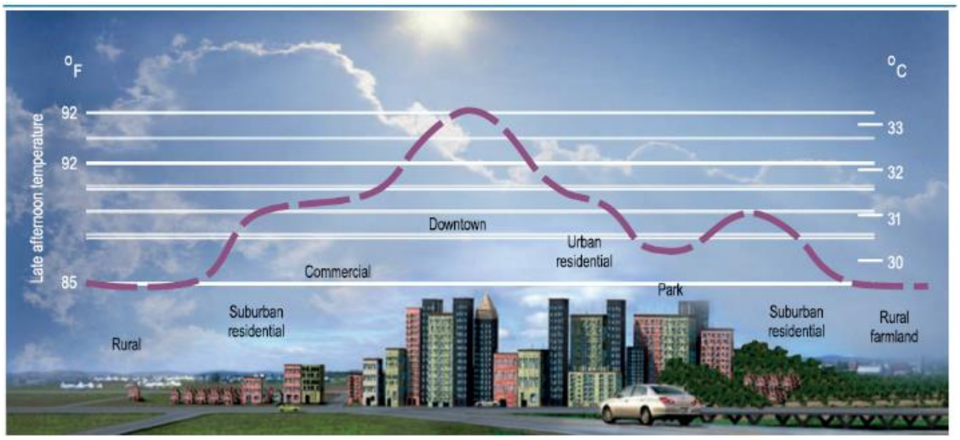


Figure 2.4: Representation of Urban Heat Island (UHI)
Source: (NSF, 2014)

2.1.4 AC energy efficiency

Energy efficiency of AC systems varies across countries or regions due to energy standards and regulations, market conditions and household income levels. (IEA, 2018b; Santamouris, 2016). Energy efficiency is evaluated by different metrics that vary according to the units used (SI or I-P), the purpose (e.g. assessing efficiency at full load in peak demand or part-load in specific seasons of the year) and test conditions (i.e. the external and internal temperatures, the relative humidity and cooling loads) (IEA, 2018b). The most common metrics are:

- Coefficient of Performance (COP): It is a dimensionless parameter, defined by the ratio between the cooling effect and the network required to achieve this effect; it is mostly used in thermodynamic books (Moran, Shapiro, Boettner, & Bailey, 2014). The internal and external temperatures of the buildings limit the maximum theoretical efficiency of the refrigeration cycle.
- Energy Efficiency Ratio (EER): The EER is calculated as the ratio of the cooling capacity (in BTU/h or W, depending on the standard of each country) to the rate of electricity consumption (in W) at full load (i.e., at the maximum deliverable cooling capacity of the equipment) (Econoler, 2011). The countries determine a representative test condition, which is specified by a single set of indoor and outdoor dry and wet-bulb air temperatures and that have to be maintained during the testing procedures (Econoler, 2011). The International Organization for Standardization (ISO) specifies performance testing, the standard conditions and the test methods for determining the capacity and efficiency ratings of AC units (ISO 13253, 2017; ISO 15042, 2017; ISO

5151, 2017). The main differences with the COP are that the EER is not a "dimensionless" parameter and can be set only at full load (IEA, 2018b).

- Seasonal Energy Efficiency Metrics: In practice, operation conditions vary and the equipment does not always run at full load. Seasonal efficiency metrics aim to address the periods in which the equipment works at part load (a large share of total time operation) (IEA, 2018b). The metrics also reflects the impact of changes in outdoor temperature. Thus, multiple test points are required, and the result indicates a seasonally weighted average efficiency. This efficiency is representative of how the AC would perform over a typical cooling season (Econoler, 2011). In some standards this metric is called Seasonal Energy Efficiency Ratio, or SEER (AHRI Standard 210/240, 2017), and in others is called Cooling Seasonal Performance Factor, or CSPF (ISO 16358-1, 2013).

Currently, there is no common accepted metric to evaluate the efficiency of cooling equipment, and often test conditions are not equal because countries have adapted them to take into account their specific climatic conditions and regulatory context. This makes difficult the comparison of energy efficiency metrics and policy settings between countries, inhibiting policy and market harmonization efforts and constituting a barrier to technology diffusion (Letschert et al., 2019).

Further efforts are needed to improve the metrics and testing procedures in order to assess more accurately assess equipment performance under real operating conditions, enabling cross-country comparisons while comparing different technologies, such as AC with inverters and absorption cooling (IEA, 2018b; Letschert et al., 2019; Pinto & Mady, 2018).

Countries where performance metrics are based only on full load conditions tend to encourage manufacturers to optimize full load performance at the expense of part load performance (Econoler, 2011). Consequently, one can have an AC that has a higher EER, but a lower SEER (IEA, 2018b). In addition, energy efficiency ratings used in testing procedures are not always appropriate to estimate operating conditions because larger temperature differences are related to lower efficiency, as compression work increases (IEA, 2018b). For this reason, energy efficiency expressed by EER (at full load) is lower than the SEER (at partial load).

Figure 2.5 and Figure 2.6 show typical EER and SEER values and their ranges in different countries. In all cases, the best available figure is better – or even much better – than the market average. The difference between the average and the best available figures can be explained, for instance, by the fact consumers are influenced by equipment purchase price and, sometimes, by operating costs (mainly when electricity is not subsidized; subsidies are common in emerging economies and developing countries). Another key factor are energy policies and regulations (IEA, 2018b).

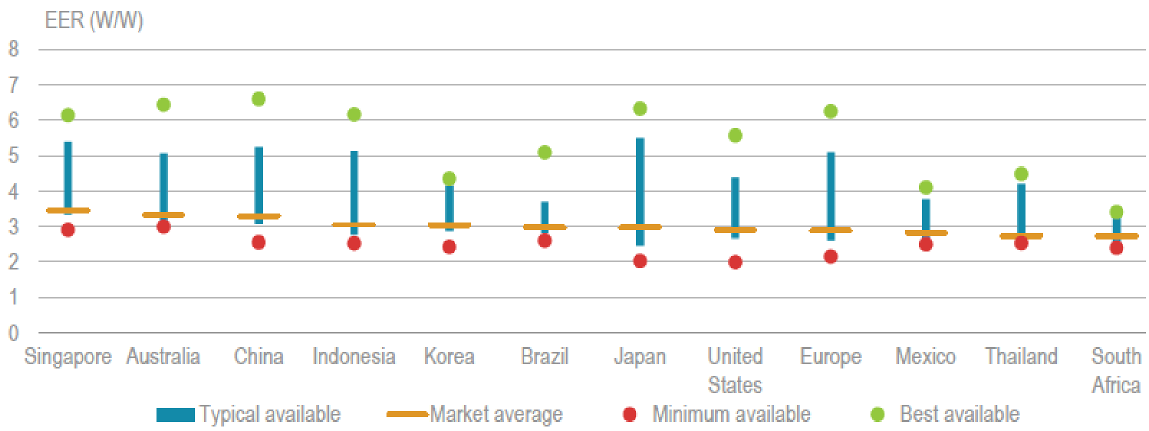
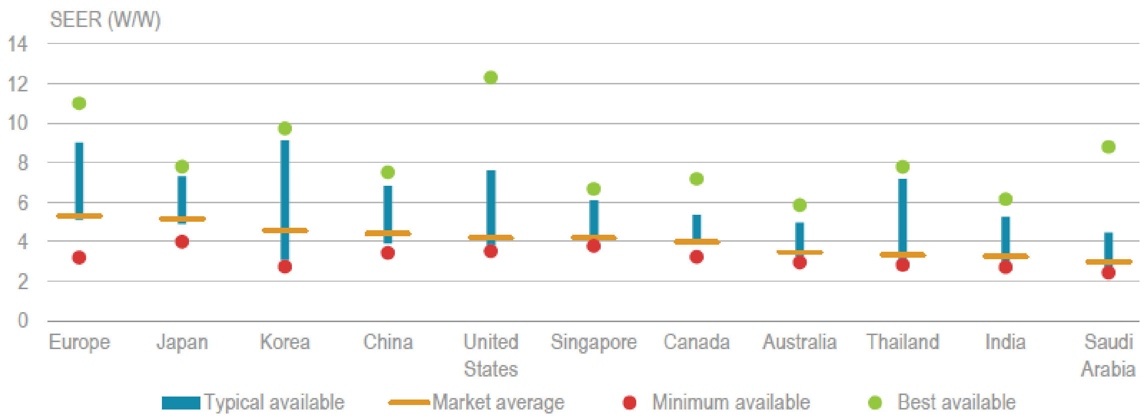


Figure 2.5: EER of residential AC units in 2018, for selected countries/regions
Source: (IEA, 2018b).



Notes: SEER = the ratio of output cooling capacity to electrical energy input, adjusted for the overall performance of the device for the weather over a typical cooling season in each given country; as the test conditions differ across countries, the average ratios are not strictly comparable; W/W = watt per watt.

Figure 2.6: SEER of residential AC units in 2018, for selected countries/regions
Source: (IEA, 2018b).

2.1.5 Buildings energy performance

The energy performance of buildings determines the level of energy consumption to meet the thermal comfort conditions of the occupants. Usually aesthetic aspects and costs are the main issues considered in the design and construction of buildings, without prioritizing the energy aspect (IEA, 2018b). The construction itself and the materials used in buildings have impacts in the energy performance, especially in hot and humid climates where the share of AC is meaningful in total electricity consumption.

The surrounding landscape also influences the buildings energy performance. In architecture and urban planning, airflow, albedo and evapotranspiration can be improved by taking advantage of the landscape and plants; for example, seasonal solar shading with deciduous trees can reduce the solar heat gain in buildings, reducing the UHI effects around them. In residential applications, some local authorities are encouraging building owners and occupants to adopt green roofs to save energy and increase sustainability; well-designed landscapes could save 25% of the energy used for heating and cooling (IEA, 2018b).

2.2 Curbing energy consumption and emissions associated with space cooling

Worldwide, manufacturers, builders, architects and planners (energy and urban) have the capabilities to produce more efficient equipment, build structures with better thermal performance, manage energy demand more efficiently (in the economic and environmental sense) and combine urban landscape with thermal comfort needs. Despite having these capabilities to curbing cooling-related energy demand (and the need for energy to meet that demand) in a sustainable way there are economic, and informative constraints that do not allow the implementation and scale deployment of several available market technological options.

Policy actions at national, regional and local levels are necessary to eliminate these constraints; some of these actions are the standards for air conditioning systems and building codes in order to reduce the energy consumption related with cooling needs. MEPS and labelling programs are policy actions that countries have to improve the energy efficiency of equipment in a quickly and cost-effectively way (IEA, 2018b). Furthermore, energy efficiency policies should be based on a holistic point of view. For example, demand-side management actions (DSM) will not be as effective if the population is not aware about the impacts of the inefficient use of high-energy consumption appliances during peak hours. In the case of air conditioning, inefficiencies could lead to higher tariffs, due to the required investments to meet peak demand (Nicholls & Strengers, 2014).

2.2.1 Minimum energy performance standards and labelling programs

MEPS define performance requirements for an energy-use device, which effectively limits the maximum energy consumed by an equipment in performing a specific task. MEPS must encourage manufacturers to develop and market products with better quality and reduced compliance costs. It is expected that through economy of scale costs, and prices consumers would be reduced (IEA, 2018b).

Energy efficiency labels highlight the most efficient products and serve as an information mechanism to facilitate decision making. This information must be clearly and easily interpreted. In addition to energy performance, labels for ACs must indicate the cooling effect, the associated power required and details of the equipment. This information must inform the consumers about expected energy costs (CLASP, 2014). There are two main types of labels: endorsement labels and comparative labels.

Comparative labels allow comparison of energy performance between similar products and should motivate manufacturers to create more efficient products than their competitors. They use a continuous scale or discrete categories of performance with minimum criteria for each level. Endorsement labels are “approval stamps” granted to products according to a specified energy efficiency criterion; they serve to identify the most energy efficient set of products and can encourage manufacturers to create products that meet specified criteria.

Standards eliminate inefficient models by establishing a baseline of energy performance that products must achieve. Together, standards and labels shift the distribution of models sold on the market toward greater energy efficiency (CLASP, 2014).

The successful establishment, application and tightening of MEPS and labelling programs must take into account the current energy efficiency levels of AC in the market, an adequate structure of monitoring, verification and enforcement (MVE) (CLASP, 2010; IEA, 2010), and also the transparent and timely communication of the program stages to stakeholders (Costa et al., 2019). A complete review of the methodology and guidelines for the implementation of these programs can be found at (CLASP, 2014; Wiel & McMahon, 2005). The main stakeholders are manufacturers, consumers, the government (national, regional and local), environment and energy interest groups, and importers, among others. Their participation, in addition to ensuring the success of these programs, provides relevant information and addresses concerns; this promotes acceptance of new regulations and helps to establish the appropriate time for their application.

Impact of MEPS and labeling programs on energy efficiency indicators

Figure 2.7 shows the countries where MEPS and labeling programs for AC equipment have been established; in some cases, they are mandatory and in other cases, they are voluntary.

Two countries with mandatory standards were chosen to illustrate how MEPS have impacted energy efficiency: Brazil and Malaysia. Brazil was chosen for being in the same region of Ecuador and Malaysia because of climate similarities with Guayaquil - Ecuador.

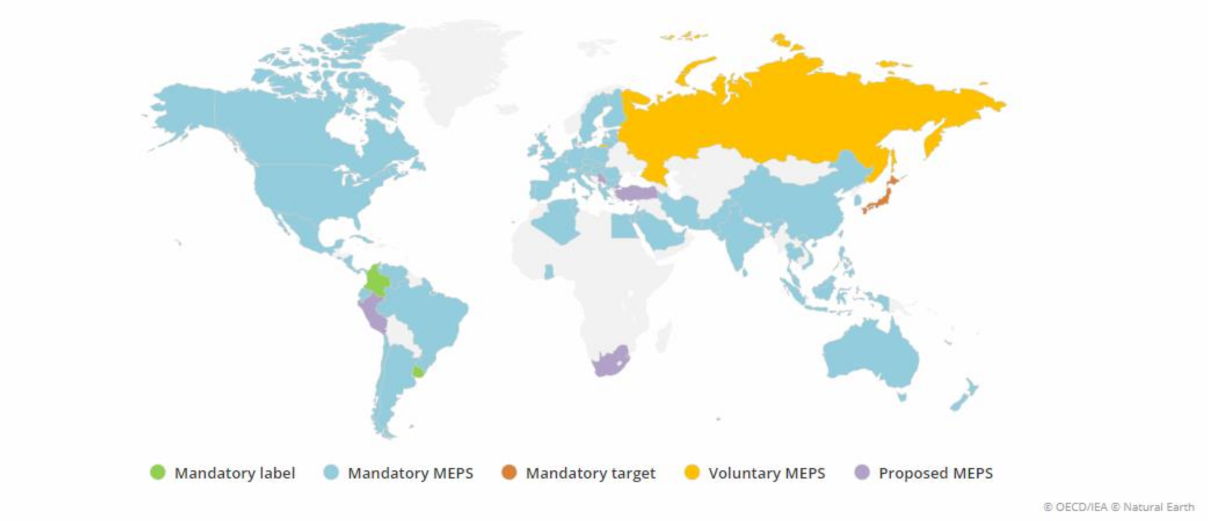


Figure 2.7: Countries with MEPS and labelling policies for air conditioners
Source: (IEA, 2018c).

Malaysia

In Malaysia, the Energy Commission is responsible for coordinating and implementing the standard and labelling (S&L) program for electrical appliances. The declared purposes of the program are to improve Malaysia's energy efficiency performance, encourage the manufacturers to develop high quality products, provide a better and fairer competition in the market and help consumers in their purchasing decisions (International Copper Association, 2016). The energy labels in Malaysia's energy program are presented in Figure 2.8. Products with the best energy efficiency in the market have an additional label that highlights their status as 5-Starappliances, which helps stand out among consumers and promotes competition between manufacturers to produce better quality products.

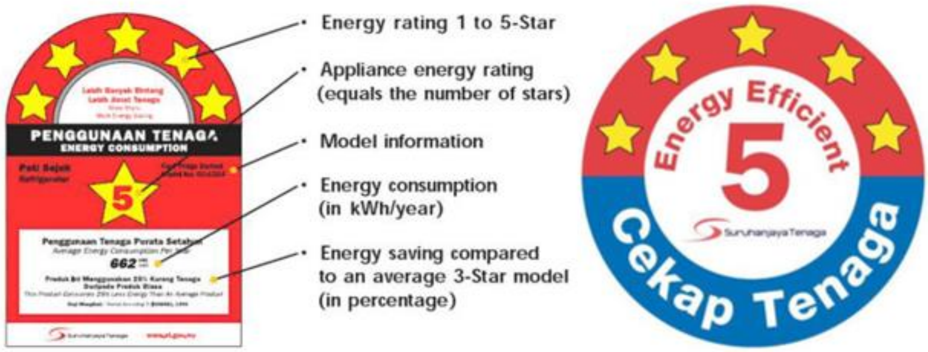


Figure 2.8: Energy labels in Malaysia
Source: (International Copper Association, 2016)

In 2013, Malaysia implemented MEPS to standardize the energy performance of ACs. The Standard and Industrial Research Institute of Malaysia (SIRIM) was tasked with developing the mandatory national standards. SIRIM has established MS 2597:2014 Minimum Energy Performance Standards (MEPS) for Air Conditioner, which specifies the requirements for room AC, classified as "single-phase, non-ducted, single split wall mounted type vapour compression air conditioners with cooling capacity up to 7.1 kW". Table 2.1 presents the energy efficiency levels for AC units according to their cooling capacity. The testing method of this standard is based on ISO5151-2010 and the minimum requirement of the energy efficiency for appliances to be sold in Malaysia is 2-Star.

Table 2.1: EER according to the Malaysia's S&L program

Star Rating Tested EER W/W	Cooling capacity < 4.5 kW	4.5 kW ≤ Cooling capacity ≤7.1 kW
5	>3.50	>3.14
4	3.27 -3.50	2.88 - 3.14
3	3.04 - 3.27	2.62 - 2.88
2	2.80 - 3.04	2.35 - 2.62
1	2.64 - 2.80	2.20 - 2.35

Source: (International Copper Association, 2016)

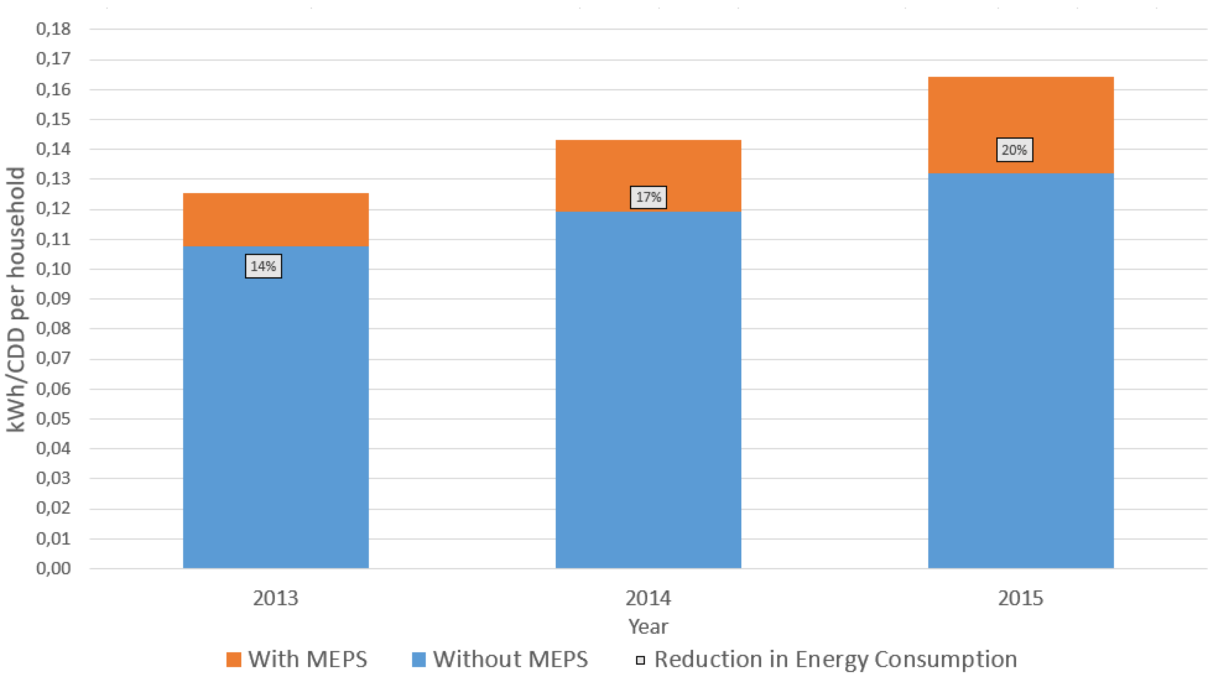


Figure 2.9: Impact of MEPS in the energy efficiency indicator for AC systems
Source: (Euromonitor, 2019; Fatihah Salleh, Mohd Isa, Eqwan Roslan, & Ab Rashid Tuan Abdullah, 2019; MESTECC, 2018)

In Malaysia, the implementation of MEPS has had a positive impact on the AC energy consumption, and this can be seen in Figure 2.9, which shows the normalized energy consumption. Between 2013 and 2015 there was a reduction in energy intensity between 14 and 20% (Fatihah Salleh et al., 2019).

Brazil

In 1984, the Brazilian Labeling Program (PBE) was created to establish comparative labels in the country; this program is coordinated by the National Institute of Metrology Quality and Technology (INMETRO) and managed in cooperation with the National Electricity Conservation Program (PROCEL) (Empresa de Pesquisa Energética - EPE, 2018). In order to strengthen labeling program, Brazil approved their Energy Efficiency Law (Law 10.295) in 2001, allowing the government to set minimum standards for equipment (MEPS); the agency responsible for determining these standards through specific regulations is Energy Efficiency Indicators Management Committee (CGIEE) (Empresa de Pesquisa Energética - EPE, 2018).

Split-type air conditioning equipment up to 11 kW was included in the labeling program in 2004 and its minimum energy efficiency standard was set in 2006. Until the date, the AC labeling program underwent three revisions, and the last one was in 2013. The energy efficiency levels in force are presented in **Table 2.2** and the existing energy labels are presented in Figure

2.10 (in the right side, the PROCEL label for products with the best energy efficiency in the market) (Empresa de Pesquisa Energética - EPE, 2018). Regarding MEPS, there have already been three revisions, being the last one approved in 2018, being the minimum EER set at 3.02 W/W. The procedures (NBR 05858, NBR 05882 and NBR 12010) adopted for testing energy performance of air conditioners are based on international standards ISO 5151 (Costa et al., 2019).

Table 2.2: MEPS Star Rating for AC in Brazil's S&L program

Star Rating Tested EER W/W	Cooling capacity < 11 kW
A	>3.23
B	3.02 - 3.23
C	2.81 - 3.02

Source: (Letschert et al., 2019)

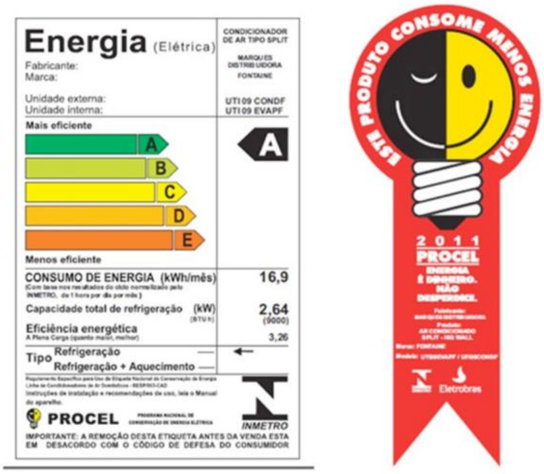


Figure 2.10: Energy labels in Brazil
Source: (Letschert et al., 2019)

Figure 2.11 shows how S&L program improve the energy efficiency of air conditioning equipment in Brazil between 2005 and 2017; it is estimate that the cumulative improvement in the EER of equipment stock reached 8%. The energy efficiency in the residential sector as a whole reached 13% in the same period.

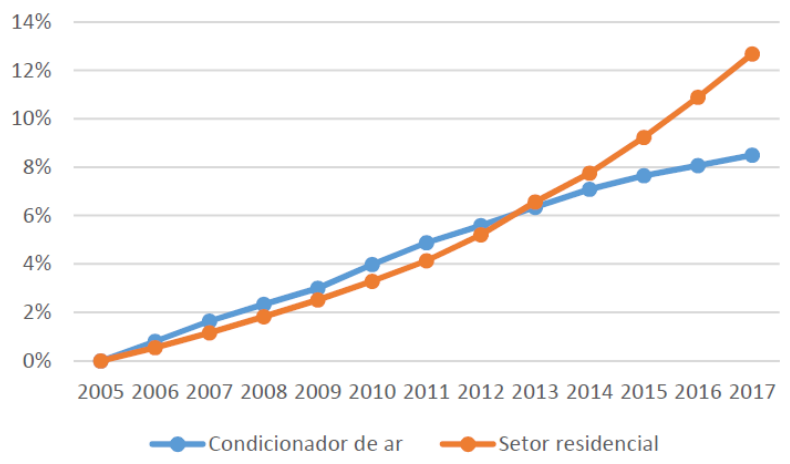


Figure 2.11: Energy efficiency improvements in the AC stock at the residential sector
Source: (Empresa de Pesquisa Energética - EPE, 2018)

3 STRUCTURAL CHARACTERISTICS OF GUAYAQUIL AND ECUADOR

This chapter presents information about Guayaquil and Ecuador that are important for energy modeling and regulation analysis, such as geographic, demographic and socioeconomic structure. Complementary information that is presented is about the labeling program in Ecuador, the more stringent MEPS that is focus of analysis in this dissertation, and ownership and use of air conditioning systems in Guayaquil.

3.1 Geographic and demographic structure

The city of Guayaquil is located in the northwestern of South America; it is the most populated city and the most important port on Ecuadorian coast. Their coordinates are 2°11′00″S 79°53′00″O. Its natural limits are to north the Daule River, to east the Daule River and the Guayas River, to south the islands formed from the Salado Estuary, and to west the Chongón-Colonche Mountain Range. Most of the city is located between the Guayas River and the Salado Estuary (see Figure 3.1). Its average altitude is four meters above sea level (m.a.s.l.) and it has easy access to the Pacific Ocean through the Gulf of Guayaquil.

According to the last population census, in 2010 Guayaquil had approximately 2.44 million people, with an annual growth rate of 1.62% (INEC, 2011). In 2018 it concentrated 16% of total population in Ecuador and has the largest number of inhabitants in the country (El Universo, 2019a). Figure 3.2 shows the estimated number of inhabitants from 2000 to 2010, and the projection to 2030 (INEC, 2017a, 2017b).

Figure 3.1: City view of Guayaquil in Google Earth
Source: Google Earth

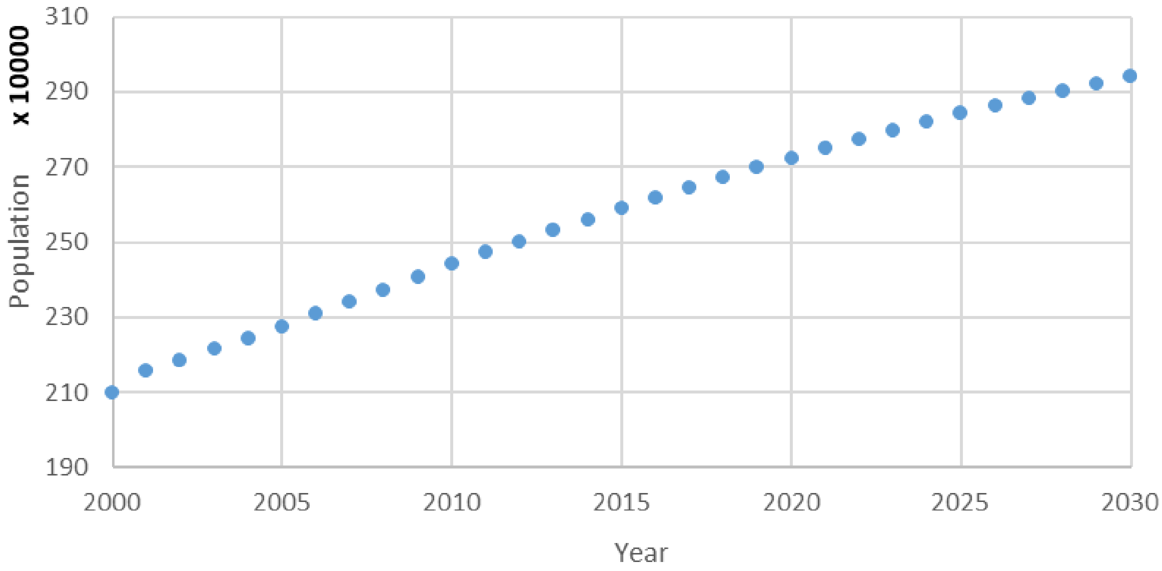


Figure 3.2: Population of Guayaquil – historical growth and forecast
Source: (INEC, 2017b)

3.2 The climate in Guayaquil

The climate of Guayaquil is Tropical Megathermal Semi-humid and has two seasons. The first one is a rainy season, from December to May. The second one is a dry season, from June to November. Figure 3.3 shows in dark bars the monthly precipitations in 2013 (INAMHI, 2017). White bars represent the monthly average precipitations in a Typical Meteorological Year (TMY); precipitation figures are in mm. The wettest month (i.e. the one with the highest rainfall) is usually March, while the driest month (with the lowest rainfall) is August. Triangles show the number of days with precipitation, and its axis is on the right side.

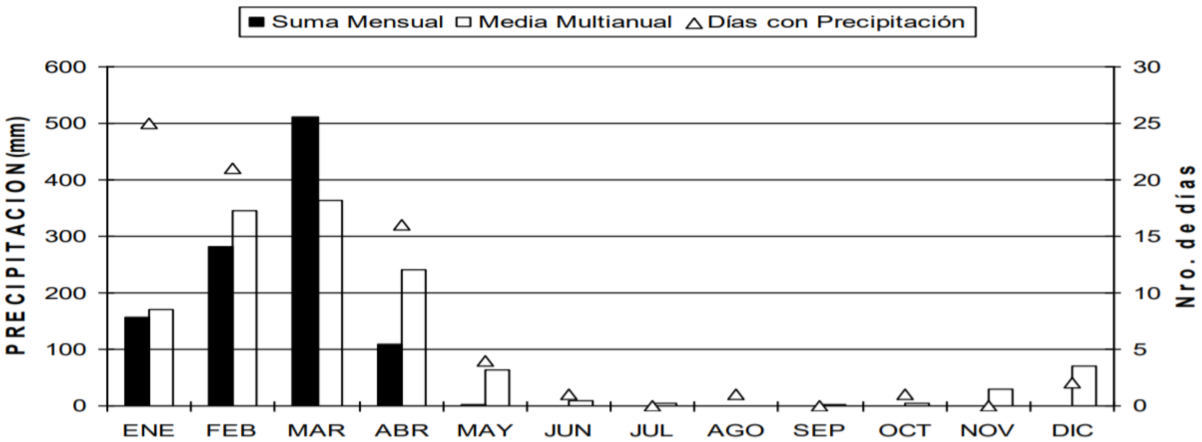


Figure 3.3: Precipitation pattern of Guayaquil in 2013
Source: (INAMHI, 2017)

The average temperature in the rainy season is 27.3°C, and in the dry season it is 25.8°C. During the months of higher rainfall, relative humidity increases the thermal sensation, being 3°C the difference between the ambient dry bulb temperature (T_{db}) and the heat index (HI). On the other hand, in the dry season it does not exceed 1°C. Figure 3.4 shows the influence of relative humidity (RH) on thermal sensation in Guayaquil, being it a representation of a TMY. The smoothing method applied is Arithmetic Moving Average (AMA).

Figure 3.4 presents peaks in the temperature, which are associated with the increase of direct solar radiation in specific moments of the year. This increase occurs due to low cloudiness resulting from general atmospheric circulation, and to the position of the sun over the Equator during equinoxes (in March and September).

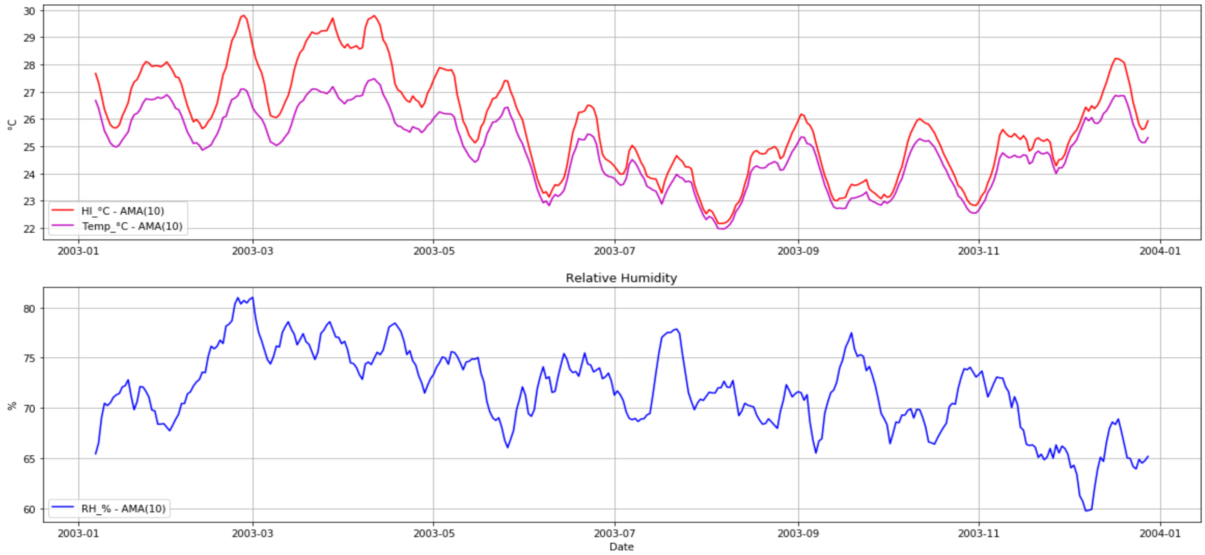


Figure 3.4: Relative humidity influence on air temperature and heat index (HI)
Source: TMY MN7 (Meteotest, 2014). **Location:** Guayaquil -2.166, -79.889, -5, 9

Figure 3.5 shows the dry bulb temperature (T_{db}) and the relative humidity (RH) of a TMY for Guayaquil in a psychometric diagram. The different colors represent a cumulative range of annual hours. The white circle in Figure 3.5 represents a well-accepted thermal comfort state, $T_{db} = 22°C$ and $RH = 50\%$. As can be seen, in Guayaquil air conditioning systems are required the whole year in order to achieve this thermal comfort condition.

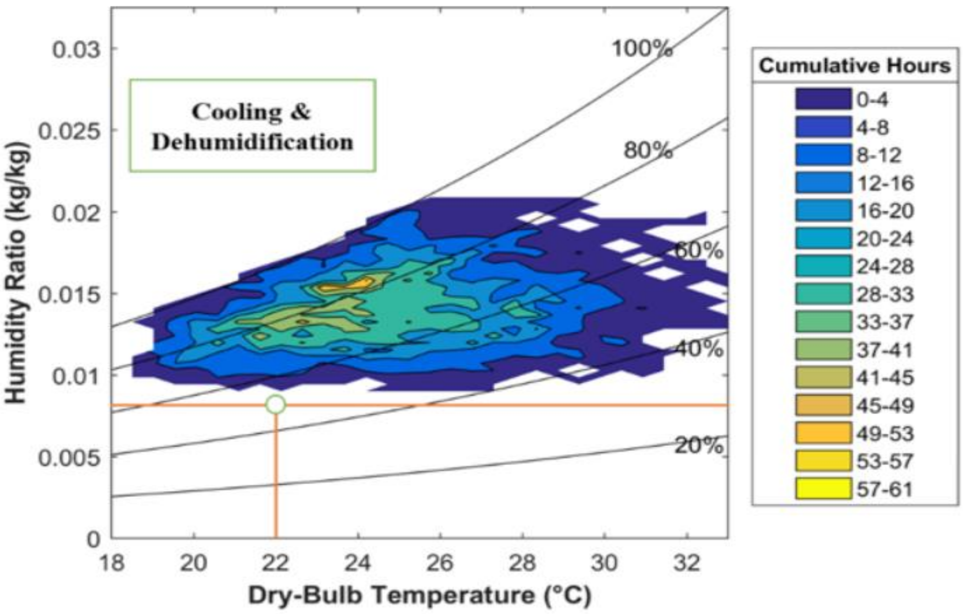


Figure 3.5: Dry-bulb temperature and relative humidity in Guayaquil for a TMY
The color scale represents the number of hours at which certain conditions of T_{db} and RH occur; the thermal comfort location indicates that cooling and dehumidification are necessaries to achieve this condition.

3.3 Socioeconomic structure

3.3.1 Gross domestic product and gross national income

Gross Domestic Product (GDP) and Gross National Income (GNI) are central statistics in the national accounts of all countries. Both are important and useful economic indicators to analyze the general economic situation of an economy, the first being useful for specifying the level of production, and the second for the aggregate income of residents. In Ecuador, the final consumption expenditure of resident households has been the most important component in the GDP. In 2017, household expenditures accounted for about 30% of GDP growth. Figure 3.6 shows, from mid 1960s to 2017, the expenditure due to the final households' consumption (thick dashed line) and the contribution of other economic sectors to GDP (BCE, 2018).

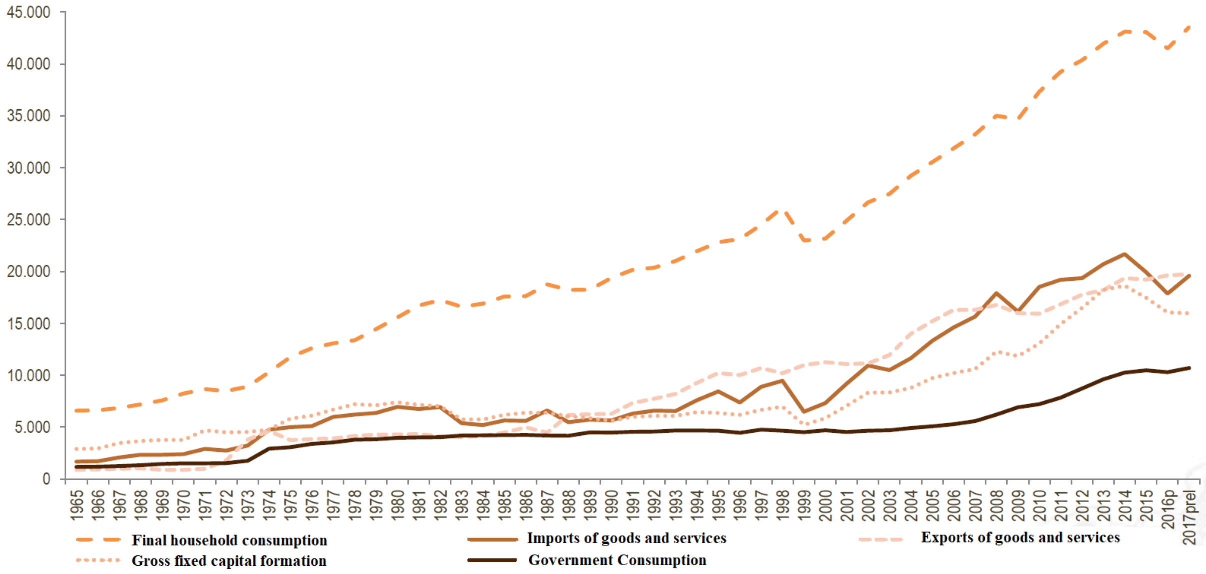


Figure 3.6: The evolution of the main components of GDP in Ecuador
Source: (BCE, 2018)

As mentioned above, residential expenditure is crucial to GDP growth and the expenditure itself depends on households' income. GNI is an indicator of total residents' income - within the national territory or from abroad. In an increasingly globalized economy, it is considered that the GNI is a better metric than GDP to estimate the overall economic well-being of a country, because in certain countries a significant amount of the income, which is part of GDP, is expended abroad (Capelli & Vaggi, 2013). To estimate GNI from GDP, three terms must be added to the last parameter:

1) Foreign income paid to resident employees.

2) Foreign income paid to resident property owners and investors.
3) Net taxes (subsidies discounted) receivable on production and imports.

The evolution of Ecuador's GNI, from 1990 to 2018, is shown in Figure 3.7. The values are available in the World Bank's database (WB, 2019).

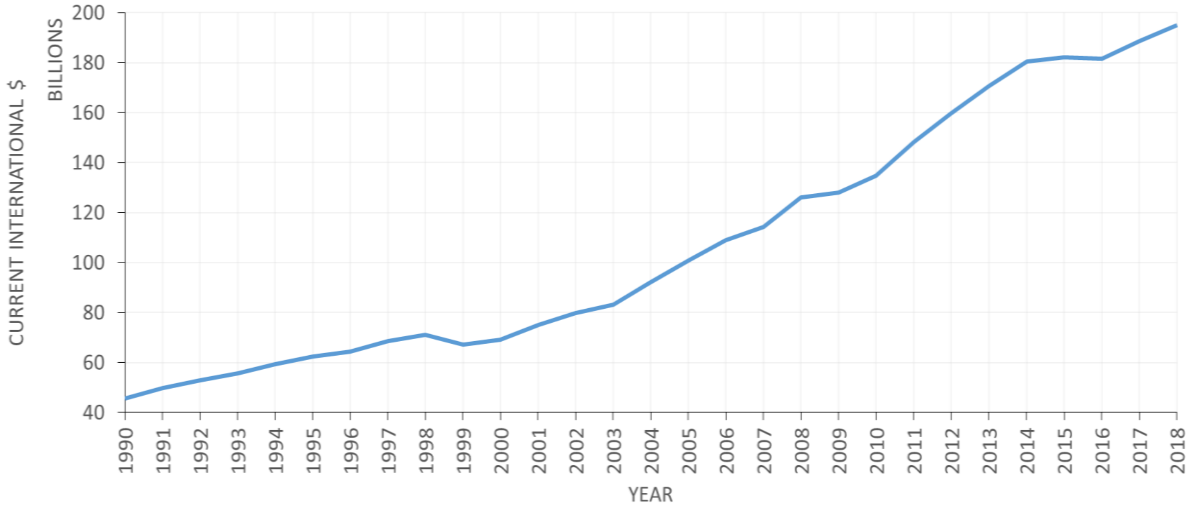


Figure 3.7: Ecuador's GNI evolution, in PPP[11] USD, from 1990 onwards
Source: (WB, 2019)

3.3.2 Economic evolution

In Ecuador, certain one-off events marked GDP growth, as indicated in Figure 3.12 (BCE, 2018). In the 1970s, there were the largest growths (on average) associated with the boom of oil prices. In the 1980s and 1990s, the economic debacle can be explained by a set of factors: the fall of oil prices, excessive external debt and high interest rates, poor governance in economy and finances, the military conflicts with Peru and El Niño phenomenon. In 1999, very high inflation rates and a sharp devaluation of national currency led to dollarization of economy (Ángel Emilio Hidalgo, 2015, 2016). Ecuador's economy is dollarized since then. In the 21st century the most relevant events for the economy were the global economic crisis in 2008-2009, the most recent fall of oil prices and the earthquake in 2016, which came to imply a decrease in the GDP (see Figure 3.8).

[11] The GNI is adjusted by Purchasing Power Parity (PPP) to take into account the cost of living, making more reliable the comparison with studies performed in other countries.

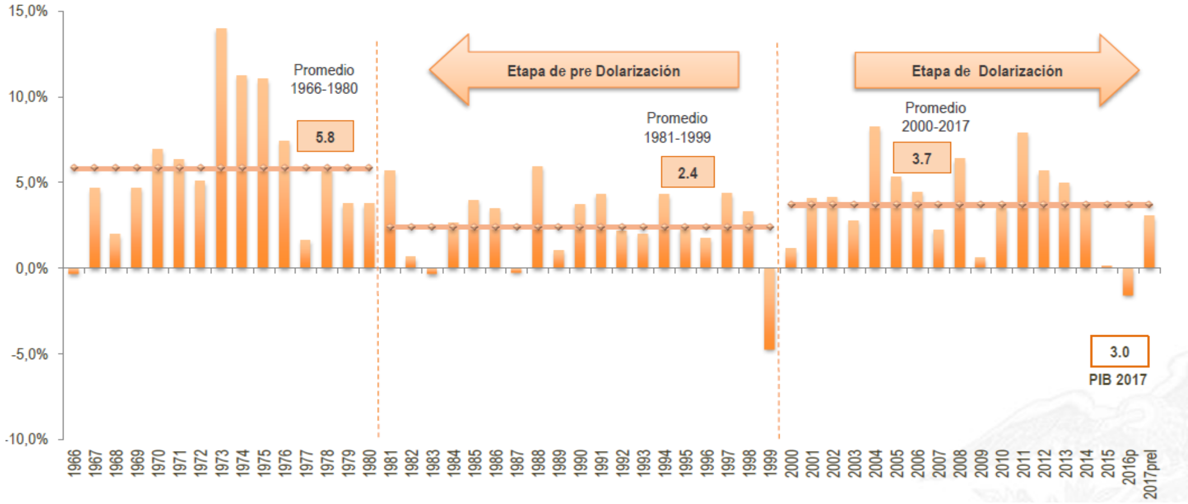


Figure 3.8: Ecuador's GDP historical growth – annual rates
Source: (BCE, 2018)

3.3.3 Income distribution in Guayaquil's households

Guayaquil is the city with the largest economic and commercial activity in the country and it contributes 25% of the national GDP (El Universo, 2019b). Figure 3.9 shows the households distribution by income level in Guayaquil, in relation to the basic salary (SBU). From Figure 3.14 it can be seen that in Guayaquil; approximately 70% of households receive between two and eight SBUs. Households with incomes over eight SBU accounted for 10% and 8.3% of the total in 2003 and 2011, respectively, while the share of households with incomes below two SBU increased during the period. The SBU trend since 2000, in US$, is presented in Figure 3.10 (Ministerio del Trabajo, 2019).

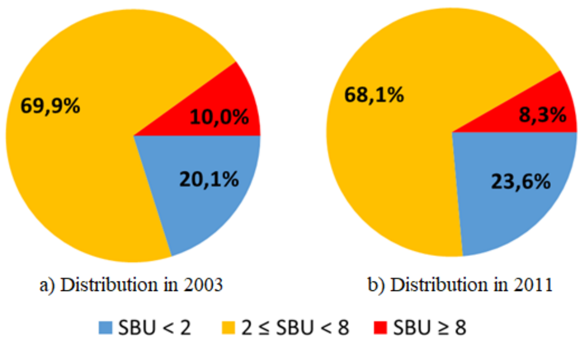


Figure 3.9: Households share by income level in Guayaquil
Source: (INEC, 2012)

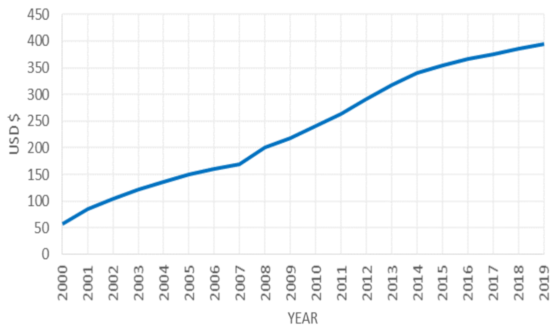


Figure 3.10: Basic salary trend in Ecuador
Source: (Ministerio del Trabajo, 2019)

In Ecuador there is a special electricity tariff, called "Dignity Tariff", aimed at subsidizing the payment of electricity for the low-income households (families with income up to two SBU)

(ARCONEL, 2007). Above two SBU, the INEC divide households into 12 categories, the first six categories (2 ≤ SBU < 8) represent the mid-income households, while the remaining ones (SBU ≥ 8) represent the high-income households (INEC, 2012).

3.4 National labeling program

The labeling program for air conditioning equipment started with the Ecuadorian Technical Regulation RTE INEN 072 “Energy efficiency for ductless air conditioners”, which entered into force in 2013 (INEN, 2017). This regulation states that all equipment with a cooling capacity up to 24,000 BTU/h sold in the country must meet the requirements set out in the labeling chapter of the technical standard NTE INEN 2495 “Energy efficiency for ductless air conditioners. Requirements” (INEN, 2012). Table 3.1 presents the energy efficiency classification related to this technical standard. The testing method of this standard is based on ISO5151-2010 (ISO 5151, 2010). Figure 3.11 shows the energy label (left) and the DMEE quality seal (right) applied to AC systems.

Table 3.1: Energy efficiency classification for AC units up to 24,000 BTU/h

Energy Efficiency Classes	EER Ranges
A	EER > 3.2
B	3.0 < EER ≤ 3.2
C	2.8 < EER ≤ 3.0
D	2.6 < EER ≤ 2.8
E	2.4 < EER ≤ 2.6

Source: (INEN, 2012)

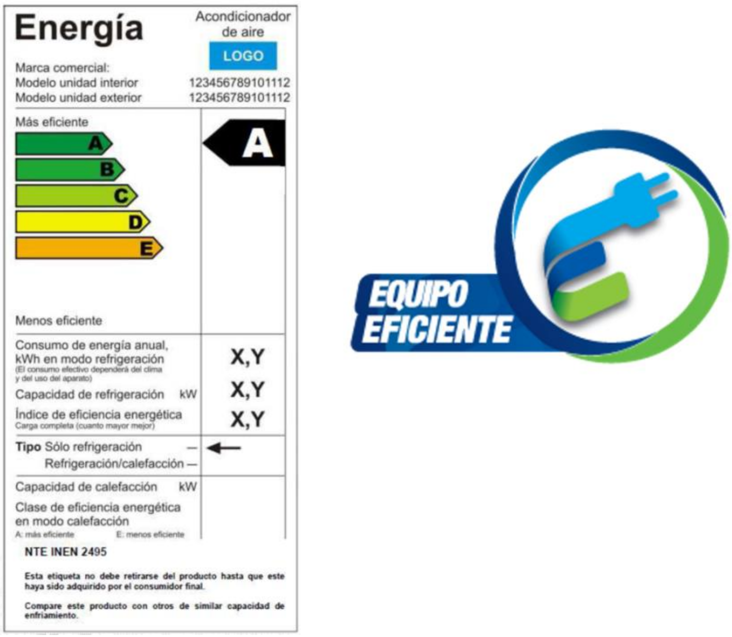


Figure 3.11: Energy label (left) and Maximum Energy Efficiency Distinctive (right) applied to AC
Source: (MEER, 2016c)

The RTE INEN 072 has undergone several modifications, being the most relevant the one in the "First Modification", which came into force by the end of 2013 and that set a MEPS at EER=3.2 (W/W). The latest version of this regulation is the RTE INEN 072 First Revision (1R), which entered into force in 2018. This version establishes that the refrigerant fluid must be ecological and without chlorofluorocarbons (CFCs) or hydro-chlorofluorocarbons (HCFCs), in accordance with Montreal Protocol, Decision XIX/6 (UNEP, 2016a, 2016c). It is currently under evaluation a Second Revision, called PRTE INEN 072 (2R), in which the MEPS remains the same (INEN, 2019).

3.4.1 Structure of monitoring, verification, and enforcement (MVE)

MVE ensures that the goals of energy performance initiatives would be achieved. Monitoring is intended to protect citizens against unfit products, ensuring compliance in accordance with expectations. Furthermore, these activities also protect suppliers, ensuring that each manufacturer is submitted to the same conditions for entering the program (IEA, 2010; OLADE et al., 2015). Details of the MVE in Ecuador are presented below.

- Monitoring involves measuring performance claims against a nominated standard in a consistent manner. The Ecuadorian Technical Standard NTE INEN 2495:2012 establishes the methodology to determine the energy efficiency class. It is based on the International Standard ISO 5151:2010, and indicates that for determination of EER (W/W), equipment must be tested on a calorimeter for an hour, or more, under operating conditions determined by the standard.

- Verification involves declarations of conformance by product suppliers. In Ecuador, the Regulation RTE INEN 072 defines that compliance is required through Conformity Certificates, or Inspection Certificates, according Ecuadorian Quality System (Law No. 2007-76). These certificates are issued by laboratories accredited by the Ecuadorian Accreditation Service (SAE) or designated by the Ministry of Industry and Productivity (MIPRO), or even by Mutual Recognition Agreements signed by Ecuador.
- Enforcement is the action taken by governments against suppliers of non-compliant products. Enforcement requires rigorous and transparent monitoring and verification processes. The Ecuadorian Quality System (Law No. 2007-76) establishes economic sanctions for non-compliance (CN, 2010). The surveillance and control is responsibility of MIPRO.

3.4.2 Stricter MEPS in energy efficiency regulation

In Ecuador, currently the energy efficiency standard for ductless mini-split air conditioners is set at 3.2 (W/W). The Latin American Energy Organization (OLADE), through a study carried out in conjunction with the United Nations Environment Program (UNEP) and the Collaborative Labeling and Appliance Standards Program (CLASP), proposed MEPS for ductless mini-split air conditioners in Latin America (OLADE et al., 2015). Nowadays equipment in compliance with these alternative MEPS are commercially available in the region. The proposed standards are in Table 3.2.

Table 3.2: OLADE proposed standards for Latin America region

MEPS	Energy Efficiency Ratio (W/W)
EER 1	3.4
EER 2	3.6
EER 3	3.8
EER 4	4.3
EER 5	4.7
EER 6	5.0
EER 7	5.2
EER 8	5.8

Source: (OLADE et al., 2015)

3.5 Electricity consumption and AC ownership in the residential sector of Guayaquil

Guayaquil, as the country's main port, has an important commercial and industrial activity. Figure 3.12 shows the share of electricity consumption in different socio-economic sectors, in 2003 and 2011 (ARCONEL, 2018). The residential sector, the former main consumer, was displaced by the industrial sector in this period. It still is the target public policies aiming energy efficiency.

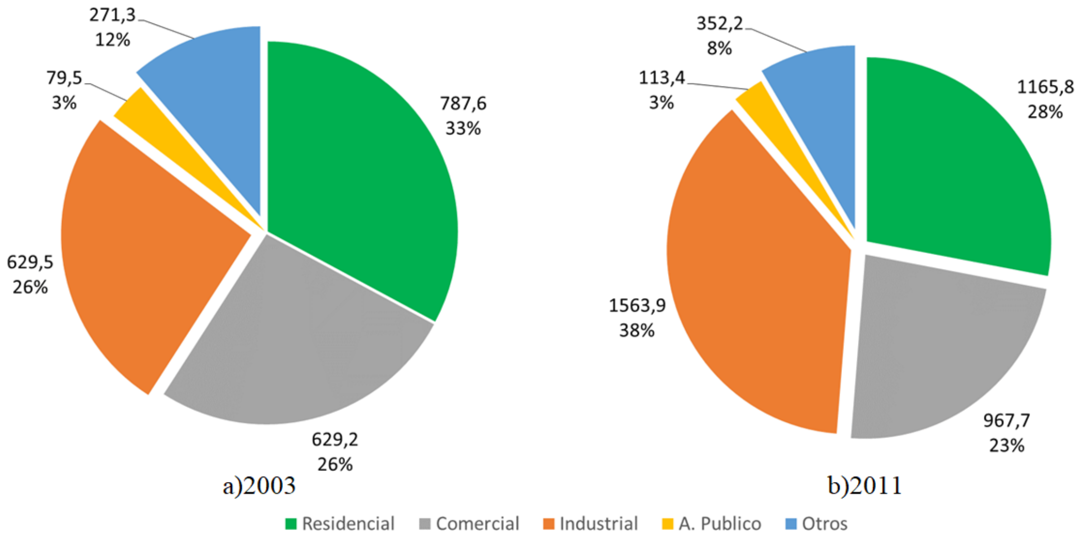
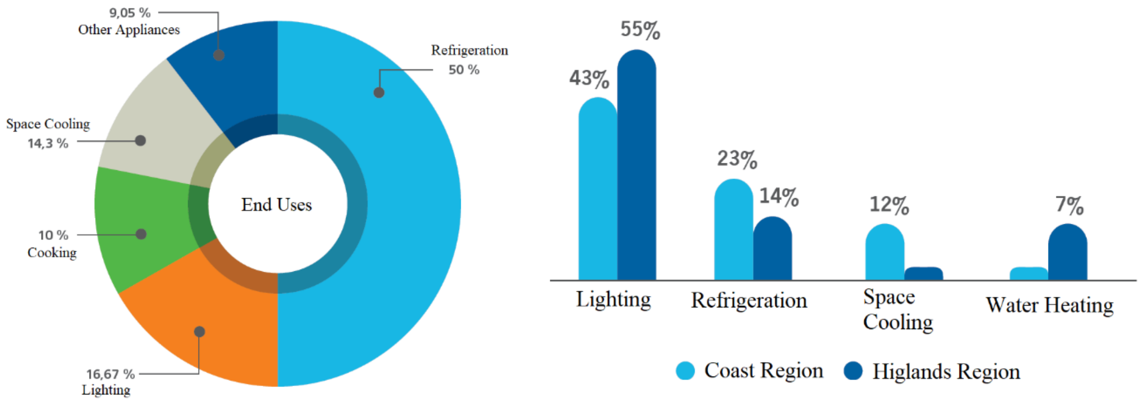


Figure 3.12: Share of electricity consumption (GWh) by different socio-economic sectors in Guayaquil
Source: (ARCONEL, 2019)

In Ecuador, the latest end-use energy study was published in 1993; unfortunately, this study is not digitally available, but there is a reference in (MEER, 2013). Figure 3.13 shows the share of each end-use in the electricity consumption in the residential sector; at that time space cooling represented 14% of total electricity consumption in the Coast Region (see Figure 3.13 (a)) and 12% of peak demand (see Figure 3.13 (b)).



a) Share in Total Demand b) Share in Peak Demand

Figure 3.13: Results for the residential sector of an end-use energy study, ex-INECEL 1993
Source: (MEER, 2013)

In Ecuador, there is little information about equipment ownership and usage habits. The Institute of Statistics and Census (INEC) collects some information through four surveys (INEC, 2017a). ENIGHUR is a national survey of income and expenses of urban and rural households. SIIH-ENEMDU is a national survey with focus on employment. ECV, is a survey on living conditions and, finally, EENSE is a socioeconomic level stratification survey. Although these surveys are conducted periodically, some questions change from one period to another. The most relevant information for studies focusing energy consumption in air conditioning appliances are presented in Table 3.3.

Table 3.3: INEC's surveys and relevant information for this dissertation

Survey	Year	Information
ENIGHUR	2011-2012 2003-2004	• Equipment ownership • Electricity consumption [kWh] • Households Income
SIIH-ENEMDU	2012	• Usage habits • Electricity consumption [kWh]

Figure 3.14 shows households electricity consumption by income levels in 2003 and 2011 in a box and whisker plot; the mean consumption in levels 2≤SBU<8 and SBU≥8 increased, while for level SBU<2, it decreased. Such reduction can be explained by the introduction of a special tariff (0.04 USD/kWh) for consumers up to 130 kWh, i.e. low-income households limit their electricity consumption in order to meet the requirement of this low-cost tariff. This special tariff is lower than the average tariff in residential sector (0.0978 USD/kWh in 2018) and it has been applied since 2007.

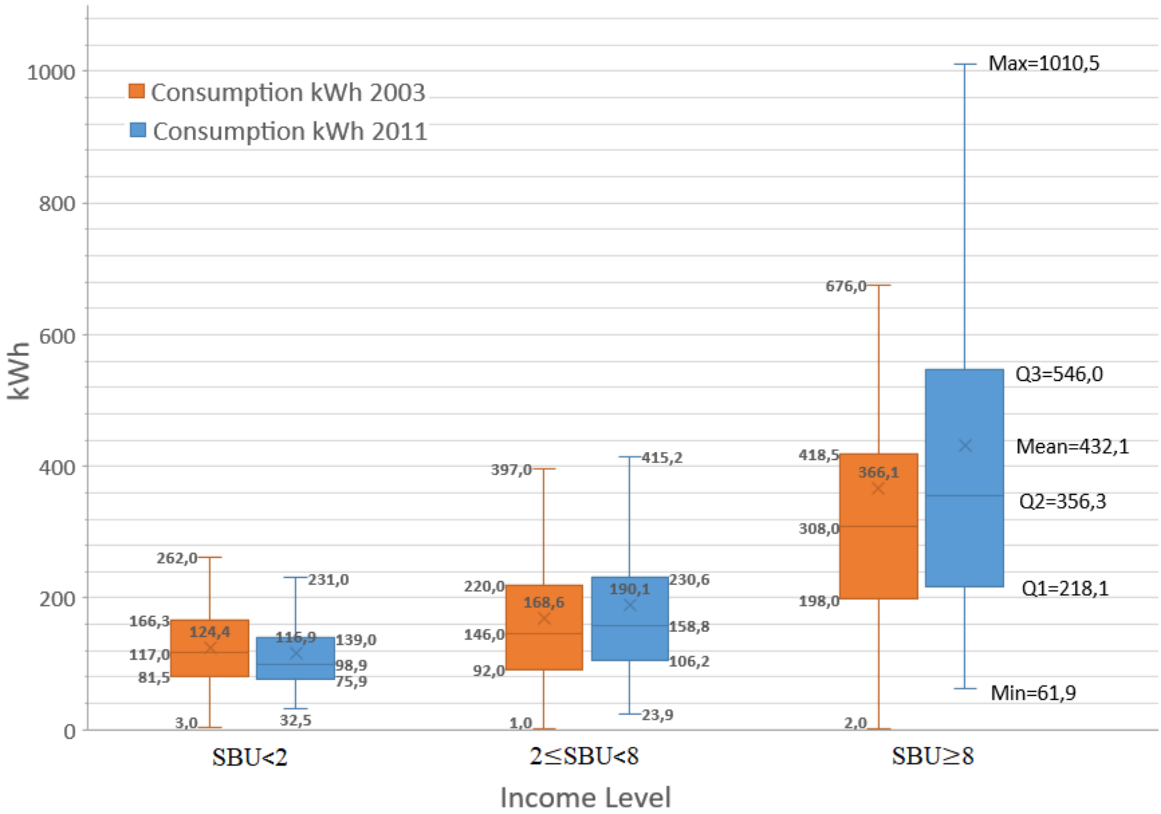


Figure 3.14: Residential electricity consumption in Guayaquil according to households' income levels

Based on INEC's surveys, Figure 3.15 presents the age distribution of AC devices in Guayaquil households. In 2003, on average the equipment was 4.79 years old and in 2011, on average, the units were 3.4 years old. In both years exhibit a distribution biased towards the left. This means that the stock of AC units was relatively new, and became newer along the years.

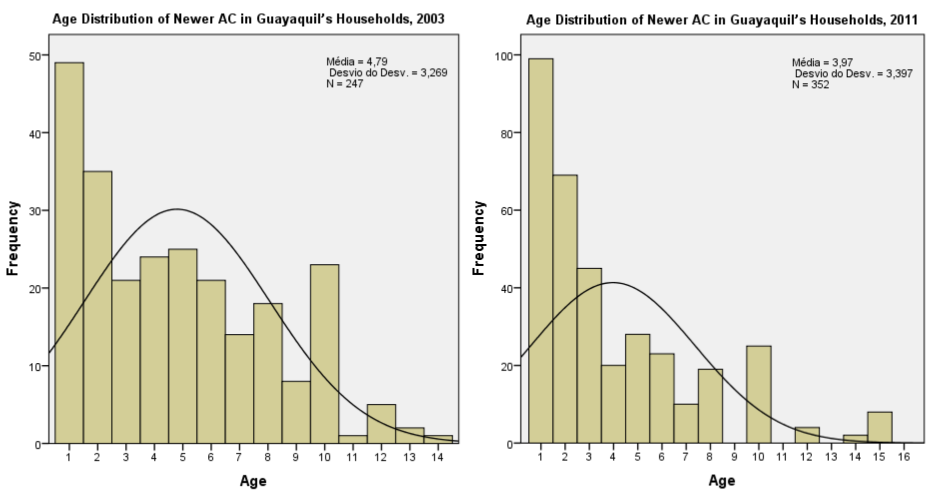


Figure 3.15: Age distribution of AC units in Guayaquil, in 2003 and 2011

Finally, Figure 3.16 shows the variation in the AC use in Guayaquil – hours per day – obtained from the INEC's surveys (INEC, 2012). In 2012, the average number of hours of use of air conditioning was 3 hours/day, with 50% of the cases between 2 and 5 hours/day.

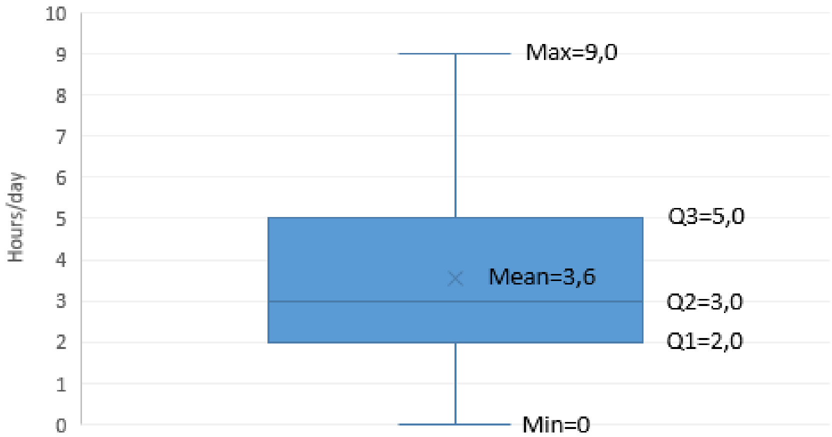


Figure 3.16: AC use in households in Guayaquil, in hours per day

4 METHODOLOGY, ASSUMPTIONS AND DATA

4.1 Cooling Degree Days and Heat Index

4.1.1 Cooling degree days (CDD)

CDD indicates how warm a location is. The value is given by summing the temperature differences over a period, between the outdoor average temperature and a reference, also known as the base temperature (CIBSE, 2006). The curve in Figure 4.1 is an example of the local temperature profile and Tb is the base temperature, CDD represent the area over Tb.

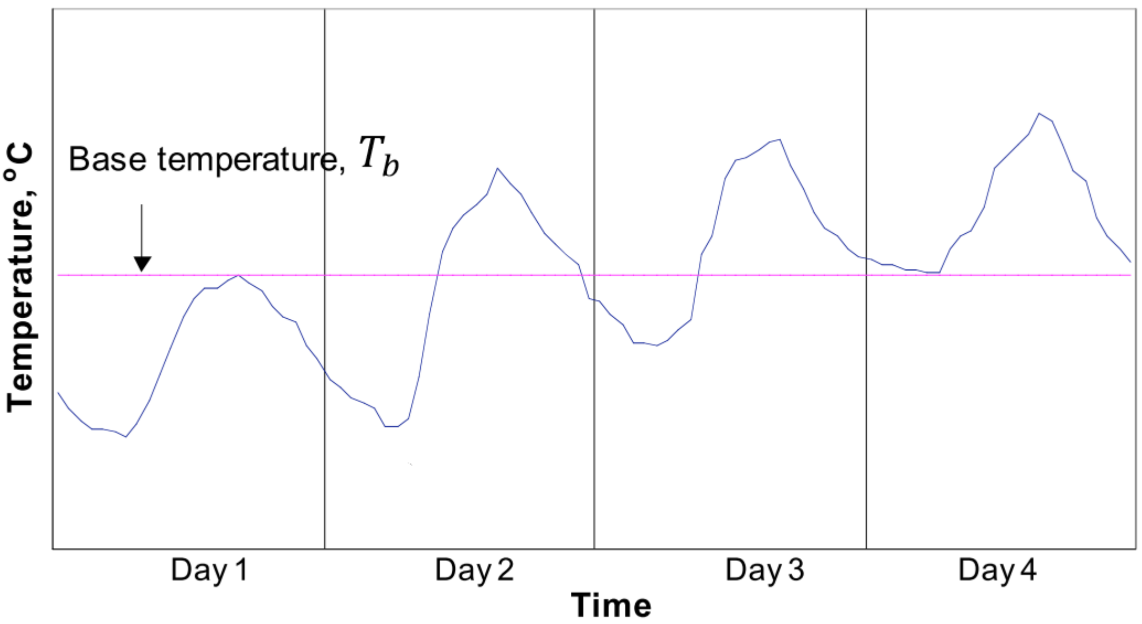


Figure 4.1: Example of local temperature profile
Source: (CIBSE, 2006)

There are several methods for estimating cooling degree-days (Mourshed, 2012), but for choosing the procedure the temporal resolution of the available data must be considered. The most common method is to sum positive hourly temperature differences and divide the result by 24, as shown by Equation 4.1; if smaller temporal resolution exists, the sum of positive differences should be divided by the number of registers that represent a day (hence the term degree-days). Smaller time periods may be used, but there is little to gain in terms of accuracy (CIBSE, 2006).

$$CDD = \frac{\sum_{i=1}^{24}(T_i - T_b)_{((T_i - T_b)>0)}}{24} \qquad \text{Eq. 4.1}$$

Where T_b represents the base temperature and T_i is the outdoor temperature at the ith hour of the day; $(T_i - T_b) > 0$ means that only positive differences between T_i and T_b must be considered. Physically, the base temperature represents a balance point; above it, cooling systems need to run in order to maintain comfort conditions for the occupants. The base temperature relates internal and external heat gains with thermal properties of the building envelope (CIBSE, 2006; David J. Sailor, 2001).

The IEA uses 18.3°C as the base temperature, and performs the CDD calculation considering an apparent air temperature called heat index (HI) (IEA, 2018b), the same approach is used to estimate the AC demand.

4.1.2 Heat index (HI)

There are several climatic variables that influence the cooling demand, such as temperature, humidity, wind speed, solar radiation, and cloudiness, among others, but the temperature is the most important (Apadula, Bassini, Elli, & Scapin, 2012; Brown et al., 2016; IEA, 2018b; David J. Sailor, 2001). Humidity can also become relevant, since when it increases the thermal sensation also increases. Heat Index (HI), or apparent temperature, is a correction in the air temperature that incorporates the effect of humidity in thermal sensation (IEA, 2018b) and also serves as a measure of the environment temperature that is perceived by the human body, i.e. an “apparent” temperature (NWS, 2016). HI depends on several biometeorological variables and the US National Weather Service (NWS) uses the algorithm presented in Figure 4.2 to quantify the HI (Brooke Anderson, Bell, & Peng, 2013).

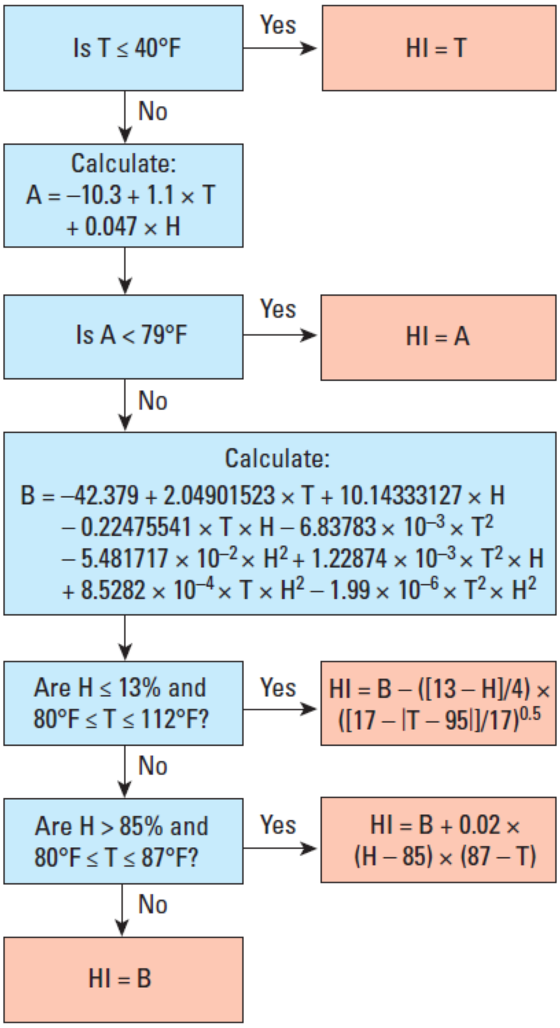


Figure 4.2: U.S. National Weather Service algorithm used for calculating HI
Source: (Brooke Anderson et al., 2013)

Where T is the outdoor dry bulb temperature, in Fahrenheit (°F), and H is the relative humidity, in percentage.

4.2 Estimating the air conditioning demand in Guayaquil

In this work, a parametric model was used in order to estimate the energy demand of ACs in Guayaquil. The model takes into account three effects: Activity (A), Structure (S) and Energy Intensity (I), and Equation 4.2 represents the mathematical expression, being E the energy demand (Santamouris, 2016).

$$E = A * S * I \qquad \text{Eq. 4.2}$$

The activity effect expresses the basic driving force of energy demand for a particular service, or sector; in the residential sector, the activity factor corresponds to the absolute the number of households. The structural effect relates the energy demand to the diffusion of the device, i.e. AC devices per household. (McNeil & Letschert, 2010). Finally, the energy intensity parameter refers to the amount of energy (e.g. kWh/ year) used per air-conditioned household or unit energy consumption (UEC). The intensity effect relates energy consumption with appliance ownership, climate, equipment efficiency and other factors, such as the quality of house insulation, lifestyle, etc.

The climate plays a dominant role in air conditioning demand because it affects the thermal comfort of people. In addition, there is a significant dependence between the degree to which the air conditioning demand is satisfied and households income (McNeil, Iyer, Meyers, Letschert, & McMahon, 2008). Therefore the climate and household income are key variables and must be considered when forecasting energy demand due to AC systems (Isaac & van Vuuren, 2009).

4.2.1 Household growth

The number of households can be expressed as function of the population and the household size (i.e. number of people per household). In Ecuador, the National Institute of Statistics and Census (INEC, 2017a) performs projections of population growth. Figure 4.3 shows the evolution of the population in Guayaquil and its projection until 2030 (it is the same figure previously presented as Figure 3.2), having data been taken from the National Information System databases (INEC, 2017b). The projection of household size (occupancy) is based on the national trend, presented in the United Nations Habitat (UN-Habitat, 2007), and also on historical information for Guayaquil, based on the National Census of 2000 and 2010. Data and results are presented in **Erro! Fonte de referência não encontrada.**.

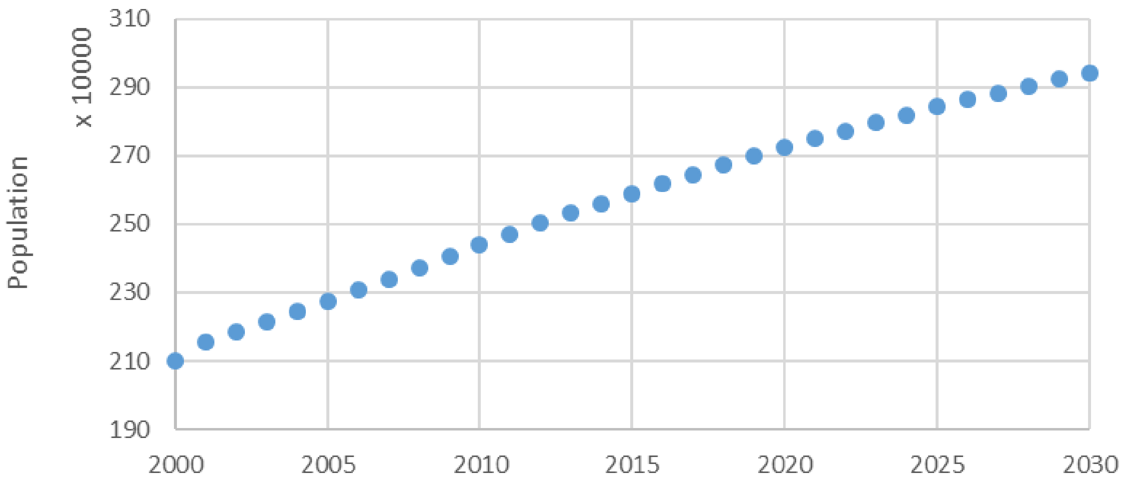


Figure 4.3: Population of Guayaquil – historical and estimates until 2030. **Source:** (INEC, 2017b)

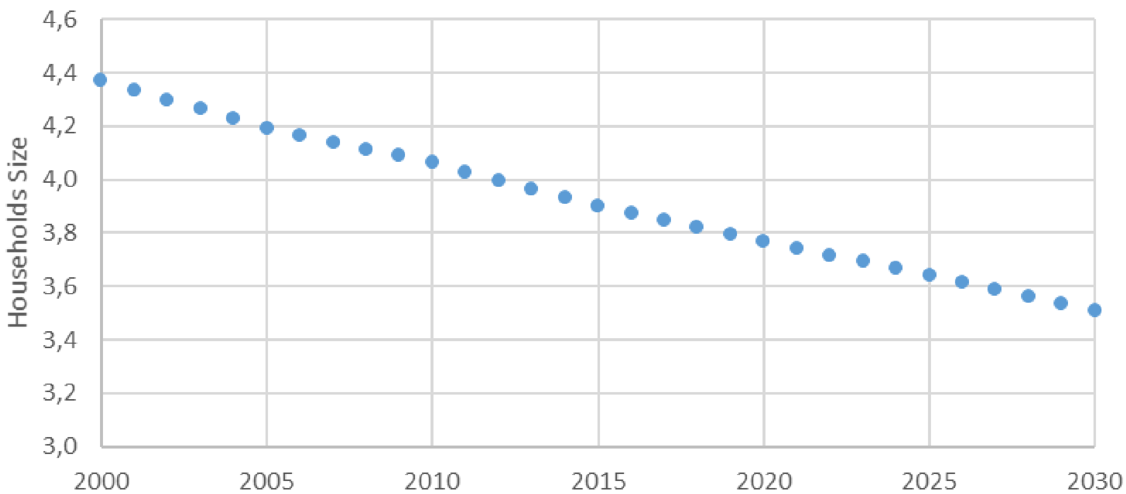


Figure 4.4: Household size (people per household) in Guayaquil, from 2000 to 2030. Source: (INEC, 2017a; UN-Habitat, 2007)

The activity factor expresses the number of households with access to electricity, and historical values and estimates until 2030 are presented in Figure 4.5. The correction related to access is important because the electric service coverage in Ecuador does not reach 100% of households. Historical coverage data is available in the National Census (INEC, 2017a), and for the years in which information is not available the coverage was estimated by interpolation. Here, for the period 2018 to 2030, growth rates were taken from the Electricity Master Plan (PME) (MEER, 2016b).

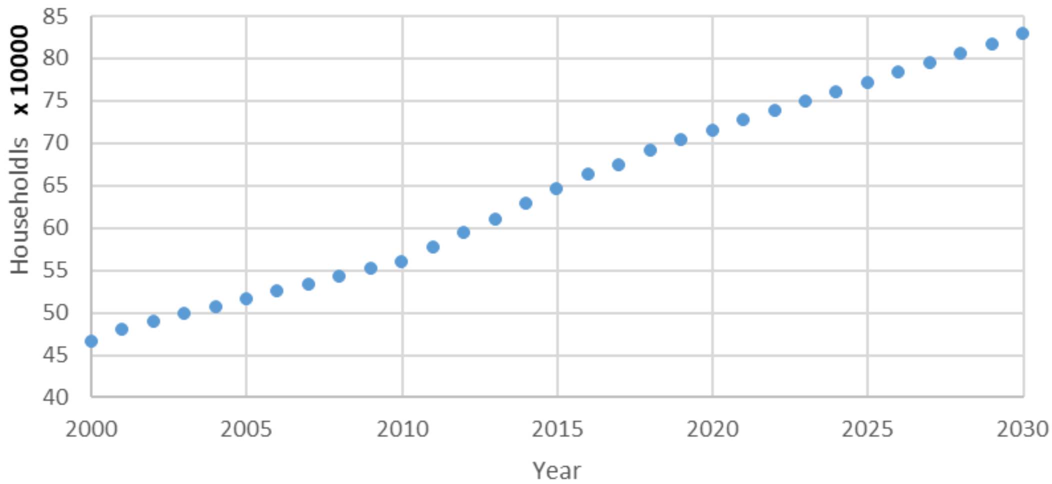


Figure 4.5: Households with access to electricity in Guayaquil – historical data and estimates

4.2.2 Diffusion of air conditioner units

The diffusion of AC units in developing countries has two issues: first, that they still are a relatively expensive good and, second, that their uptake is climate dependent (e.g. in some wealthy regions, such as Northern Europe, the use of air conditioner remains low even though air conditioners are affordable). The approach for modelling diffusion is based on an econometric model that depends on two factors. The first one is the climate maximum saturation (CMS), which is function of the CDD (Eq. 4.1). The second one is the availability (Av), which represents the affordability of households to have an AC unit. The diffusion itself is the product of both parameters, as shown by Equation 4.3 (McNeil & Letschert, 2008).

$$Diff = Av(Income) * CMS(CDD) \quad \text{Eq. 4.3}$$

Diffusion is the ratio between households with AC units and total households, and in some studies it is called penetration (Isaac & van Vuuren, 2009; Santamouris, 2016). The diffusion model assumes that saturation of ACs in developing countries will reach the climate maximum saturation given by Equation 4.4 (but never exceed it) (McNeil & Letschert, 2010).

$$CMS = 1 - 0.949 * \exp(-0.00187 * CDD) \quad \text{Eq. 4.4}$$

This equation is the result of a data regression for several regions in United States (McNeil & Letschert, 2010) and here it is assumed that saturation rates in the USA represent the maximum level. The same approach was used in other studies (Henderson, 2005; Isaac & van

Vuuren, 2009; D. J. Sailor & Pavlova, 2003). CMS is expressed in percentage of households with air conditioning, and its maximum value is 100%. Assumed Cooling Degree Days and Climate Maximum Saturation values for Guayaquil are presented in Table 4.1.

Table 4.1: Cooling Degree Days and Climate Maximum Saturation for Guayaquil

Variable	Values for Guayaquil
CDD[(a)]	2,748°C
CMS	99.4%

[(a)]The CDD was calculated from a typical meteorological year (TMY) and corrected by the heat index (HI); the base temperature (T_b) is 18.3°C

On the other hand, availability is a dimensionless factor that varies between 0 and 1 and can be estimated by a logistic model, as presented by Equation 4.5 (Isaac & van Vuuren, 2009; McNeil & Letschert, 2010). Household availability is related to the binary choice consumers have whether or not to buy a CA unit according to their income. (Train, 2009).

$$A = \frac{Diff}{CMS} = \frac{1}{1 + \gamma * \exp(\beta_{inc} * Income)} \qquad \text{Eq. 4.5}$$

Since the availability increase with the household income, the income coefficient must be $\beta_{inc} < 0$; and the determination of availability coefficients follows a linear regression, as shown by Equation 4.6.

$$\ln\gamma + \beta_{inc} * Income = \ln\left(\frac{1}{A} - 1\right) \qquad \text{Eq. 4.6}$$

In the work performed by McNeil et al. (McNeil & Letschert, 2010) the authors measure the overall model accuracy with the root mean squared deviation (RMSD) of all data points (in that case, data for 24 countries, including Paraguay, Brazil, Panama and Honduras, among them). Equation 4.7 shows the error equation of the model.

$$Error = \frac{\sqrt{\sum_{i=1}^{N}(Diff_{Model} - Diff_{Data})^2}}{N} \qquad \text{Eq. 4.7}$$

Where N is the number of data points. In the reference, the calculated error was 3.9% for air conditioners, and their linear regression model has R^2= 0.69.

Here, the diffusion of AC equipment is obtained from the datasets of the INEC's surveys. Households' data were aggregated by income level, the class range is 1 SBU and the income of each household class is the mean of the class. Then the ratio between the households with AC and the total households for each class was calculated. Finally, an ordinary least squares (OLS) regression was performed in order to obtain the coefficients of Eq. 4.6; the final expression for the AC diffusion in Guayaquil is presented in the results.

4.2.3 Unit energy consumption (UEC)

The unit energy consumption is the average energy consumption due to the usage of air conditioning equipment per air-conditioned household, as expressed by Equation 4.8.

$$UEC = P * t \qquad \text{Eq. 4.8}$$

Where UEC is in kWh per year, P is the average power of installed air conditioners in kW, and t is the hours of AC usage per year.

The climate plays a dominant role in air conditioning demand because it affects the thermal comfort of people. In addition, there is a significant dependence between the degree to which the air conditioning demand is satisfied and households income (McNeil, Iyer, Meyers, Letschert, & McMahon, 2008). The UEC can be estimated according to models present in the literature (Isaac & van Vuuren, 2009; McNeil, Letschert, de la Rue du Can, & Ke, 2013), which are both climate and income dependent, as expressed by Equation 4.9.

McNeil et al. (McNeil et al., 2013) use different UEC values (Equation 4.8) obtained from surveys in different countries, and then perform a linear regression to obtain the Equation 4.9 as function of CDD and income. In the reference, the annual GDP per household, divided by twelve and adjusted by purchasing power parity (PPP), in 2000 USD, serves as an estimate of households' income.

$$UEC = \frac{0.0276 * Income + 1.46 * CDD - 1332}{Efficiency\ improvement} \qquad \text{Eq. 4.9}$$

Wealthier households can afford to spend more on improving their thermal comfort by purchasing more and/or larger AC units but mostly keeping their units running longer (using them more intensely), the ownership of more than one AC unit will increase the UEC (McNeil & Letschert, 2010).

The efficiency improvement parameter takes into account improvements in energy efficiency from the base year y_0 to the year y. The average EER in 2000, for the global market, was 2.4, and estimates shown that by 2020 and 2030 EER could be 3.2 and 4.3, respectively (IEA, 2018b; McNeil & Letschert, 2008; Rong, Clarke, & Smith, 2007; Santamouris, 2016). In Ecuador, AC equipment are usually imported and thus, EER should be very similar to the world market. Equation 4.10 shows the efficiency improvement equation (Isaac & van Vuuren, 2009).

$$Efficiency\ improvement = \frac{EER_y}{EER_{y0}} \qquad \text{Eq. 4.10}$$

Where EER is the energy efficiency ratio, which is calculated as the ratio between cooling load and UEC (Isaac & van Vuuren, 2009).

4.3 Income growth scenarios and forecasting residential electricity demand

This section presents the scenarios of economic growth assumed for the estimation of AC demand until 2030 and the methodology followed to forecast the residential electricity demand in Guayaquil.

4.3.1 Income growth scenarios

This work considers two economic scenarios based on different GDP growth rates. The first one is the business as usual scenario (BAU): it represents the mean between the past-ten years of historical GDP information (see Figure 3.8) and the IMF's economic growth outlook (IMF, 2019). The other one is the alternative scenario (A1); it is derived from the average of the last ten years of economic growth, without the years of sudden[12] negative variations

[12] It is important to mention that the GDP in Ecuador is very susceptible to falls in international oil prices; in this sense, and considering that the national economy has faced problems since 2015, the A1 represents an optimistic scenario for the period 2019-2030.

associated with falling oil prices and natural disasters (see Figure 3.8). Table 4.2 shows a summary of the annual average GDP growth rates for the scenarios considered.

Table 4.2: Considered scenarios – annual GDP growth rates for the period 2019-2030

Scenario	Growth Rates
BAU	2.4
A1	3.6

The average monthly income per household in Guayaquil was calculated from the annual GNI per household, PPP basis (USD 2000) (Mcneil, Letschert, & Buskirk, 2007) Figure 4.6 shows the historical values of income per capita in Ecuador and its projection according to the considered scenarios.

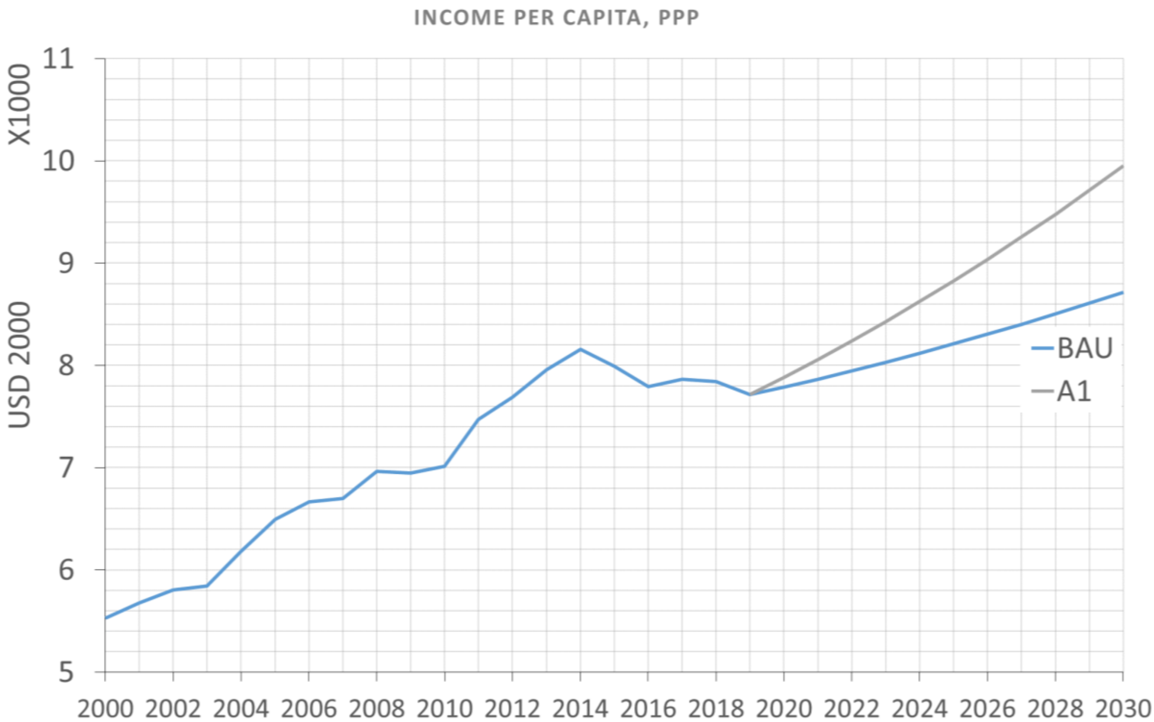


Figure 4.6: Evolution of the income per capita in Ecuador, PPP adjusted – historical values and projections based on the considered scenarios. Source: Income historical values GNI (WB, 2019)

4.3.2 Electricity demand in the residential sector

Figure 4.7 shows the evolution of residential electricity consumption in Guayaquil for the 2000–2018 period (ARCONEL, 2018). Projections of residential electricity demand are based on the historical correlation between electricity consumption and GNI[13] (from 2000 until 2018). As can be seen in Figure 4.8, it was found that a single linear equation fits very well (R^2 = 0.95).

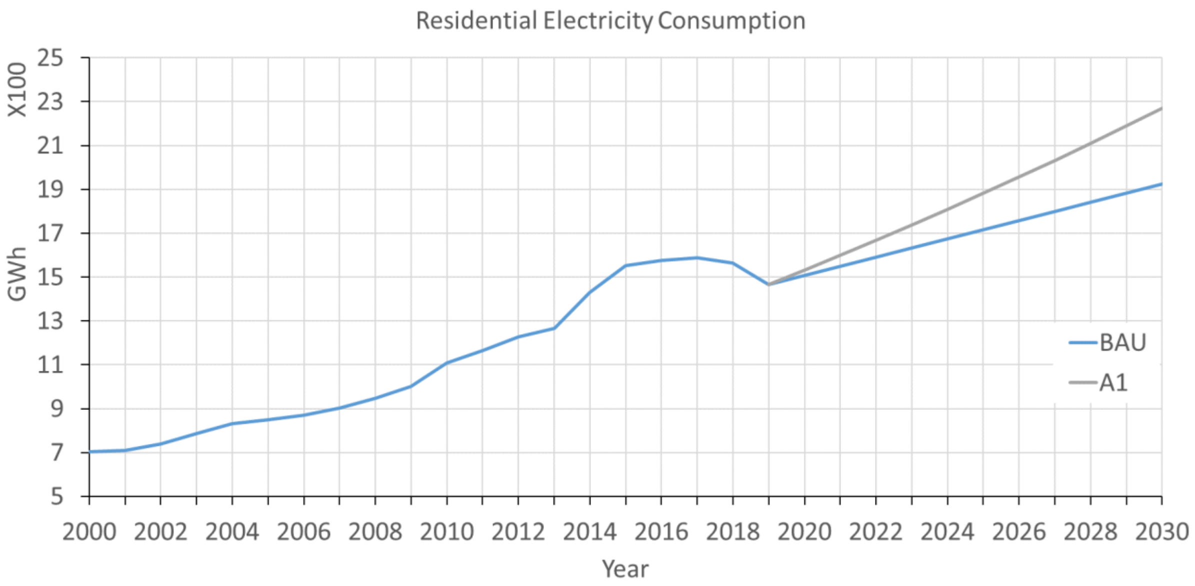


Figure 4.7: Annual residential electricity consumption in Guayaquil – historical values and projections
Source: Historical values of residential electricity demand (ARCONEL, 2019)

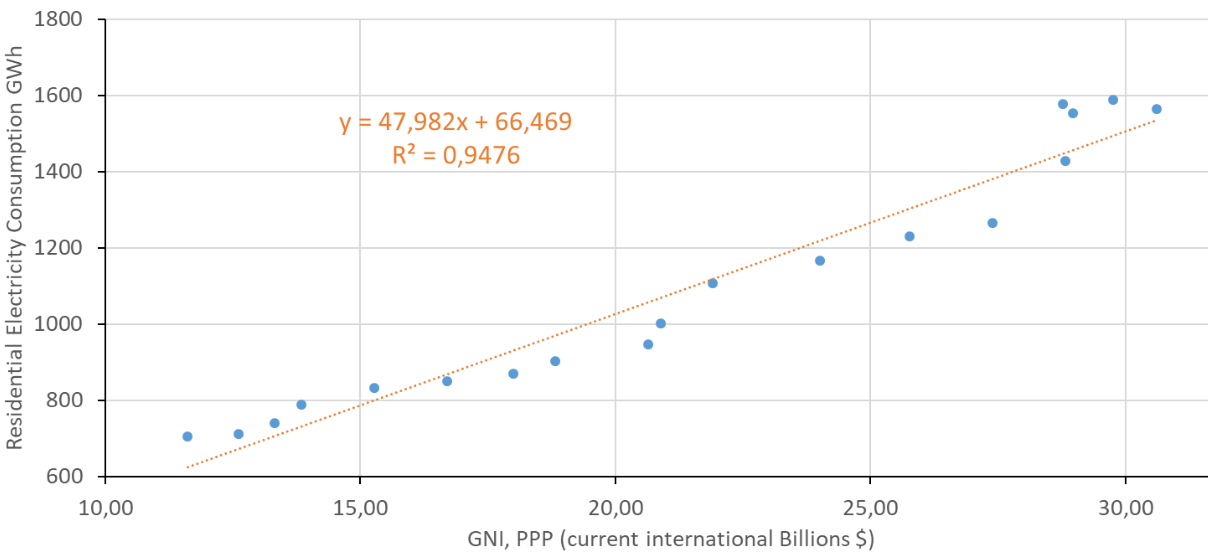


Figure 4.8: Electricity consumption vs income in Guayaquil – distribution and adjusted linear function for the period 2000 to 2018

[13] GNI per capita is a proxy for the income per capita in Guayaquil.

4.4 Assessment of minimum energy performance standards (MEPS)

This section presents the methodology used to assess the different energy efficiency standards. The procedure is to quantify the impacts that the adoption of stricter MEPS would have in relation to a baseline value. The baseline is associated with an equipment whose energy efficiency level is defined by the current Ecuadorian technical regulation (INEN, 2017). This equipment is here called the base case, which is compared with more efficient options, called the standard cases. The standard case is defined by different energy efficiency levels (Mcneil, Letschert, & Van Buskirk, 2007).

The assessment considers the impacts from the consumer (individual household) and society perspectives[14] and is not a complete regulatory impact study due to the assumptions made and its scope[15] (i.e. does not consider impacts on manufacturers and private sectors).

4.4.1 Base case and standard cases

Base Case

The base case assumes an ordinary common equipment in the AC stock, with cooling capacity of 3.5 kW (12000 BTU/h); this is the regional average for ductless mini-split air conditioners (OLADE et al., 2015). The AC usage is based on the annual average obtained from INEC's surveys (see Figure 3.6). Table 4.3 shows a summary of parameters assumed for the base case.

Table 4.3: Parameters assumed for the base case

Equipment Retail Price (USD)	390
Usage[(a)] (h/year)	1,095
EER[(b)] (W/W)	3.26
Cooling Capacity (kW)	3.5
Annually UEC (kWh)	1,175.6

[(a)]Households with at least one AC unit. **Source:** (INEC, 2012)
[(b)]Based on Ecuadorian technical regulation. **Source:** (INEN, 2017)

[14] In the Appendix C, there is a comparison between the different perspectives. Society perspective represents the whole residential sector in Guayaquil.
[15] The assessment was broaden by calculating the impacts that the adoption of more stringent MEPS would have on household electricity demand, emissions avoided due to the use of more efficient equipment and appliance diffusion.

Standard Cases and equipment cost

Standards above the energy efficiency levels of commercially available equipment can cause drawbacks to manufacturers and importers. For this reason, it is necessary to consider in the assessment, standards compatible with international practice, i.e. an equipment characterization carried out through a market study (Wiel & McMahon, 2005).

A regulatory impact study also includes engineering and economic analysis to reduce uncertainties related to efficiency and costs. Such uncertainties arise because the equipment that complies with targeted standards may not be widely marketed. Engineering and economic analysis determine the required improvements and associated costs. The different stages of these analysis are presented in (Costa et al., 2019).

Given information and resources constraints to conduct a local market study and also economic and engineering analysis, data from studies conducted in the region (Latin America) were used. The standards proposed by OLADE (OLADE et al., 2015) were assumed as the MEPS to be assess, once they are based on energy efficiency levels of commercially available equipment in the region (see Table 3.2). On the other hand, since the purchase price of AC units in Ecuador is similar to the region, the same cost structure of regulatory impact studies conducted in Latin America was assumed (Letschert et al., 2019).

Finally, in order to obtain the energy efficiency level and the cost for each assumed case, an optimization procedure was carried out. The optimization tool used was the Binary Integer Linear Programming[16]. **Erro! Fonte de referência não encontrada.** shows the solutions of the optimization problem, or designs, which define the standard cases; it is also presented the purchase price and the ratios regarding the base case (MEPS 3.2 W/W).

Table 4.4: Results of the linear optimization performed

Design	MEPS	Purchase Price (E_q in USD $)	EER	Price Ratio	EER Ratio
Design #1	3.4	435.84	3.47	1.18	1.15
Design #2	3.6	491.25	3.68	1.33	1.22
Design #3	3.8	550.35	3.95	1.49	1.31
Design #4	4.3	602.06	4.38	1.63	1.45
Design #5	4.7	738.72	4.72	2.00	1.56
Design #6	5.0	834.75	5.03	2.26	1.67
Design #7	5.2	886.46	5.21	2.40	1.72
Design #8	5.8	1,074.84	5,98	2.91	1.98

[16] Details about the optimization problem are presented in Appendix D.

4.4.2 Policy Analysis Modeling System (PAMS)

This section details the use of the Policy Analysis Modeling System (PAMS) tool to assess the impacts of stricter MEPS (Mcneil, Letschert, & Van Buskirk, 2007). The basic assumption is that after the standard adoption (i.e. the standard year) all equipment available in the market would be similar or superior to the MEPS defined.

Input data for PAMS-MEPS

Electricity price

This work considers two electricity prices: the first one is based on residential billing (without subsidies) from Guayaquil electricity utility in 2017 (ARCONEL, 2018; CNEL, 2018), while the second is based on world average price for the residential sector in 2017 (IEA, 2019).

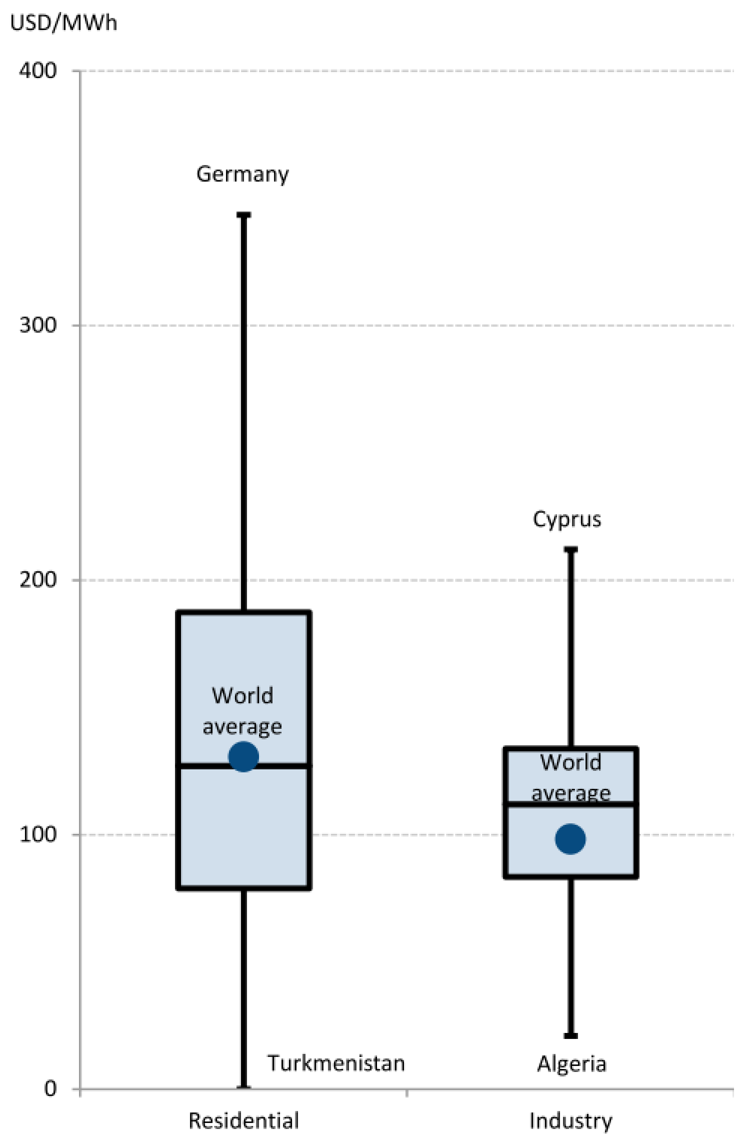
Table 4.4 shows the residential electricity average price in Guayaquil in 2017; it was 10.90 USD ¢/kWh.

Table 4.4: Estimated electricity average price without subsides in Guayaquil, in 2017

Electricity billing (GWh)	Electricity billing (MUSD)	Subsides (MUSD)	Mean Price (USD ¢/kWh)
1,587.54	155.27	4.92	10.90

Source: (ARCONEL, 2018; CNEL, 2018)

Figure 4.9 shows the distribution of the electricity price worldwide in 2017; the average price in the residential sector was 13.33 USD ¢/kWh.



Note: In this box-plot chart, the whisker tops are the countries with the highest prices and the whisker bottoms are the countries with the lowest prices. The top and bottom edges of the boxes represent the 75th and 25th percentiles, respectively. The lines inside the boxes represent the medians.

Figure 4.9: Distribution of the electricity price, worldwide, in 2017. Source: (IEA, 2019)

T&D Loss Factor (TD)

Transmission and distribution loss factor (TD) is the percentage of electricity lost in the transmission and distribution electric system regarding the total electricity generated. Combined with other parameters presented below, TD was used to calculate primary energy savings and CO_2 emissions mitigation (Mcneil, Letschert, & Buskirk, 2007). Table 4.5 shows the T&D Loss Factor for the Ecuadorian electricity system in 2018 (ARCONEL, 2019).

Table 4.5: Estimated transmission and distribution losses for Guayaquil in 2018

Generated electricity for Guayaquil GWh[(a)]	SNI Transmission Losses	Available electricity for distribution GWh	Distribution Losses[(b)]	Total Commercialized Electricity GWh	T&D Loss Factor
5,673	3.22%	5,496	11.10%	4,886	0.14

[(a)] Calculated from the available electricity for distribution and SNI transmission losses
[(b)] Distribution losses include technical and non-technical losses (ARCONEL, 2019)
[(c)] Total distributed electricity without losses (ARCONEL, 2019)

Generation Factor (GF)

Generation Factor (GF) is the ratio between the input of fossil fuels (energy basis) and the net electricity (kWh) generated in fossil fuel plants. Equations 4.11 to 4.13 were used on calculation; FG is the share of fossil generation and HR is the thermal heat rate (Mcneil, Letschert, & Buskirk, 2007). GF together with TD are used to estimate primary energy savings, in Mtoe.

$$GF = RG * HR \qquad \text{Eq. 4.11}$$

$$FG = \frac{non - renewable\ generation}{Total\ SNI\ generation} \qquad \text{Eq. 4.12}$$

$$HR = \frac{fossil\ fuel\ energy}{non - renewable\ generation} \qquad \text{Eq. 4.13}$$

Table 4.6 presents the electricity generation mix for Ecuador in 2018 and 2025 (ARCONEL, 2019; MEER, 2016b). The marginal electricity generation (ME) represents the case in which the electricity is generated by internal combustion engines using fuel oil. The percentages in the electricity generation mix 2025 were obtained from the electricity master plan of Ecuador 2016 – 2025 (MEER, 2016b). The mix 2025 represents a simplification of the of electricity generation in the coming years.

Table 4.6: Electricity generation mix for Ecuador, in 2018 and 2025

Technology	2018	2025	ME 2018
Hydropower	81.42%	85.40%	0
Wind	0.29%	0.44%	0
Photovoltaics	0.14%	0.20%	0
Biomass	1.51%	2.69%	0
Biogas	0.18%	0.12%	0
Fuel oil – Internal combustion engines	5.71%	2.60%	100%
Natural gas – Gas turbine	4.03%	5.68%	0
Fuel oil – Steam turbine	6.73%	2.88%	0

Source: (ARCONEL, 2019; MEER, 2016b)

Table 4.7 shows the heat rate of each non-renewable generation technology (Ramirez, Rivela, Boero, & Melendres, 2019), as well as its share to the total electricity generation (ARCONEL, 2019; MEER, 2016b). The table also presents the GF of the SNI generation mix in Ecuador in 2018, and the estimate for 2025, and the GF of marginal electricity generation in 2018 (ME).

Table 4.7: Estimated generation factor of the SNI in Ecuador

Non-Renewable Technologies	FO-SP[(a)]	FO-IEC[(b)]	NG-GT[(c)]
Heat Rate	3.1	2.1	3.0
Share in the generation mix 2018	6.73%	5.71%	4.03%
Generation Factor 2018	0.45		
Share in the generation mix 2025	2.88%	2.60%	5.68%
Generation Factor 2025	0.31		
ME 2018		100%	
Generation Factor ME	2.13		

[(a)] Fuel oil in steam power plants
[(b)] Fuel oil in internal combustion engines power plants
[(c)] Natural gas in gas turbine power plants

CO_2 Emission Factor (CF)

The CO_2 emission factor (CF) is the ratio between the estimated total emissions of CO_2eq due to burning fossil fuels (in kg) and the electricity generated by power plants (in kWh) (Mcneil, Letschert, & Buskirk, 2007). Here, this factor represents an average value for the SNI. Table 4.8 shows the CO_2 emissions for the Non-Renewable generation technologies in Ecuador (Ramirez et al., 2019) and the CO_2 emissions factor in kg CO_2eq/kWh for different generation mixes. CF together with TD were used to calculate the estimated mitigation of CO_2 emissions.

Table 4.8: Estimated emission factor of the SNI in Ecuador

Non-Renewable Technologies	FO-SP[(a)]	FO-IEC[(b)]	NG-GT[(c)]
kg CO_2 eq/kWh	9.32E-01	7.76E-01	6.80E-01
Share in the generation mix 2018	6.73%	5.71%	4.03%
Emission Factor 2018 (kg CO_2 eq/kWh)		0.13	
Share in the generation mix 2025	2.88%	2.60%	5.68%
Emission Factor 2025 (kg CO_2 eq/kWh)		0.09	
ME 2018		100%	
Emission Factor ME 2018 (kg CO_2 eq/kWh)		0.78	

[(a)]Fuel oil in steam power plants
[(b)]Fuel oil in internal combustion engines power plants
[(c)]Natural gas in gas turbine power plants

Discount Rates

The consumer discount rate (CDR) indicates consumer's preference for short- versus long-term costs and benefits, and is generally related to prevailing interest rates. In this work the consumer discount rates are based on effective passive interest rates by the Central Bank of Ecuador (BCE, 2019). On the other hand, the assumed national discount rate (NDR) is based on values from a study prepared by the Development Bank of Latin America (CAF, 2016) in which opportunities to improve energy efficiency in Ecuador were assessed; the reference work assumed national discount rates between 5% and 7% per year. Table 4.9 presents the used discount rates; for CDR three values were considered to address the variation in the rates published by the Central Bank, the reference rate is roughly 8%

Table 4.9: Discount rates for Ecuador

Consumer discount rates			National discount rate
6%	8%	10%	6%

Consumer perspective

Figure 4.10 shows the main steps to assess costs and benefits from the consumer perspective (i.e. individual household), being input data presented in a blue frame, the intermediate calculations in brown and the outputs in green.

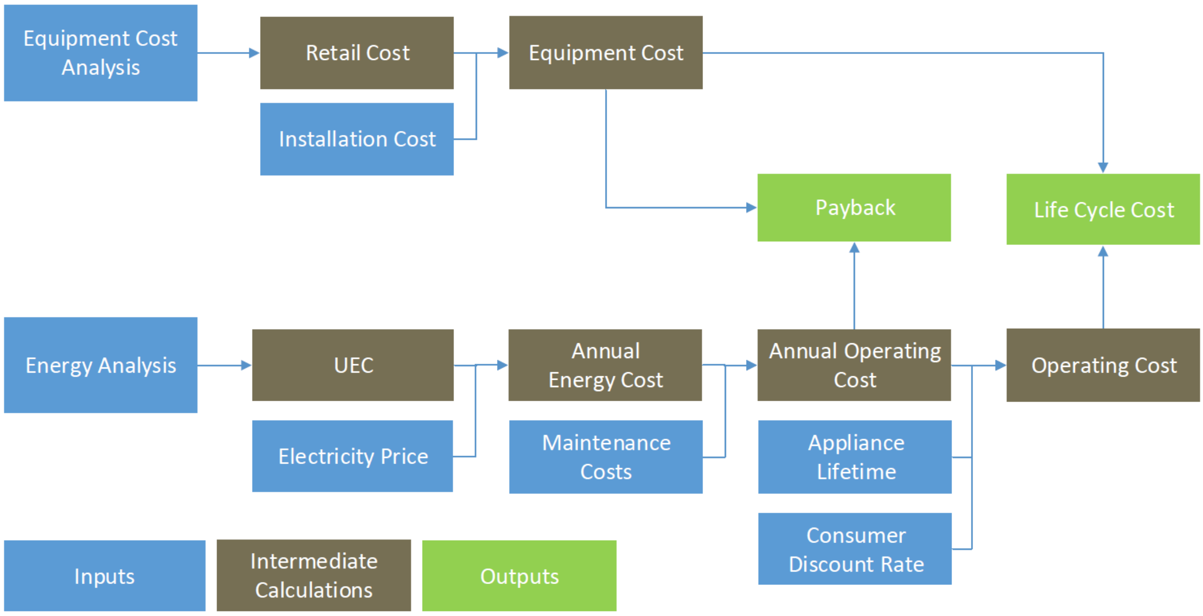


Figure 4.10: Flow chart of Policy Analysis Modeling System procedure – consumer perspective

From the consumer perspective, both the Life-Cycle Cost (LCC) and the payback period are useful metrics for estimating the financial impact of a MEPS policy (i.e. for each household using the appliance). This evaluation is critical in taking decisions about the most appropriate minimum efficiency standard (Wiel & McMahon, 2005).

Life-Cycle Cost (LCC)

The life-cycle costs (LCC) of any energy-consuming equipment is the total expense over its lifetime, including purchase cost, installation, operating (also including energy expenditures) and maintenance costs. Costs in the future (operation & maintenance) over the lifetime of the appliance are discounted to the time of purchase (Mcneil, Letschert, & Van Buskirk, 2007; Vendrusculo, Queiroz, Jannuzzi, da Silva Júnior, & Pomilio, 2009). Equation 4.14 is an expression for calculating the LCC.

$$LCC = EC + \sum_{n=1}^{L} \frac{OC}{(1 + CDR)^n} \qquad \text{Eq. 4.14}$$

Where EC is equipment cost plus installation (e.g. retail price), n is the year since purchase, OC is the annual operating cost, including maintenance, L is the appliance lifetime and CDR is the discount rate from the consumer perspective.

In practice, installation and maintenance costs can be neglected because they are not significant with respect to the other costs (Mcneil, Letschert, & Van Buskirk, 2007). The appliance lifetime was assumed 12 years for base case equipment (ASHRAE, 2013a). Operating cost is equal to the Unit Energy Consumption (UEC, in kWh/year) multiplied by the electricity price (P, in dollars per kWh), as presented by Equation 4.15:

$$OC = UEC * P \qquad \text{Eq. 4.15}$$

Payback time

The payback time, as presented by Equation 4.16, is the time required to recover the additional investment on purchasing a more efficient model, as an alternative to the reference equipment, due to lower operating costs.

$$Payback\ Period\ (years) = -\frac{\Delta EC}{\Delta OC} \qquad \text{Eq. 4.16}$$

Society perspective

The society perspective corresponds to take into account the whole set of households, indicating the impact of MEPS from an economic (e.g. costs and net present value), strategic (e.g. energy savings) and environmental (CO_2 emissions mitigation) point of view. Figure 4.11 is a scheme of the rationale, showing the inputs, intermediate calculations and the outputs.

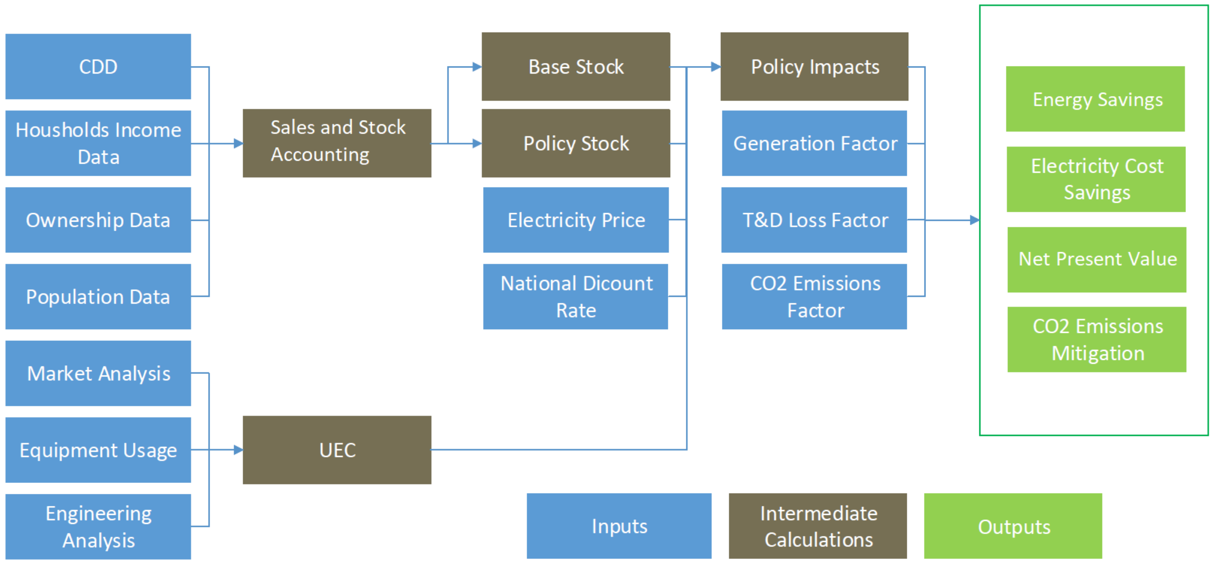


Figure 4.11: Flow chart of Policy Analysis Modeling System procedure – society perspective

Unlike the consumer impacts, those to the society impacts are calculated since the standard year, introducing an important temporary component to the analysis. In the first year after MEPS implementation, the savings are small, since the standard only affects to the units purchased in that year. Over time, the stock is increasingly impacted by the standard. The estimate of the to the society takes into account the changes in the stock profile, what gives a time profile to the costs and benefits (Mcneil, Letschert, & Van Buskirk, 2007)..

Sales and stock accounting

To describe the evolution of the stock, it is necessary to establish a model of sales and stock accounting. (Mcneil, Letschert, & Van Buskirk, 2007). This model accounts sales and replacement of equipment due to failures and/or lifetime end. In developing countries, and in markets far from diffusion saturation, the first purchase component is the dominant driver of sales. In developed countries, where the household market may be saturated, replacements play a more important role. Equation 4.17 allows estimates of the first purchases (FP) in the year (y).

$$FP(y) = HH(y) * Diff(y) - HH(y-1) * Diff(y-1) \qquad \text{Eq. 4.17}$$

Where HH is the number of households and Diff is the ownership growth rate. The replacement of equipment (REP) is expressed as function of an annual retirement probability

P_r, as can be seen in Equation 4.18. P_r varies as a function of the equipment age, as expressed by Equation 4.19.

$$REP(y) = \sum_{age=1}^{L} Stock(y-1, age) * \frac{P_r(age) - P_r(age-1)}{1 - P_r(age-1)} \quad \text{Eq. 4.18}$$

$$P_R(age) = \frac{1}{1 + e^{(age_0 - age)/D_{age}}} \quad \text{Eq. 4.19}$$

Where $\text{age}_0 = 12$ correspond to the average lifetime of the product – 12 years –, and D_{age} is the mean deviation of replacement ages, assumed to be two years (ASHRAE, 2013a). Each year, the number of units remaining is $\text{Stock}(\text{y}, \text{age})$ (Equation 4.16). Finally, Equation 4.20 gives the total sales in a year (y).

$$Sales\ (y) = FP(y) + REP(y-1) \quad \text{Eq. 4.20}$$

The final step is to adjust the number of older products remaining in the stock, according to Equation 4.21.

$$Stock\ (y, age) = Stock(y-1, age-1) * \left(1 - P_R(age-1)\right) \quad \text{Eq. 4.21}$$

Energy Savings

Annual electricity savings ES(y) is the difference between the annual electricity consumption (E_{Con}) in the base case compared to the standard case, as expressed by Equation 4.22.

$$ES(y) = E_{Con,Base}(y) - E_{Con,Policy}(y) \quad \text{Eq. 4.22}$$

The annual electricity consumption is estimated considering AC units with different ages. The UEC is expected to change, due to the introduction of more efficient equipment in the market. Equation 4.23 indicates the rationale.

$$E_{Con}(y) = \sum_{age} Stock(y, age) * UEC(y, age) \quad \text{Eq. 4.23}$$

Equation 4.24 is used to estimate the UEC of the stock.

$$UEC(y, age) = UEC_{Base} * \frac{EER_{Base}}{EER_{Standard}(y, age)} \quad \text{Eq. 4.24}$$

Where $EER_{Standard}$ represents the energy efficiency ratio in the standard case. According to the assumption that after the standard adoption (standard year) all equipment available in the market would be equal or superior to the EER in the MEPS regulation, if y < standard year, $UEC(y,age) = UEC_{Base}$.

Primary energy saving (PES), can also be calculated from the annual electricity savings, taking into account the electricity generation fuel mix, or the generation factor (GF) and losses due transmission and distribution (T&D). Equation 4.25 is used to estimate PES.

$$PES = \frac{ES}{1 - TD} * GF \quad \text{Eq. 4.25}$$

Where TD is the fraction of energy lost in transmission and distribution, and GF is the generation factor, as presented in Table 4.7.

Electricity Cost Savings

Electricity Cost Savings (ECS), as mentioned earlier, is the difference in electricity consumption cost between two cases, and is estimated by Equation 4.26. A discount factor (DF) is used to move future savings to the analysis year (y_0), as shown by Equation 4.27.

$$ECS\ (y) = [EC_{Base}(y) - EC_{Policy}(y)] * DF(y) \quad \text{Eq. 4.26}$$

$$DF(y) = \frac{1}{(1 + NDR)^{y - y_0}} \quad \text{Eq. 4.27}$$

Where EC is the electricity cost in each case.

The annual electricity cost EC is equal to the of annual electricity consumption E_{Con}, multiplied by the average electricity price E_{Price}, as shown by Equation 4.28.

$$EC(y) = E_{Con}(y) * E_{Price} \quad \text{Eq. 4.28}$$

Net present value (NPV)

The NPV is an indicator of the net benefit due to the standard implementation, as expressed by Equation 4.29. It is the sum of the incremental equipment costs (IEC) (see Equation 4.30) to the electricity cost savings (ECS) (see Equation 4.26).

$$NPV(y) = IEC(y) + ECS(y) \quad \text{Eq. 4.29}$$

$$IEC(y) = [E_{q,Base}(y) * Shipment_{Base}\ (y) - E_{q,Policy}(y) * Shipment_{Policy}\ (y)] * DF(y) \quad \text{Eq. 4.30}$$

Where E_q is the equipment retail price, and DF is the discount factor.

CO_2 emissions mitigation

Finally, CO_2 emissions mitigation (CEM) are calculated from energy savings, by applying a emission factor, or carbon factor (CF), according to Equation 4.31 and values shown in Table 4.8.

$$CEM = \frac{ES}{1 - TD} * CF \quad \text{Eq. 4.31}$$

4.4.3 Index decomposition analysis of air conditioning energy consumption

Index decomposition analysis (IDA) is commonly used to study the determinants of change in energy consumption. It is also used to identify the contribution of energy efficiency, isolating it from other factors that impact energy consumption, such as economic structure and physical or economic activity. IDA is also useful in the analysis of energy policies, that is, to understand the past, assess the current situation and predict the future, both related to energy consumption and energy-related carbon emissions (IEA, 2014b; Xu & Ang, 2014).

In this work IDA[17] was used to quantify the relative contributions of the driving factors (activity, structure and energy intensity) related to AC energy consumption and, in addition, to track the reasons for changes in energy consumption. In some cases IDA is used to estimate the effectiveness of energy policies (Empresa de Pesquisa Energética - EPE, 2018; Nie & Kemp, 2014).

The Logarithmic Mean Divisia Index I (LMDI-I) was the method chosen to perform the decomposition of air conditioning electricity consumption. It has some advantages compared to other methods, such as perfect decomposition, consistent aggregation of decomposed terms and symmetrical relative variations, or time reversibility (Andrade & Pinheiro, 2005; Nie & Kemp, 2014; X. Zhao, Li, & Ma, 2012). The method is relatively easy to use and the results are easily interpreted, but it is not suitable when there are null or negative values in the data set (Ang, 2004; IEA, 2014b).

Equation 4.32 gives the increase in energy demand (ΔE). This increase is equal to the sum of the variations of each driver factor in a time period (year T and year 0) (Equation 4.33). For the air conditioning electricity demand, the effect of the activity (Act), structure (Str) and energy intensity (Int) are the drivers; T represents the 2030 horizon and 0 is the standard year (2020).

$$\Delta E = E^{Year\,T} - E^{Year\,0} \qquad \text{Eq. 4.32}$$

$$\Delta E = \Delta E_{Act} + \Delta E_{Str} + \Delta E_{Int} \qquad \text{Eq. 4.33}$$

The Divisia index is based on the logarithmic change concept; the Equations 4.34 to 4.36 show the energy demand drivers (IEA, 2014b).

$$\Delta E_{Act} = L(E^{Year\,T}, E^{Year\,0}) * \ln\left(\frac{A^{Year\,T}}{A^{Year\,0}}\right) \qquad \text{Eq. 4.34}$$

$$\Delta E_{Str} = L(E^{Year\,T}, E^{Year\,0}) * \ln\left(\frac{S^{Year\,T}}{S^{Year\,0}}\right) \qquad \text{Eq. 4.35}$$

$$\Delta E_{Int} = L(E^{Year\,T}, E^{Year\,0}) * \ln\left(\frac{I^{Year\,T}}{I^{Year\,0}}\right) \qquad \text{Eq. 4.36}$$

[17] Additional information about IDA is presented in Appendix E

Where $L(a,b)$ is presented in Equation 4.34, with $a,b > 0$ and $a \neq b$

$$L(a,b) = \frac{a-b}{\ln(a) - \ln(b)} \qquad \text{Eq. 4.34}$$

5 RESULTS AND DISCUSSION

5.1 Climate influence on the electricity consumption of Guayaquil

Figure 5.1 presents the correlation between electricity consumption and heat index (HI[18]) for the period 2015-2018; to avoid noise in electricity consumption data, the register of the main industrial consumers was removed. As can be seen, there is a strong positive linear correlation between electricity consumption and heat index. It is reasonable to assume that the variation in electricity consumption due to apparent temperature increases is associated with the consumption of air conditioners.

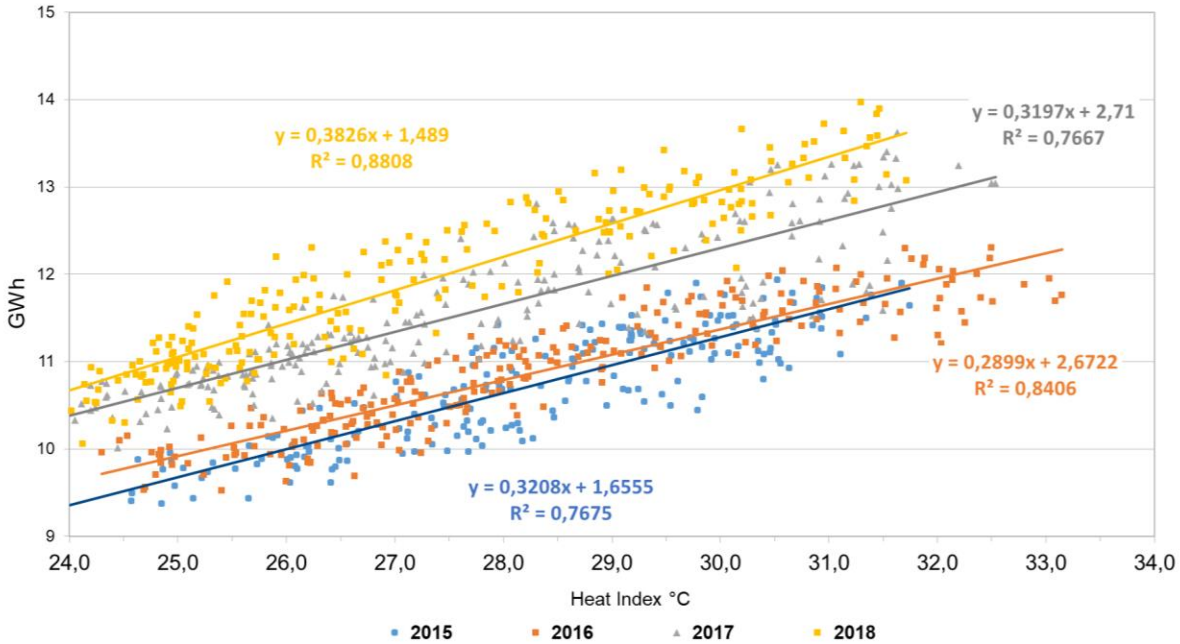


Figure 5.1 Electricity consumption vs heat index in Guayaquil, between 2015 and 2018

5.2 Air conditioning diffusion in the residential sector

Figure 5.2 is a scatter plot between AC diffusion and households monthly income data, for Guayaquil. The blue line shows the logistic trend that the correlation between the two variables. As can be observed, there are some outliers (marked as black dots); these points were

[18] As mentioned, HI takes into account the increase in thermal sensation due to relative humidity of the environment.

removed with the use of PyOD toolkit for Python. Note that below 1,000 USD, the difussion of air conditioning is under 20%.

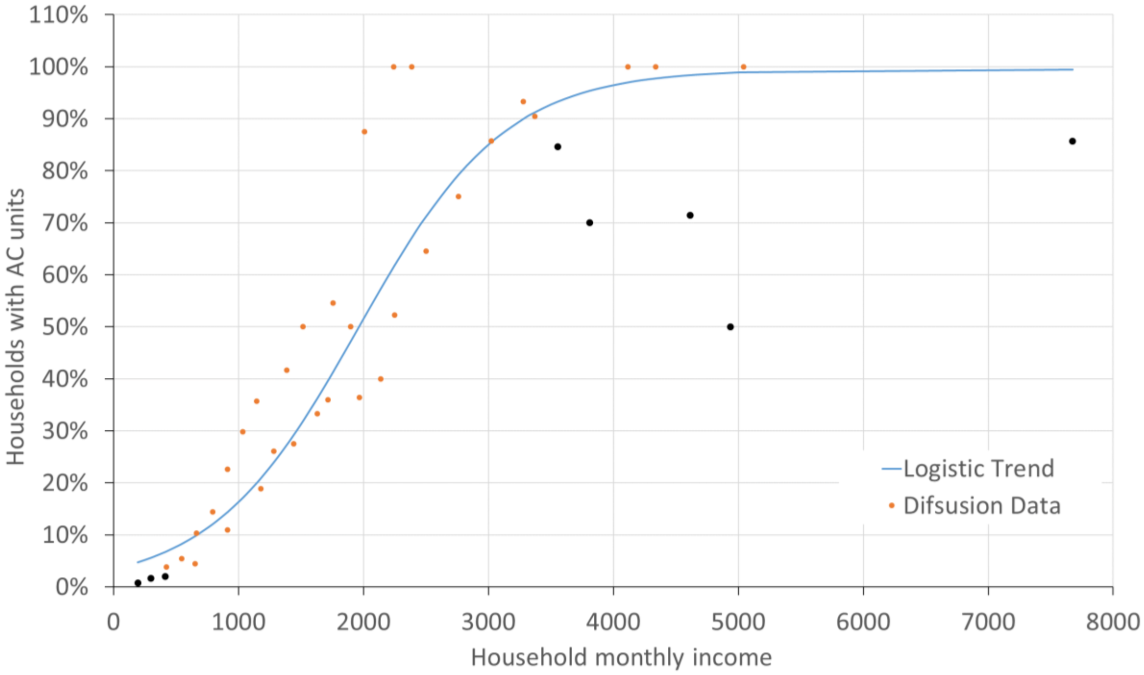


Figure 5.2: AC diffusion for Guayaquil

Table 5.1 shows the parameters of the difussion model obtained for Guayaquil (current model); it is compared with the diffusion model found in the literature for developing countries (McNeil & Letschert, 2010). The goodness-of-fit (R^2) for the current model is 0.90, which means that the variables have a strong linear correlation (Reddy, 2011).

The parameters β_{inc} and γ don't have physical meaning. In (McNeil & Letschert, 2010), households income is annual and diffusion data are an average for the countries considered, which explains that the parameter β_{inc} in the reference study is lower than that found for Guayaquil. The diffusion in rural areas and in milder climates is lower than in warmer and urban areas, such as Guayaquil.

The root-mean-square deviation (RMSD) in the diffusion model for Guayaquil gives an roughly error of 2%. The model significance is tested by means of the F-statistic, and in both cases the Null Hypothesis is rejected. A more detailed ANOVA is presented in the Appendix F.

Table 5.1: Comparison between AC availability models

Source	N	β_{inc}	$\ln \gamma$	R^2	RMSD	F-Statistic
Current Model[(a)]	26	-1.70E-03	3.333	0.90	1.7%	220
McNeil et al. (2010)[(b)]	24	-8.28E-04	4.843	0.69	3.9%	49

[(a)]Model for Guayaquil
[(b)]Model for selected developing countries

Figure 5.3 presents the diffusion of ductless mini-split air conditioners in Guayaquil between 2000 and 2018, and its projection until 2030 for the two considered scenarios. Between 2000 and 2014 there was a continuous growth (on average 4% annually), and since 2014 the diffusion remains constant at 26%. This is due to the fact that household income has not increased since 2014 (see Figure 4.6).

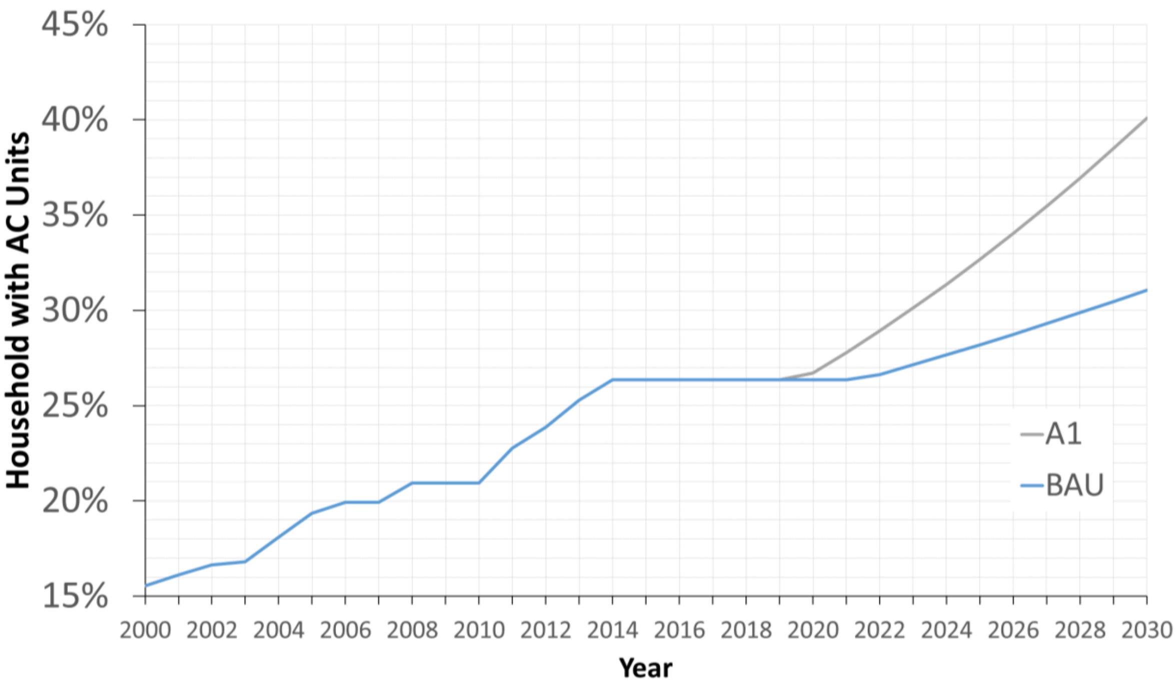


Figure 5.3: AC diffusion in Guayaquil for the base case (EER=3.2 W/W), and projections for the economic scenarios

5.3 Air conditioning demand and related CO_2 emissions

Figure 5.4 shows the estimated annual energy consumption of air conditioners in the residential sector, in Guayaquil. It can be seen that between 2000 and 2019 the consumption tripled. The same figure shows the projections for the considered scenarios, in the period 2019-2030.

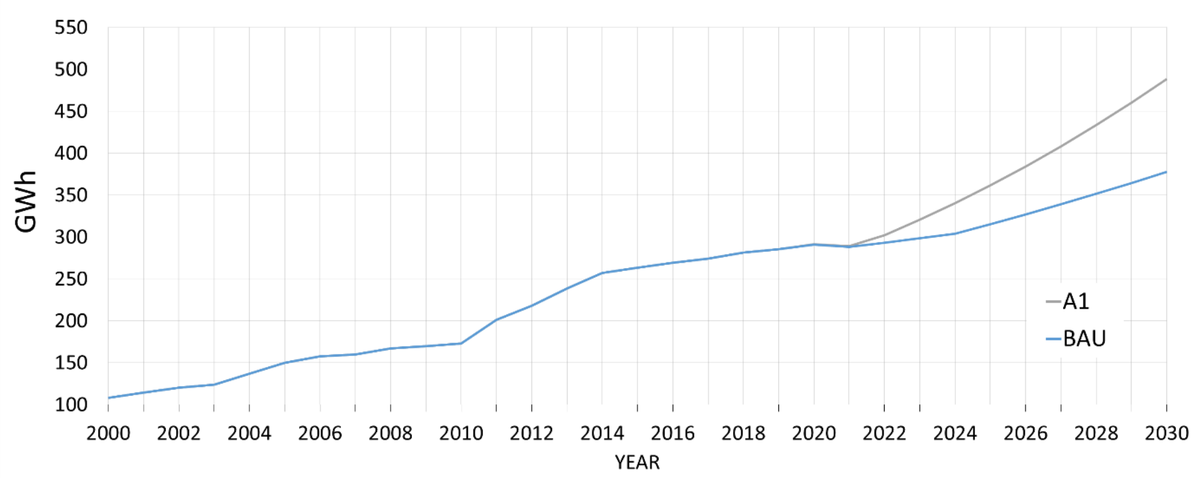


Figure 5.4: Estimated AC electricity consumption in Guayaquil, from 2000 to 2018, and forecasted demand until 2030 in two economic scenarios

Figure 5.5 presents the share of AC devices in total electricity demand of the residential sector. Between 2000 and 2018 there was frequent oscillation, despite the average growth tendency observed; the maximum value was close to 19% in 2013. The share could reach between 20 and 22% by 2030, accordingly to the considered scenario. Although demand for electricity in AC devices increases over most of the period, its share regarding the total consumption only increases from 2022 or 2024 onwards, depending on the economic scenario.

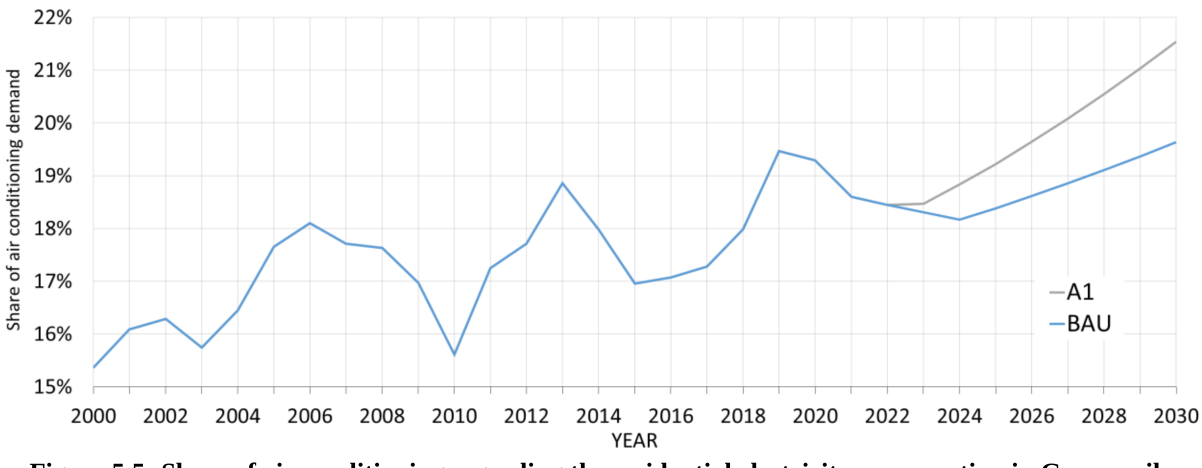
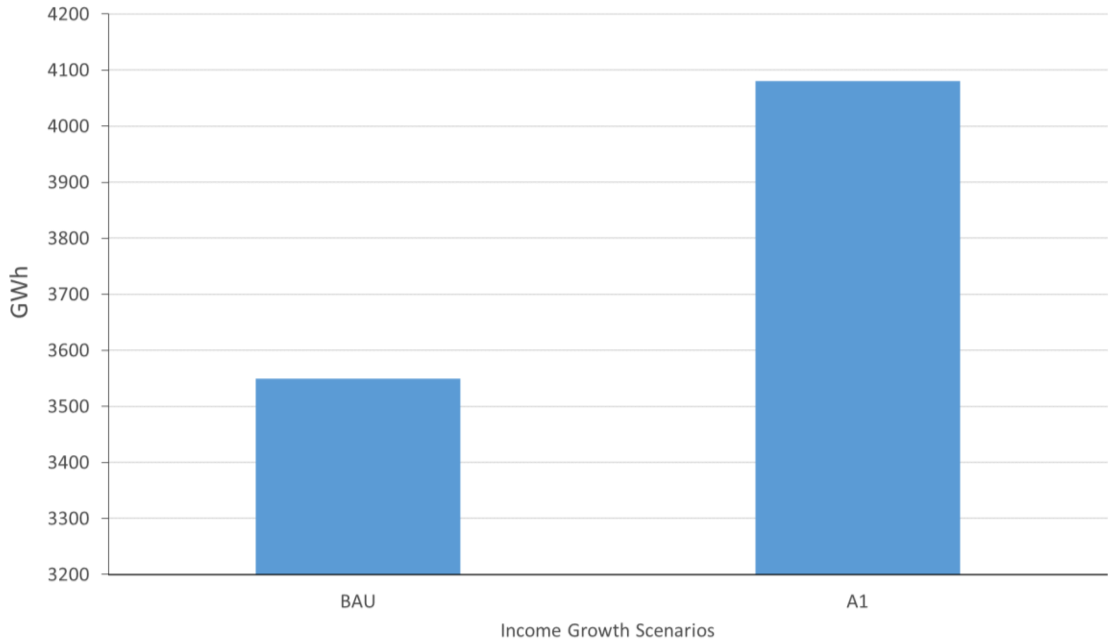
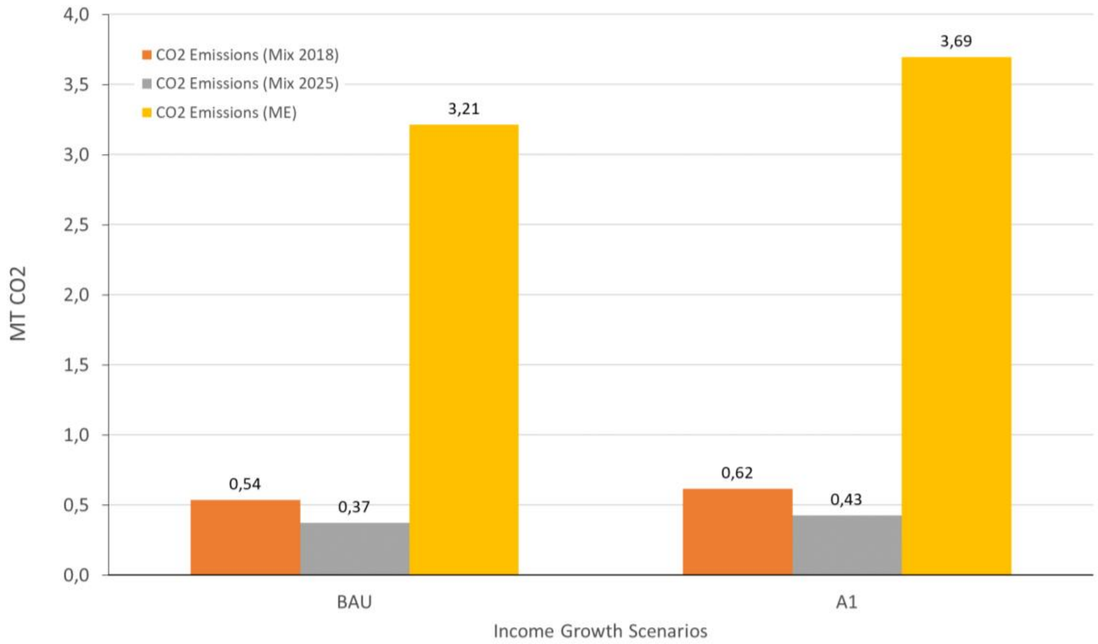


Figure 5.5: Share of air conditioning regarding the residential electricity consumption in Guayaquil; estimated tendency from 2000 to 2018 and forecasts from 2019 to 2030

Higher economic growth favors greater use of AC equipment and, therefore, more electricity-related GHG emissions. Figure 5.6 (a) shows the aggregate AC electricity consumption and Figure 5.6 (b) the related CO_2 emissions between 2020 and 2030 for both economic scenarios.



a) Aggregate AC electricity consumption in the 2020-2030 period



b) Aggregate CO_2eq emissions in the 2020-2030 period

Figure 5.6: Aggregate AC electricity consumption and related CO_2eq emissions in the 2020-2030 period, in Guayaquil, for both economic scenarios

The CO_2 emissions in Figure 5.6 (b) are presented for three assumptions of the electricity generation mix in the SNI. The worst case (yellow marks), in the less likely case, is the one in which all electricity consumed by AC devices would derive from marginal generation (EM), using only internal combustion engines. In orange, emissions are associated with the electricity generation mix in 2018 (Mix 2018), while black marks indicate results related to the expected generation mix for 2025 (Mix 2025).

The emission factor of marginal generation is high due to the use of fuel oil in internal combustion engines, contrary to the large share of hydroelectricity both in the 2018 and, mainly, in the 2025 generation mix. Marginal generation could be significant in the case of intense use of AC equipment at peak hours.

5.4 Estimates by income level

Figure 5.7 presents the average number of AC units per household in Guayaquil by income level, in 2003 and 2011. It can be seen that the ownership of higher income households is about seven times higher than households with mid income. On average, higher income households have more than one device and the ownership grew 32% from 2003 to 2011. Proportionally, ownership grew more – 120% - in mid income households in the same period, but it is clear that there are a large number of households without an AC system. For this reason, it is expected a significant growth as long as adequate conditions are given, and this aspect is important because the bulk of households are those of mid-income level (70% of the population) (see Figure 3.14). Also in Figure 5.7 it can be seen that the ownership of AC systems is very small (0.02 units/household) in low income level, and did not change significantly in the 2003-2011 period.

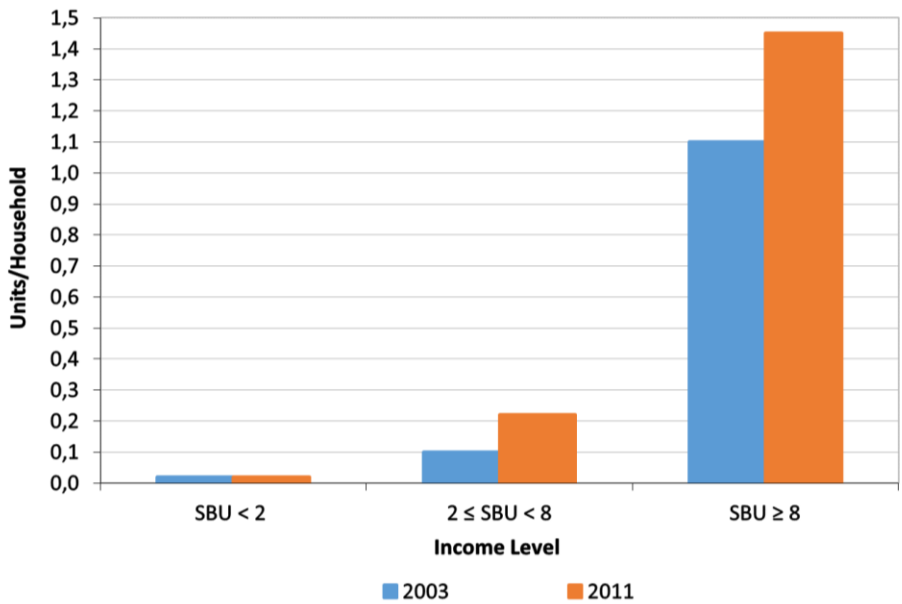


Figure 5.7: AC ownership in Guayaquil according to the income level, in 2003 and 2011

The income stratification shows that high-income households (≥ 8 SBU) represented 65% and 55% of the total electricity consumption due to residential AC in 2003 and 2011, respectively. Mid-income households (2 ≤ SBU < 8) represented 32% of the electricity consumption in 2003 and 46% in 2011. Low-income households did not represent even 2%. Figure 5.8 shows these results.

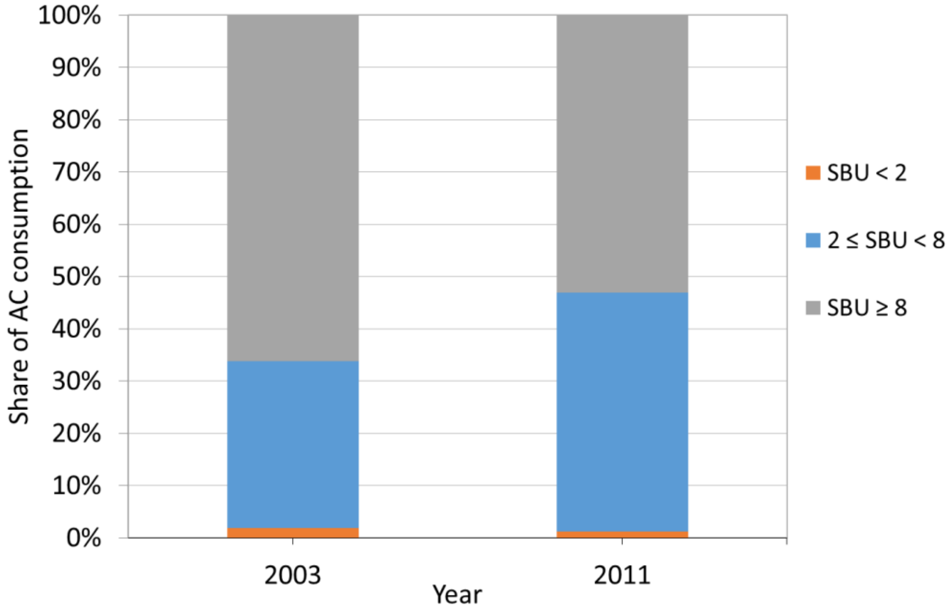


Figure 5.8: Share of AC electricity consumption by households' income levels in 2003 and 2011, in Guayaquil

The largest increase in electricity consumption due to AC was in middle-income households, with 57%, 23% in high-income households and 8% in low-income households.

Figure 5.9 shows the share of electricity consumption due to AC units in relation to total household electricity consumption. In low-income households, this share fell by 5% between 2003 and 2011.. This reduction was also observed in total electricity consumption (Figure 3.14), and it is possible that the differentiated tariff for consumers under 130 kWh / month (implemented since 2007) induced this result. In middle-income households, the increase in electricity consumption due to AC was 90%, also with an increase in their share of total consumption (but still less than 13% of total consumption).

For high-income households, the electricity consumption due to AC reached 50% and its increase was 17% in the period. As shown in Figure 5.7 and Figure 5.8, AC ownership in these households is above 1.4 units/household and their use is intensive.

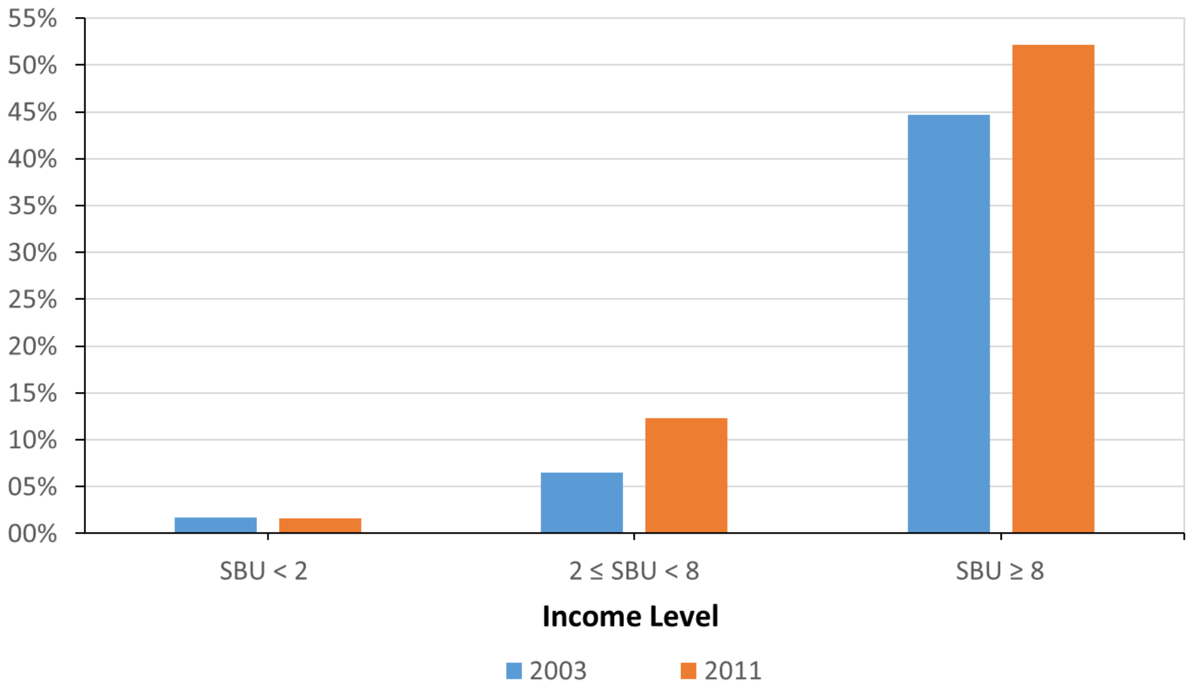


Figure 5.9: Share of AC devices in total electricity consumption by income levels, in two years

5.5 Comparison between AC energy indicators across different countries

This section is devoted to a comparison of current energy performance indicators of AC systems in Ecuador, Malaysia and Brazil. The aim was to check the estimates done in this dissertation regarding the consumption due to AC systems in the household sector in Guayaquil. Table 5.2 shows estimated cooling degree-days (CDD[19]) and the MEPS in these three countries. The AC MEPS program for Ecuador and Malaysia were established in 2013, and in the case of Brazil it was established in 2011 (Empresa de Pesquisa Energética - EPE, 2018; Fatihah Salleh et al., 2019). For the whole country, the CDD is lower for Brazil, due to its several climatic conditions associated with its continental dimensions, while it is similar between Malaysia and Guayaquil. On the other hand, MEPS is stricter in Ecuador.

Table 5.2: Annual CDD and MEPS of Guayaquil-Ecuador, Malaysia and Brazil

Country	CDD (Tb=17.03°C)	MEPS (W/W)
Guayaquil - Ecuador	3,125	3.2
Malaysia	3,227	2.8
Brazil	2,162	2.6

[19] In the literature, the annual CDD for Malaysia and Brazil were calculated from a typical meteorological year (TMY) and corrected with the heat index (HI); the base temperature (Tb) was 17.03°C (Atalla, Gualdi, & Lanza, 2018; Atallah, Gualdi, & Lanza, 2015). The base temperature for Guayaquil was changed from 18.3°C to 17.3°C in order to perform the comparison with the other countries.

Figure 5.10 shows a comparison for the estimated AC electricity consumption in the residential sector. The electricity consumption per household was normalized using the estimated CDD in order to make feasible the comparison (IEA, 2014b). As can be seen, the energy indicator for AC systems obtained from the estimated demand is similar to that of countries with similar climates and economic realities.

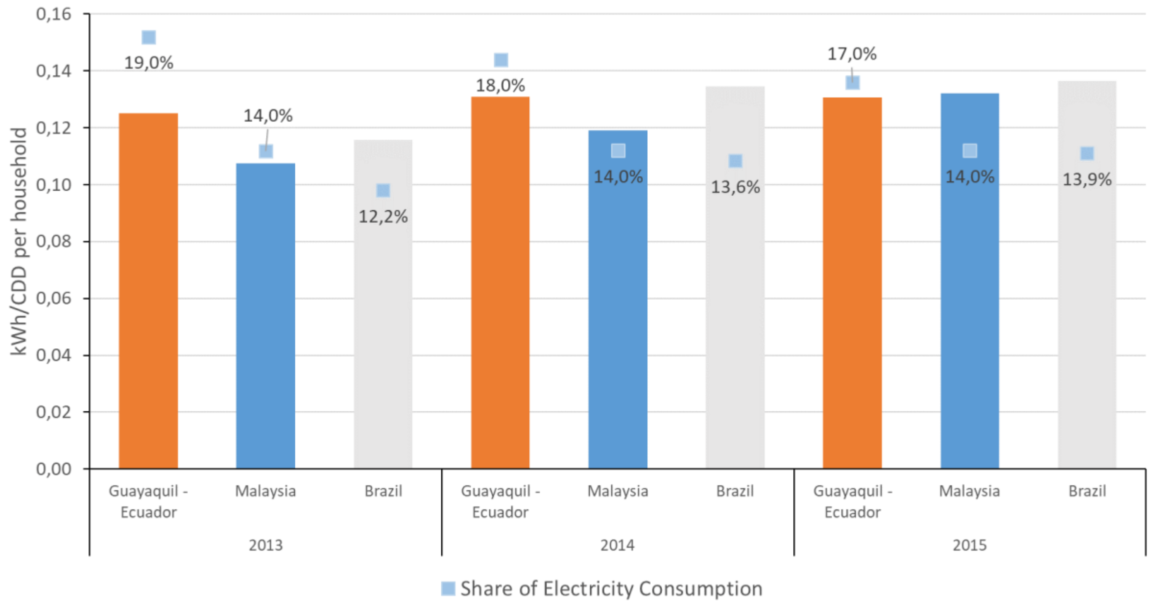


Figure 5.10: Share of electricity consumption in households due to AC, and estimated energy indicator in Guayaquil, Malaysia and Brazil, from 2013 to 2015

This energy indicator provides an insight of the trends in AC energy consumption, but the preferred one by IEA as a proxy of energy efficiency is AC energy consumption per floor area cooled, since that only a fraction of dwellings in most countries have air conditioning, and sometimes only a fraction of the total floor area in the dwelling is cooled (IEA, 2014b).

5.6 MEPS assessment

As previously mentioned, here the results of the assessment only consider the standpoint of the consumer and society (or public entities). The point of view of manufacturers, importers and other private stakeholders would also be important, since the regulation on energy efficiency can impact manufacturing costs and the equipment market.

Taking into account the aspirations of the private sector during the adoption of new MEPS improves the analysis and helps to reduce the uncertainties of decision makers (Costa et al., 2019). Some manufacturers are opposed to government regulations because they understand that there is unwarranted interference or that inefficiency is imposed on markets, but most manufacturers have a positive attitude if the standards are found to be fair. In this sense, they must be technologically achievable and must preserve competition between manufacturers. Also, the new regulations must be applied uniformly, without favor, and the implementation schedule should allow manufacturers to have enough time to adapt (usually 3 to 5 years) (Wiel & McMahon, 2005).

The assessment of impacts on private sectors[20] is beyond the scope of this work, given data and resources constraints. A simplified application of the PAMS-MEPS methodology was made, based on, based on (Mcneil, Letschert, & Buskirk, 2007; Mcneil, Letschert, & Van Buskirk, 2007) and applied by (MINEN, 2017). With adequate information, the complete impact assessment of stricter MEPS would be possible, and this is one of the aims of the author of this dissertation.

5.6.1 Consumer perspective

A stricter standard implies more efficient equipment, which are usually more expensive. Thus, analyzing willingness to pay is important in the definition of public policies, as high acceptance is a necessary condition. An initial step is to establish tradeoffs between purchase price and energy savings of new equipment. Figure 5.11 shows the tradeoffs from the consumer's perspective, with percentages determined relative to the base case (EER=3.2 W/W) and having 2019 as base year.

[20] Ecuador does not have AC industries. However, assessing impacts on importers, sellers, and other private stakeholders may be important considering the goal of implementing a successful MEPS program (Wiel & McMahon, 2005).

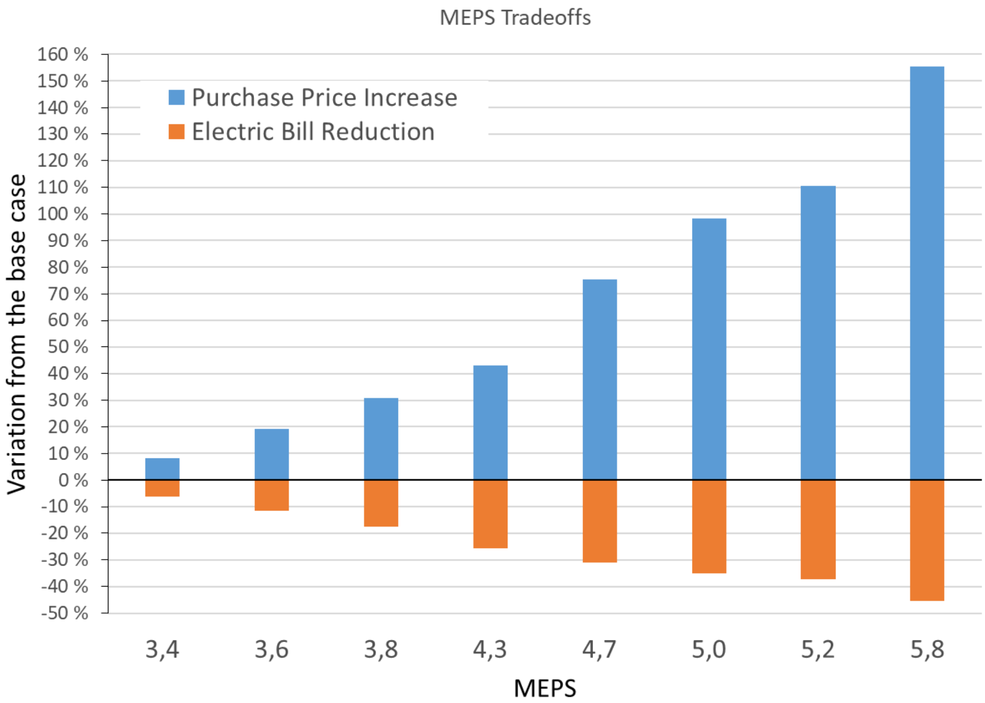


Figure 5.11: Tradeoffs of setting higher MEPS from the consumer's perspective - Guayaquil

Life Cycle Costs

Table 5.3 presents the results of Life-Cycle Cost (LCC) and payback time, from the point of view of the consumer., As can be seen, the LCC varies with the impoased level of energy efficiency, and has its minimum for MEPS 4.3 W/W.

The MEPS 4.3 W/W has the highest Life-Cycle Cost Savings (LCCS), turning to negative with higher MEPS once the savings due to the lower electricity consumption do not overcome the higher upfront cost of more expensive devices. As can be seen in Table 5.3, as LCCS are low, in principle the consumer would not be encouraged to make an investment to change its air conditioning equipment. The payback time rises with MEPS and is never below 4.5 years.

Economic results are impacted by two factors. First, due to the low price of electricity in Ecuador (10.09 USD ¢/kWh)[21] and, secondly, due to the use of EER to express energy efficiency, when it would be more appropriate to use SEER. Using the EER does not adequately reflect increased energy efficiency, especially for options above 3.6 W / W with inverter technology (see Table D3 in the appendix).

[21] Roughly 30% below the average worldwide, which is 13.33 USD ¢/kWh.

Table 5.3: Life cycle cost (LCC) results

MEPS	Purchase Price (USD)	UEC (kWh/Year)	Annual Electric Bill (USD)	LCC (USD)	Efficiency Improvement	Payback Time (years)	LCCS (USD)
3.2	390	1,176	119	1,284			
3.4	423	1104	111	1262	6.5%	4.5	22
3.6	465	1041	105	1256	13.0%	5.5	28
3.8	510	971	98	1,248	21.1%	5.8	36
4.3	558	876	88	1,223	34.3%	5.5	60
4.7	684	812	82	1,302	44.7%	8.0	-18
5.0	773	761	77	1,352	54.4%	9.2	-68
5.2	821	736	74	1,381	59.7%	9.7	-97
5.8	996	641	65	1,483	83.4%	11.2	-199

Note 1: Calculations of Life-cycle cost and payback period use an electricity price without subsides (10.09 USD ¢/kWh) (ARCONEL, 2019; CNEL, 2018). Life-cycle cost is for 8%/year a lifetime of 12 years.
Note 2: An electricity price of 13.33 USD ¢/kWh reduce the payback time by 24.3%.

The LCC results presented in Table 5.3 are compared with the counterpart results in which the electricity price would be equal to that of the world average. Results of this comparison are presented in Figure 5.12. For all MEPS cases considered there would be an increase of the LCC - 17% on average. With higher electricity prices LCCS would also increase; for example, in the MEPS 4.3 W/W case, the rise would be 120%. It is expected that in the analyzed period the price of electricity in Guayaquil would not achieve the world average.

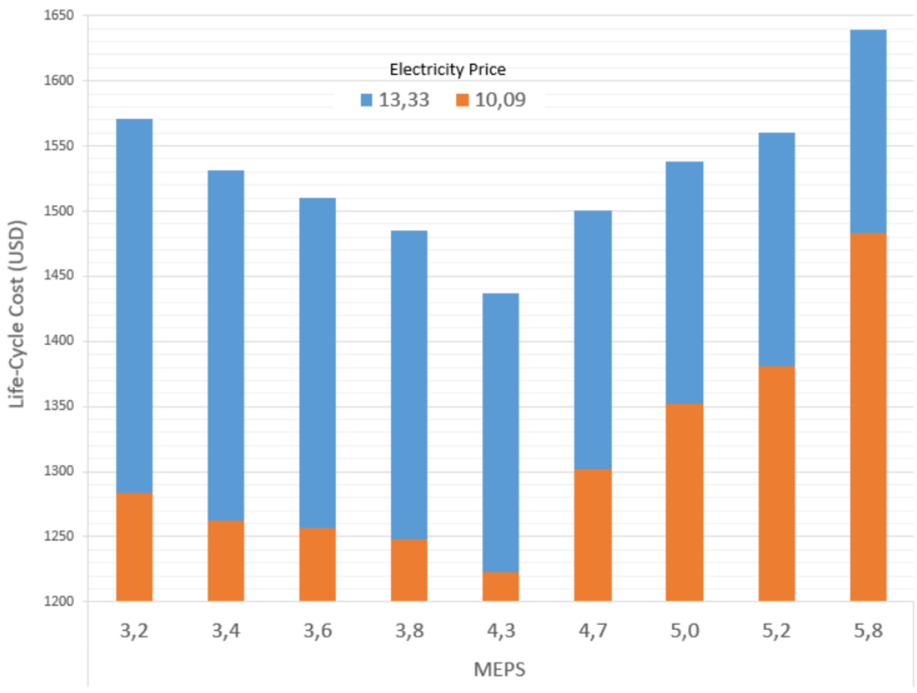


Figure 5.12: Results of the life cycle cost (LCC) for two different electricity prices in Guayaquil

Figure 5.13 shows results of a sensitivity analysis. Three efficiency standards were considered, besides two levels of electricity prices anddiscount rates. The reference are the results presented in Table 5.3. The three selected standards levels are the base case (3.2 W/W), the standard case (3.4 W/W) that represents the immediate superior and the standard case (4.3 W/W) which has the lowest LCC. The LCC decreases with the discount rates and with higher electricity prices. For the same conditions, 4.3 W/W always has the best resuls.

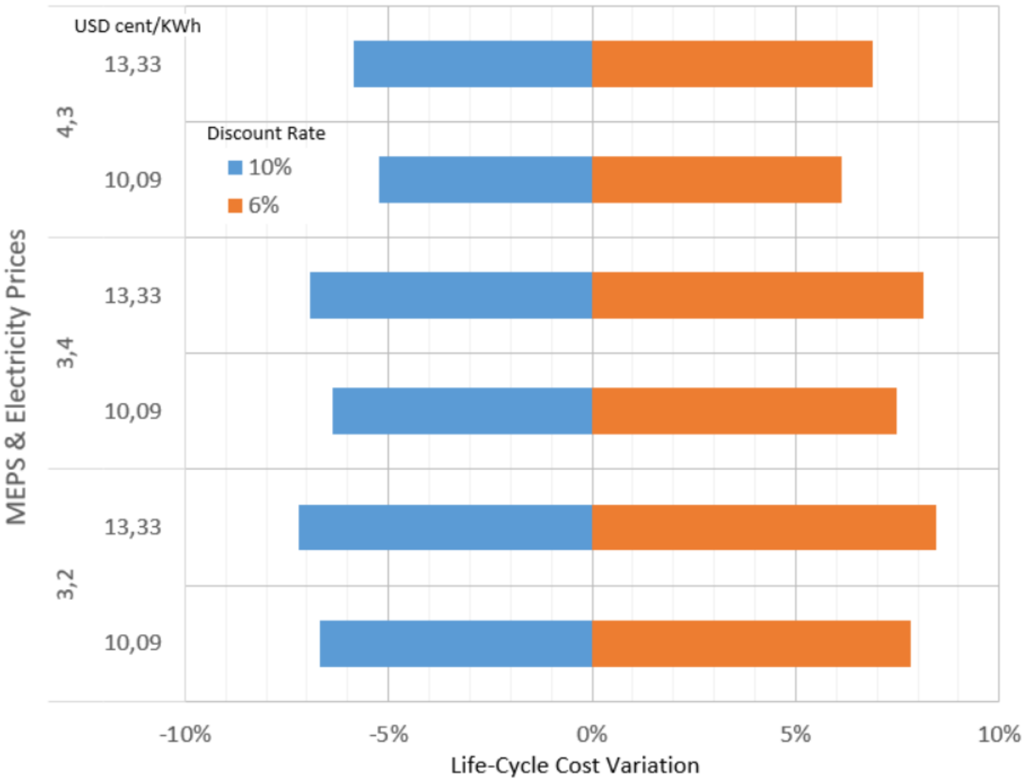


Figure 5.13: LCC sensitivity analysis for different standard levels, electricity prices and discount rates

5.6.2 Society perspective

Electricity Savings

Figure 5.14 presents the aggregate electricity savings (ES) between 2020 and 2030 for all MEPS, taking into account the two economic scenarios (Figure 5.6 presents the total AC electricy demand in absolute terms).

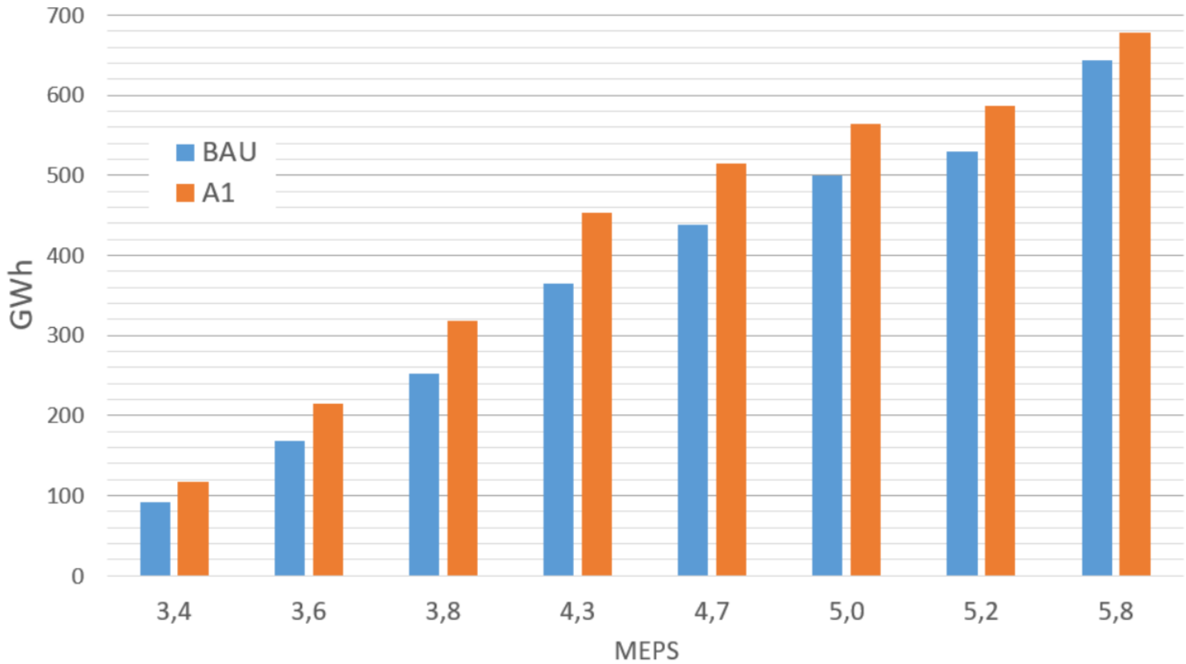


Figure 5.14: Aggregate electricity savings until 2030 for all MEPS, for BAU and A1 scenarios

Net Present Values and Electricity Cost Savings

Tradeoffs are similar than in the previous case. The net present value (NPV) indicates the cost-benefit of the analysed alternativas. Figure 5.16 show the NPV (in orange) for each MEPS in BAU and A1 scenarios, respectively. In both figures the blue bars represent the electricity costs savings (ECS); the difference between NPV and ECS is the increment in equipment costs. Both figures illustrate aggregate values between 2020 and 2030.

For both economic scenarios, the maximum NPV is at the 4.3 W/W standard, like LCCS from a consumer perspective. Negative NPVs correspond to the situation in which the increment in equipment costs overcome the electricity cost savings, and this is the case for all MEPS above 4.3 W/W. Higher economic growth enables wider diffusion of AC equipment and therefore greater electricity savings, but also an increase in equipment cost, and this explains the more pronounced negative result, for example MEPS 4.7 W/W in Figure 5.16.

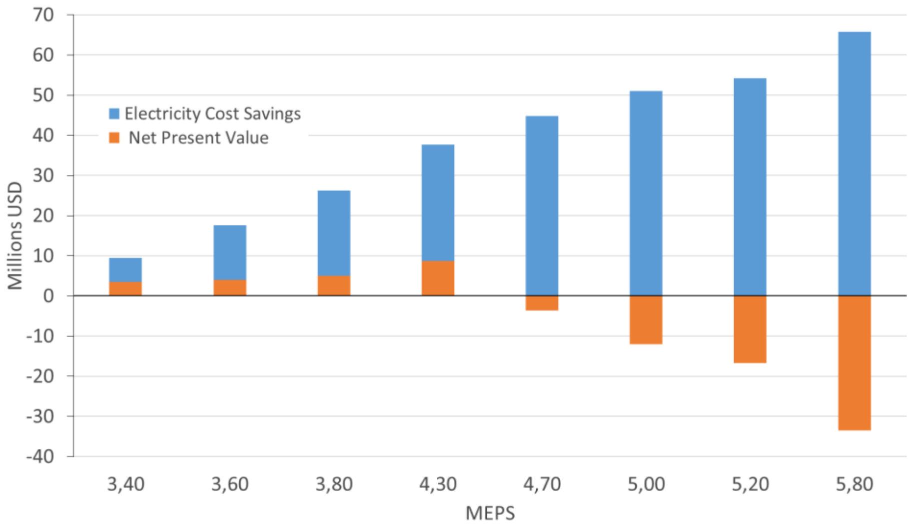


Figure 5.15: Tradeoffs of stricter MEPS for the residential sector in Guayaquil - BAU scenario

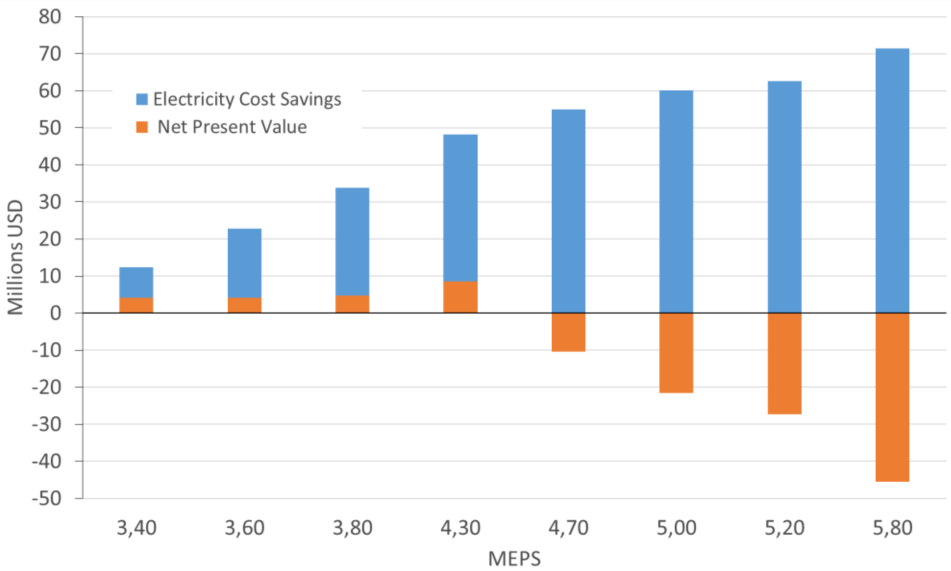


Figure 5.16: Tradeoffs of stricter MEPS for the residential sector in Guayaquil - A1 scenario

Emission mitigation

Figure 5.17, Figure 5.18 and Figure 5.19 present the aggregate CO_2 emissions mitigation (CEM) between 2020 and 2030 for all MEPS studied and for both economic scenarios. Each figure corresponds to the results for a given matrix of electricity generation. The case of generating all electricity consumed by AC equipment with fuel-oil, in internal combustion engines, is an unlikely scenario (Figure 5.6 presents the total CO_2eq emissions related to residential AC).

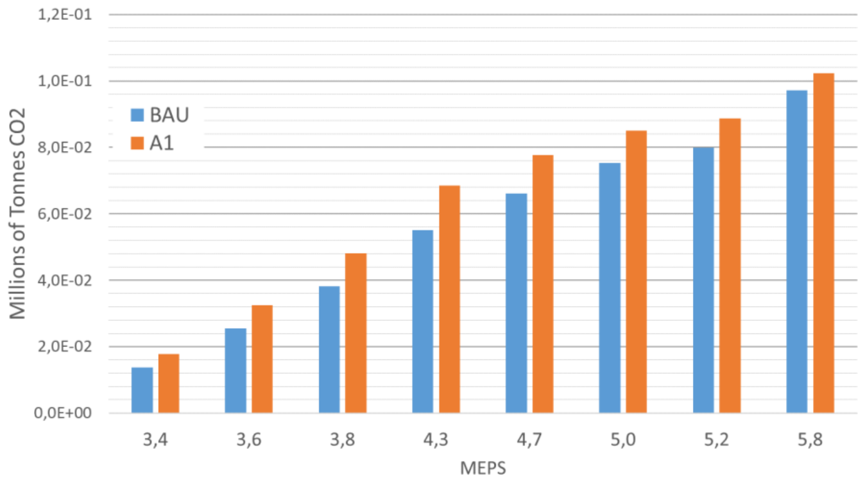


Figure 5.17: Total mitigated CO_2 emissions until 2030 for all MEPS - BAU and A1 scenarios. Electricity generation mix 2018

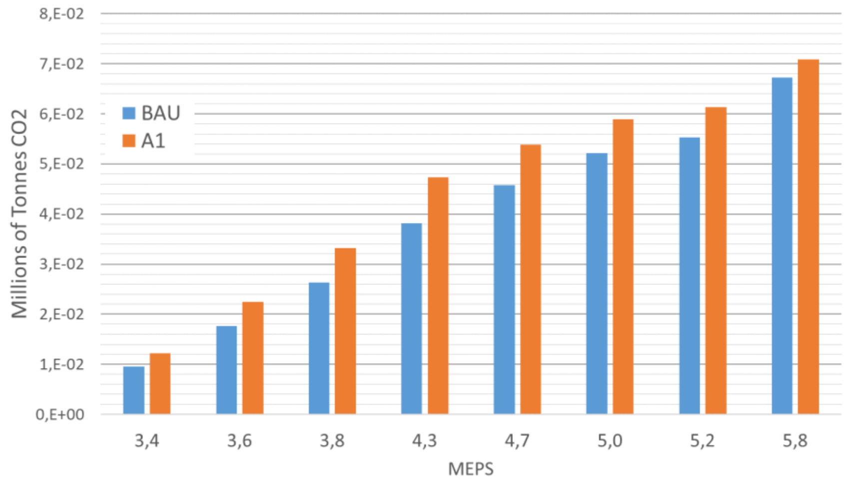


Figure 5.18: Total mitigated CO_2 emissions until 2030 for all MEPS - BAU and A1 scenarios. Electricity generation mix 2025

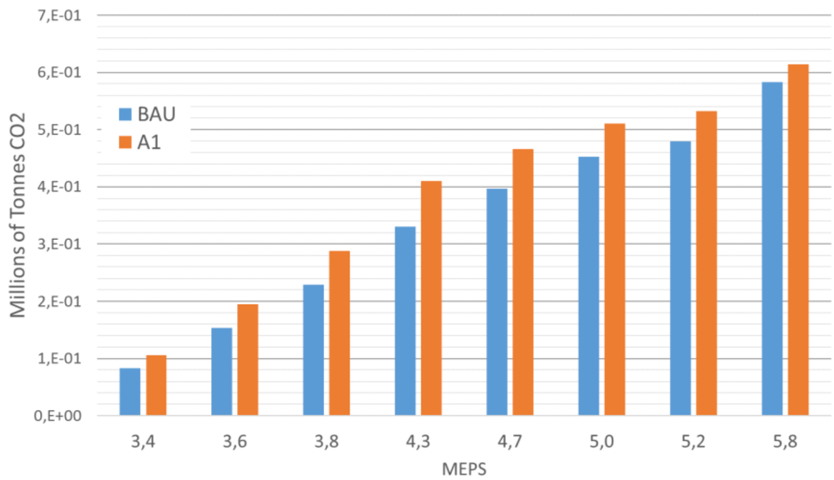


Figure 5.19: Total mitigated CO_2 emissions until 2030 for all MEPS - BAU and A1 scenarios. Marginal electricity generation in 2018

The CO_2eq emissions in 2018, due to the use of fossil fuels in electricity generation for Guayaquil-Ecuador were estimated at 0.73 MtCO_2eq, being the share of residential sector 32% (ARCONEL, 2019) and the share of AC energy demand 6%. Thus, avoided emissions due to the adoption of more stringent MEPS would be small but not negligible within the residential sector.

5.6.3 Best Rated MEPS

From the eight standards considered, two were selected for further analysis. The 3.4 W/W standard has the shortest payback and the impact on AC diffusion is smaller due to the slight increase in purchase price over the base case. On the other hand, the 4.3 W/W standard has the smallest LCC and the largest NPV. Figure 5.20 shows the aggregate electricity savings by 2030 as a percentage for both cases. Electricity savings and emissions mitigation results are similar.

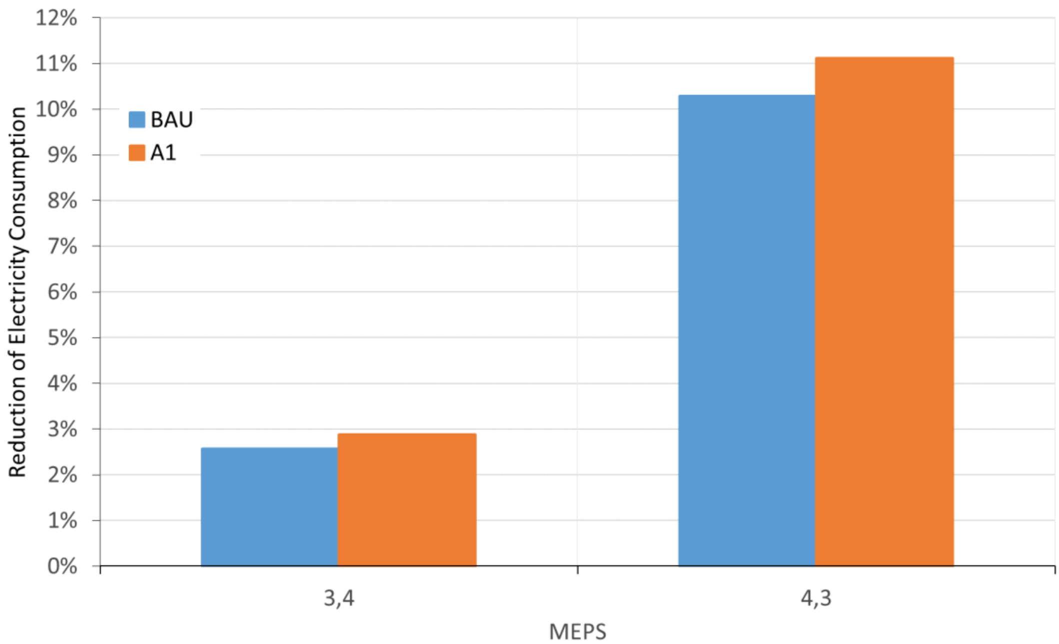


Figure 5.20: Aggregate reduction of electricity consumption between 2020 and 2030 for best-rated standards, for BAU and A1 scenarios

Impact on AC diffusion in middle-income households

Figure 5.21 shows the estimated reduction in AC diffusion in middle-income households if MEPS 3.4 W/W is adopted. For such households, the reduction in equipment diffusion may reach 1.1%, while for households with lower income (in the same household group) it could reach up to 1.6%. Figure 5.22 shows similar results for MEPS 4.3 W/W. In households with lower income (in the same group), it is estimated that this reduction could reach up to 8.1% over the base case (5.4% is the average result).

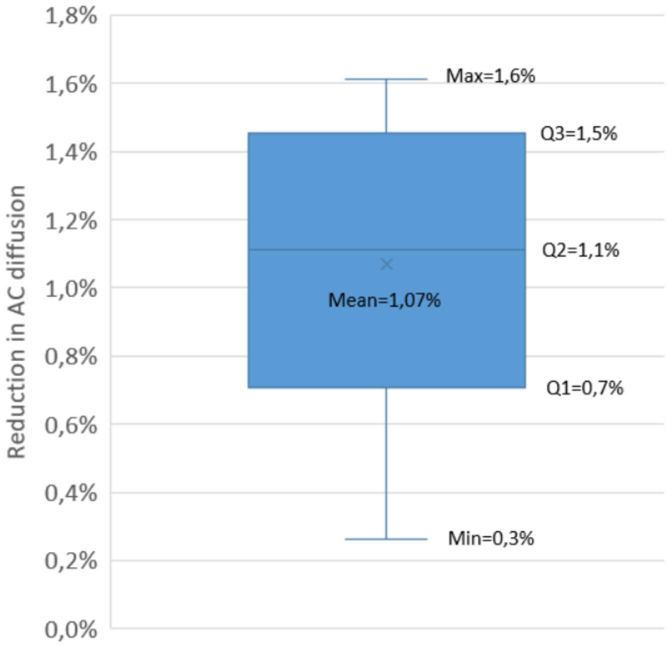


Figure 5.21: Reduction in AC diffusion, MEPS 3.4 W/W

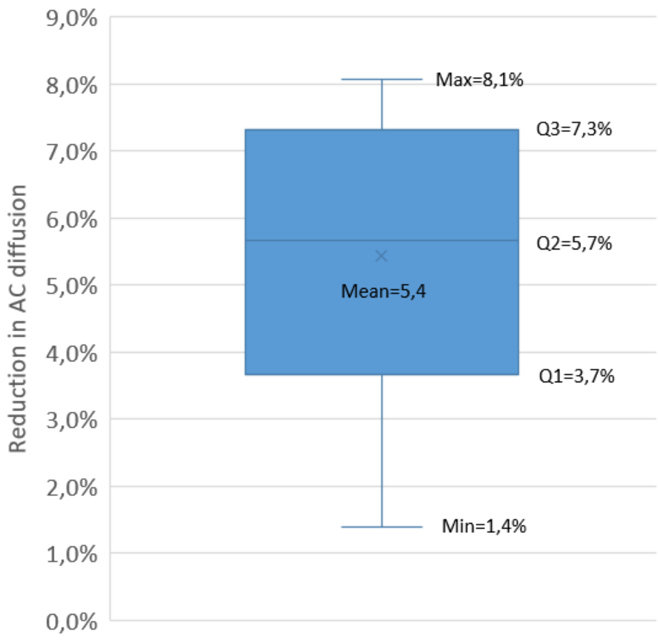


Figure 5.22: Reduction in AC diffusion, MEPS 4.3 W/W

Decomposition of energy demand

Here, the Index Decomposition Analysis (IDA) indicates the impacts of different MEPS on drivers of air conditioning use and electricity consumption, according to the economic growth scenario. Table 5.4 and Table 5.5 show the components for IDA for the base case (MEPS 3.2 W/W) in the BAU and A1 scenarios, respectively, in 2020 and 2030. Figure 5.23 and Figure 5.24 show the decomposition of annual AC electricity demand in its drivers; the impacts of stricter MEPS in the BAU and A1 scenarios are illustrated in both figures.

As previously mentioned, by hypothesis the number of households does not vary according to the economic scenario. The effect of the structure is represented by the AC diffusion. The effect of energy intensity is represented by the unit energy consumption (UEC), which increases as household income increases. In the BAU scenario the energy intensity in 2030 is lower than in 2020, as a consequence of improved energy efficiency over time. In scenario A1, the income growth overcomes the effect of improved energy efficiency.

Table 5.4: Values of AC drivers and AC electricity demand in the BAU scenario – base case

Year	Activity (Households)	Structure (% of households with AC)	Energy Intensity (kWh/year)	AC Demand (GWh/year)
2030	828,311	29.6%	1,540.7	378
2020	715,107	26.4%	1,541.7	291

Table 5.5: Values of AC drivers and AC electricity demand in the A1 scenario – base case

Year	Activity (Households)	Structure (% of households with AC)	Energy Intensity (kWh/year)	AC Demand (GWh/year)
2030	828,311	35.2%	1,578.2	489
2020	715,107	26.4%	1,544.6	291

The improved energy efficiency induced by more stringent MEPS, leads to the reduction of the AC energy intensity; Figure 5.23 and Figure 5.24 illustrate this impact as negative values. On the other hand, there is an impact on AC diffusion, which decreases as consequence of higher equipment prices, and this causes an additional reduction in electricity consumption, on average this impact represents 28% of the total reduction.

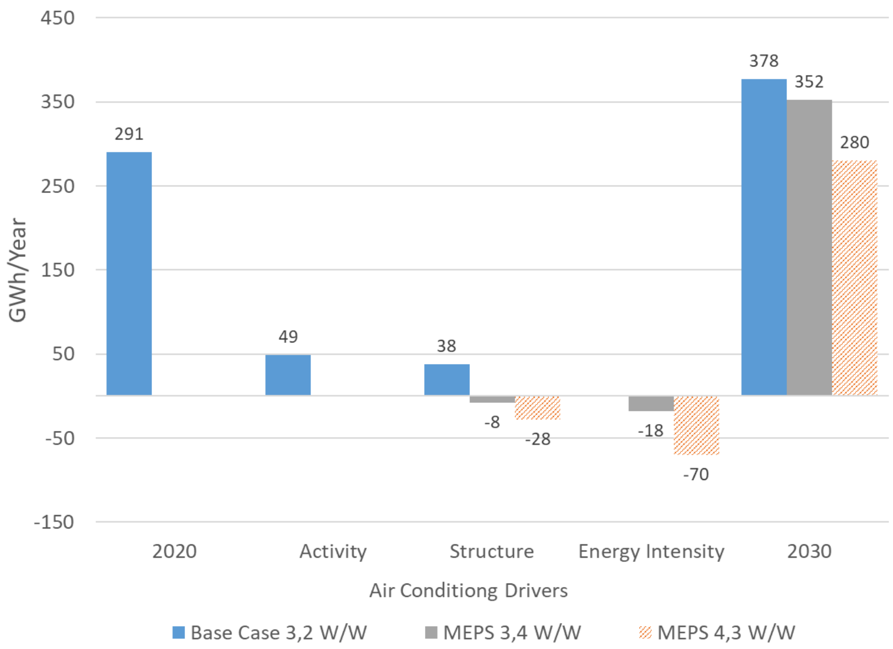


Figure 5.23: Impact of air conditioning drivers in total AC electricity demand for the base case (EER = 3.2 W/W) and the standard cases (EER = 3.4 W/W and 4. 3W/W) - BAU scenario

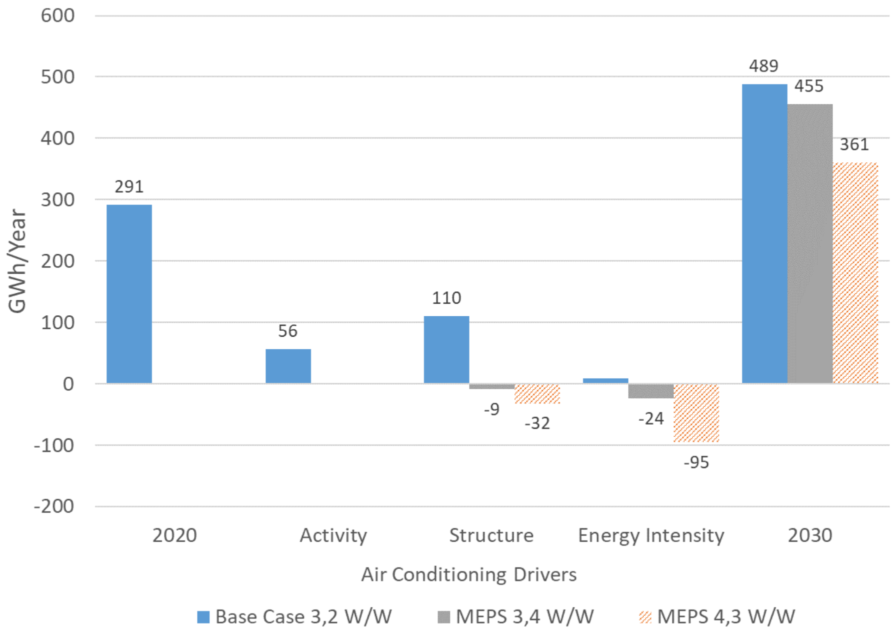


Figure 5.24 : Impact of air conditioning drivers in total AC electricity demand for the base case (EER = 3.2 W/W) and the standard cases (EER = 3.4 W/W and 4.3W/W) - A1 scenario

6 CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

6.1 Conclusions

The electricity consumption in Guayaquil is impacted by its weather conditions, as indicates the positive linear correlation between the electricity consumption and mean apparent temperature; this is related with electricity consumption by space cooling appliances. Based on a bottom-up model, it has been estimated that annual electricity consumption due to AC equipment increased by 164% over the 2000-2019 period. It has also been estimated that it currently represents 19.5% (285 GWh) of Guayaquil's annual residential electricity consumption and could reach between 378 GWh and 489 GWh by 2030, depending on the scenario of economic growth.

Associated with this electricity consumption there are greenhouse gas emissions, which value depends on the emission factor (kg CO_2eq/kWh) of the national interconnected system (SNI). This factor is low in Ecuador as electricity generation is mainly based on renewable energy sources (essentially hydroelectricity) (approximately 83.5% in 2018) and its share is expected to even grow in the following years (to 88.9% by 2025). However, carbon emissions due to the use of AC devices could increase considerably since their operation can occur significantly at peak hours. Ecuador's marginal electricity generation is based on fuel oil, which is used in internal combustion engines.

High-income households are those with the highest electricity consumption due to AC, although they represent only 8 to 10% of households in Guayaquil. On the other hand, the greatest potential for growth in electricity demand is in middle-income households, since they represent almost 70% of households and their AC ownership is ten times smaller than that of high-income households. Between 2003 and 2011, AC ownership in middle-income households doubled from 0.1 units to nearly 0.2 units per household, with an estimated increase in AC consumption from 40 GWh to 92 GWh per year, i.e. a significant growth of 130% in just eight years.

The PAMS-MEPS tool was used to assess the impacts both from the perspective of an individual consumer as well as from the whole society. From the consumer's point of view, the maximum life cycle cost savings (LCCS) would be achieved with MEPS 4.3W/W, but given the low price of electricity in Guayaquil-Ecuador compared to the world average (for the residential sector) and the cost of equipment with higher energy efficiency, the payback time for more efficient equipment is high (about five years) and life cycle cost saving is low (60 USD). Therefore, consumers would hardly have the incentive to switch their air conditioning equipment to more efficient options, unless there are additional policies to cover the additional upfront cost.

Also from a societal perspective, the best option is MEPS 4.3 W/W. For this standard level, the net present value (NPV) would be maximum and the cumulative electricity savings compared to the base case (3.2 W/W) would be between 10% and 11% until 2030 (365 and 453 GWh), respectively in the BAU and A1 scenarios. On the other hand, with MEPS 4.3 W/W, the accumulated mitigation of greenhouse gas emissions would be between 0.04 Mt and 0.4 Mt CO_2eq, depending on the economic scenario and the electricity generation mix. On average, this would represent a 10.7% reduction in emissions related to AC electricity consumption.

Defining stricter MEPS would affect AC diffusion due to equipment purchase costs. With MEPS 4.3 W/W, the diffusion of AC in middle-income families would be impacted by 1.4%-8.1% in comparison to the base case (3.2 W/W). As function of the lower equipment price, a less ambitious MEPS would imply a smaller impact, estimated between 0.3% and 1.6% for the 3.4 W/W standard.

The adoption of the MEPS 4.3 W/W would have a significant impact on the driving factors of AC demand especially in the structural and energy intensity factors. However, the main contribution for the reduction of the electricity consumption would come from the decrease in AC energy intensity (70%). The reduction in electricity consumption due to less equipment diffusion is not considered savings.

The assessment presented in this dissertation shows that, for the current economic conditions and prices in Guayaquil - Ecuador, setting the MEPS at 4.3 W/W could, from a societal point of view, contribute to a substantial reduction in electricity consumption and also to reductions of energy-related emissions, but it would be a too ambitious target from the consumer's perspective. Also for the same conditions considered, MEPS above 4.3 W/W would not be justifiable both from the standpoint of individual consumers and of the society as a whole.

6.2 Recommendations

An important consideration is that Guayaquil is the case study for the assessment presented here. However, MEPS would be defined nationwide and, in Ecuador, average climate conditions are less severe (i.e. lower use of AC) and household income are lower. Thus, stricter MEPS would be less justifiable. For this reason, it is important to know the impact of the adoption of stricter MEPS taking into account other important consumer markets. The definition of regulatory standards requires studies that allow the assessment of impacts in all social segments, and, in the case of AC systems in Ecuador, regional differences make additional studies even more important. .

There are no deadlines for reviewing the decisions in the S&L program in Ecuador. Nevertheless, as household income increases, regular reviews are necessary in order to take advantage of the benefits of energy efficiency standards.. In the case of Brazil, there was already three revisions of the standard (2007, 2011 and 2018) since the S&L program was established in 2006 (Empresa de Pesquisa Energética - EPE, 2018).

Although Ecuador's Standards and Labeling (S&L) program began in 2013, information on the energy efficiency of the stock of AC equipment is not yet available. This information is necessary to reduce the uncertainties of adopting stricter MEPS because a better baseline would be found. Another action to reduce uncertainties is to conduct a market study of commercially available technology options. Information could be obtained more easily if all stakeholders are represented in the process.

In Ecuadorian regulations, the EER metric used for AC units does not adequately reflect increased energy efficiency, particularly for equipment with inverter technology. In this sense, it would be better to use the seasonal energy efficiency index (SEER). Currently, some countries have introduced the seasonal cooling performance factor (CSPF) to estimate actual operating conditions and technological changes; the methodology is described in the international standard ISO 16538.

6.3 Future Work

The methodology presented in this dissertation can be applied to estimate impacts at the national level. In this sense, a complete regulatory impact study is a suggested topic for future work. To generalize the results at national level, a distinction must be made between the climatic regions of the country since the impact will vary from region to region. Another aspect to take into account is variations in household income, affecting the impact of new MEPS in the diffusion of AC equipment.

Another suggestion for future work is to evaluate the impacts of new MEPS on peak load, especially in terms of avoided emissions and avoided expansion of generating capacity. These potential benefits may more adequately indicate the rationality of adopting stricter standards.

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APPENDIX

APPENDIX A – Impacts of space cooling

Impact on health and wellness

Thermal comfort and human health are related with ambient temperature and relative humidity, since these affect the thermoregulatory capacity of the human body and, under specific threshold conditions, it can be lethal. Several authors show how temperature and humidity are combined through heat indexes to obtain thresholds (Brooke Anderson et al., 2013; Rothfusz, 1990; Willett & Sherwood, 2012).

Nowadays episodes of deaths related to heat waves (i.e. temperature and humidity near to deadly threshold) are well documented especially in developed countries, but there is little information about deaths in developing countries (Guo et al., 2018). The statistics by the World Health Organization (WHO) shows that heat waves already produces 12,000 deaths annually worldwide, and estimate that, by 2050, deaths could reach 255,000 annually (WHO, 2014).

In 2000, approximately 30% of world population was exposed to 20 or more days of risky climatic conditions to vulnerable groups (SEforALL, 2018) and, considering a climate change scenario, by 2100 this percentage would be 48% (Mora et al., 2017). A study developed in 2018 shows how in Brazil children, elderly people, and patients admitted for endocrine, nutritional, and metabolic diseases were most susceptible to heat exposure (Q. Zhao et al., 2019).

Heat extremes can also cause economic losses as maximums temperature limit outdoor activity and labor productivity. For tropical climates in Latin America, it is estimated that there will be a 2% work-hour losses by country associated with excessive heat in a climate change scenario by 2050 (Mora et al., 2017).

The WHO recommends developing adaptation plans, called heat action plans, where the use and accessibility to air conditioning is a fundamental part for protecting the health and well-being of population, especially in cities were the UHI effect exacerbates the impacts of heat (Baeker & Stutzinger-schwarz, 2017; PAHO, 2019).

Impact on the electrical infrastructure

The use of energy in space cooling equipment is growing fast in buildings, and since 1990 this consumption has tripled, reaching 2020 TWh in 2016 (99% as electricity and 1% as fossils fuels, mainly natural gas used in chillers) (IEA, 2018a). It is estimated that in 2016 the electricity consumption associated with space cooling was on average 10% of the total electricity consumption, and that this consumption represented about 13% of the growth in electricity demand between 1990 and 2016. In terms of total electricity consumption in buildings, electricity consumption of space cooling equipment went from 13% to 18.5% (2000 TWh) in the same period, which represents a 22% increase in electricity use in buildings.

The report prepared by the IEA in 2018, "Future of Cooling: Opportunities for energy efficient air conditioning", presents the global perspectives until 2050 for cooling energy demand through the adoption of two scenarios (IEA, 2018b). The Baseline Scenario reflects a departure from the business-as-usual trend, since it takes into account political actions currently implemented and those announced to curb the energy consumption and protect the climate. It also considers a 25% increase in CDD global average associated with global warming. In this scenario, space cooling demand triples between 2016 and 2050, and reaches 6,200 TWh (about 70% of the increase corresponds to residential sector, due to the fact that commercial and services sectors already have air conditioning systems, and also due to the potential growth of residential AC ownership). The share of space cooling over total electricity use in buildings jumps from 18.5% in 2016 to 30% by 2050, and from 10% to 16% of total global electricity consumption in the same period.

The alternative Efficient Cooling Scenario considers a wide adoption and the strengthening of energy efficiency policies (such as setting minimum energy efficiency standards, or MEPS, and construction codes related with energy performance in buildings), a deeper decarbonization of electricity generation matrix, and a 20% increase in CDD due to global warming. In this scenario, there would be a 45% reduction in energy consumption compared to the baseline scenario i.e. savings of about 2,800 TWh. Worldwide, the need of additional generating capacity between 2016 and 2050 just to meet the demand from AC was estimated at 1,170 GW in the Efficient Cooling Scenario, compared with 2,500 GW in the Baseline Scenario.

Space cooling can account for a large share of peak demand, placing further stress on power generation and distribution capacity, especially during periods of extreme heat. In tropical countries, where potentially there is demand for cooling throughout the entire year, the share of air conditioning in peak load can be as high as 50%, or even more (IEA, 2018c). Improvements in energy efficiency in the stock of air conditioning equipment allow significant reduction in peak load. Shah et al (2015) showed that a 30% increase in stock's EER would lead to a reduction between 340 and 793 GW (of avoided power generation capacity) in the peak demand by 2030, and between 544 and 1270 GW by 2050 (Shah, Wei, Letschert, & Phadke, 2015). This would avoid the construction of new peak power plants (e.g. between 676 and 2540 new plants of 500 MW).

At the end of the day, the costs of building, maintaining and operating electricity capacity to meet peak demand are transferred to the electricity tariff and normally represents a large portion of the total cost of supplying electricity at peak. In general, peaking capacity typically has a relatively low cost of construction per kilowatt of capacity, but high costs of operation. In many countries, diesel generators or single-turbine gas-fired plants are the main devices to meet peak capacity. Other options, such as pumped storage hydroelectricity and batteries, can have lower operating costs but they typically have much higher capital costs. Demand management can lower peak demand in a cost-effective way (IEA, 2018b).

Impact on the environment

The main impact on the environment of using air conditioning equipment is related to direct and indirect CO_2eq emissions. Direct emissions come from the leakage of refrigerants to the atmosphere, during initial charging, servicing, end-of-life disposal, and other events. Indirect emissions result from electricity generation to operate the air conditioning systems.

Refrigerants are the heat transfer fluid of vapor compression systems that are widely used in air conditioning applications. Not any fluid or solution can be a refrigerant; the selection criteria is a trade-off between several factors including the thermodynamic performance (e.g., capacity, temperatures, efficiency) as well as considerations for safety (e.g., pressure, toxicity, and flammability), compatibility with materials, availability, cost, and environmental impact. Therefore, the industry adopts a limited number of refrigerants for each application, and often builds consensus around a single refrigerant for specific equipment types (DOE, 2016). Refrigerants have evolved, with the goal of improving safety and performance and, lately, reducing environmental impacts. Table A1 illustrates the timeline evolution.

Table A1: Refrigerant's timeline evolution

Refrigerant Category	Timeline	Main Concerns	Example of Refrigerants
1st Generation	1830–1930	Security: "whatever worked", first-generation refrigerants based on non-fluorinated substances are toxic and flammable.	HCs (butane, propane, naphtha, gasoline), NH_3, carbon disulfide, carbon dioxide, carbon tetrachloride, dichlorethylene, ethane, ethylamine, ethyl bromide, methyl bromide, methyl formate, methylene chloride, methylamine, methyl chloride, trichloroethylene, and trimethylamine
2nd Generation	1931–1990	Safety and durability: second-generation refrigerants, although efficient, contribute significantly to the depletion of stratospheric ozone and often have high global warming potential.	CFCs, HCFCs (e.g., R-12, R-22)
3rd Generation	1990–2010	The international effort to phase out ozone depleting culminated in the adoption of the Montreal Protocol.	HFCs (e.g., R-410A, R-134a)
4th Generation	2010–now	Global Warming. Kigali Amendment to the Montreal Protocol is an international treaty to phase down high GWP HFCs, with two associated decisions addressing energy efficiency (XXVIII 2 and 3).	Low-GWP HFCs and blends (e.g., R-32 and R-452B), low-GWP HFOs (e.g., R-1234yf), and HCs (e.g., R-290), and others

Source: **(DOE, 2016; Park, Shah, & Gerke, 2017)**

The concern of international community about ozone-depleting substances (ODS) in the 1970s and 1980s leads to the regulation of their production and consumption through a multilateral environmental treaty, called the Montreal Protocol (DOE, 2016). Adopted in 1987, the original Protocol only concerned the phase down of chlorofluorocarbons (CFCs) production and consumption in a stepwise manner, with different timetables for developed and developing countries (referred to as "Article 5 countries") (UNEP, 2017a). Typically, non-A5 Parties have earlier and faster control schedules than A5 Parties that are allowed a "grace period", while new technology is commercialized and achieves economy of scale and competitive prices (Shah, Wei, Letschert, & Phadke, 2019). Since 1987, several amendments have been adopted (IIR, 2017). The London Amendment (1990) required the complete phase out of CFCs between 1996 and 2000 in developed countries, and by 2010 in developing countries.

In order to meet the refrigerants demand, from 1990 the consumption of hydrochlorofluorocarbons (HCFCs) raised sharply and new products appeared, such as hydrofluorocarbons (HFCs). Although both refrigerants' families offered a significant or total reduction in the ozone depletion potential (ODP), they still have great global warming potential (GWP). Table A2 shows GWP and ODP values for commonly used refrigerants (UNEP, 2017b). Subsequently, the HCFCs were added to the list of controlled substances to be phased out, with different deadlines established in the Copenhagen Amendment (1990) for developed countries, and in the Montreal Amendment (1997) for developing countries (IIR, 2017). Recognizing the potential benefits to the Earth's climate, in 2007 the parties decided to accelerate their schedule to phase out HCFCs: non-A5 and A5 parties will completely phase them out by 2020 and 2030, respectively (UNEP, 2017a).

Another group of substances, HFCs, introduced as non-ozone depleting alternatives to support the timely phase out of CFCs and HCFCs, are now widespread used in cooling appliances (UNEP, 2017a). The drawback with these substances is that they still have a high GWP, some even higher than HCFCs (see Table A2), and the fastest growing GHG emissions (between 8-15% per year) (Shah et al., 2019; UNEP, 2017a). These issues have led to the Kigali Amendment to the Montreal Protocol (UNEP, 2016b, 2016a), with added schedules to reduce their production and consumption by 80-85% by the late 2040s, in both developed and developing countries (IIR, 2017; UNEP, 2017a, 2017b). This phase-down in the global consumption of HFCs could save as much as 0.5°C of warming (UNEP, 2017b), and combining it with energy efficiency in the air conditioner and refrigeration sectors, can be an engineering and policy 'win-win' that could together avoid 1.0°C of warming by 2100 (K-CEP, 2018).

Table A2shows the GWP and the ODP of commonly used refrigerants in air conditioning and refrigeration sectors.

Table A2: Refrigerants commonly used and their GWP, ODP and application sectors

Type	Gas	GWP	ODP	Application sectors
ODS	CFC-12	10,900	1.0	CFC-12 classed as a 1st generation refrigerant; the operation pressure is similar to HFC-134a, which was replaced it in many applications.
	HCFC-22	1,810	0.055	Used in Article 5 countries, mostly for refrigeration and air conditioning appliances.
HFC	HFC-404A	3,922	0	Industrial and commercial refrigeration.
	HFC-410A	2,088	0	Unitary and commercial ACs, commonly used in non-Article 5 countries.
	HFC-134a	1,430	0	Large chillers, refrigeration, mobile air conditioning.
	HFC-32	675	0	Residential A/C systems (Packaged & Split-Systems).
HFO (Hydrofluoroolefin)	HFO-1234yf	4	0	Commercial A/C systems (Chillers).

Source: (DOE, 2016; Shah et al., 2019; UNEP, 2017b, 2018)

In 2016, the International Energy Agency estimated that indirect GHG emissions of space cooling appliances (including air conditioning, electric fans and dehumidification in the residential and commercial (service) sectors) accounted 1,135 Mt of CO_2eq (included direct emissions from the use of fossil fuels, almost entirely natural gas in chillers), which represented 12% of total energy-related emissions from buildings (IEA, 2018b). Indirect GHG emissions related with unitary air conditioning or UAC (including ductless split, ducted split and rooftop ACs, variable refrigerant flow (VRF) systems and self-contained units) accounted 950 Mt of CO_2eq, while AC direct emissions accounted 330 Mt of CO_2eq both in 2016.

Despite the partial decarbonization of electric matrixes, in the Baseline Scenario defined by IEA (in 2016 the carbon intensity was 505 gCO_2/kWh, and the Baseline Scenario considers 270 gCO_2/kWh in 2050), emissions almost would double from 1,135 Mt of CO_2 in 2016 to 2,070 Mt of CO_2 in 2050 (IEA, 2018b). In the Efficient Cooling Scenario, the measures to make ACs more energy efficient, coupled with an even greater decarbonization of fuel mix in power generation (177 gCO_2/kWh) would lead to 93% reduction compared to the Baseline Scenario in 2050.

APPENDIX B – The structure of the electrical sector in Ecuador

The last Ecuadorian Constitution, of 2008, established the current structure of the electric sector in Ecuador (AN, 2008), which is mostly state-owned. The Electricity Public Service Law (AN, 2015) regulates the participation of the different stakeholders in this structure. Figure B1 shows the public institutions of the electricity sector and their participation.

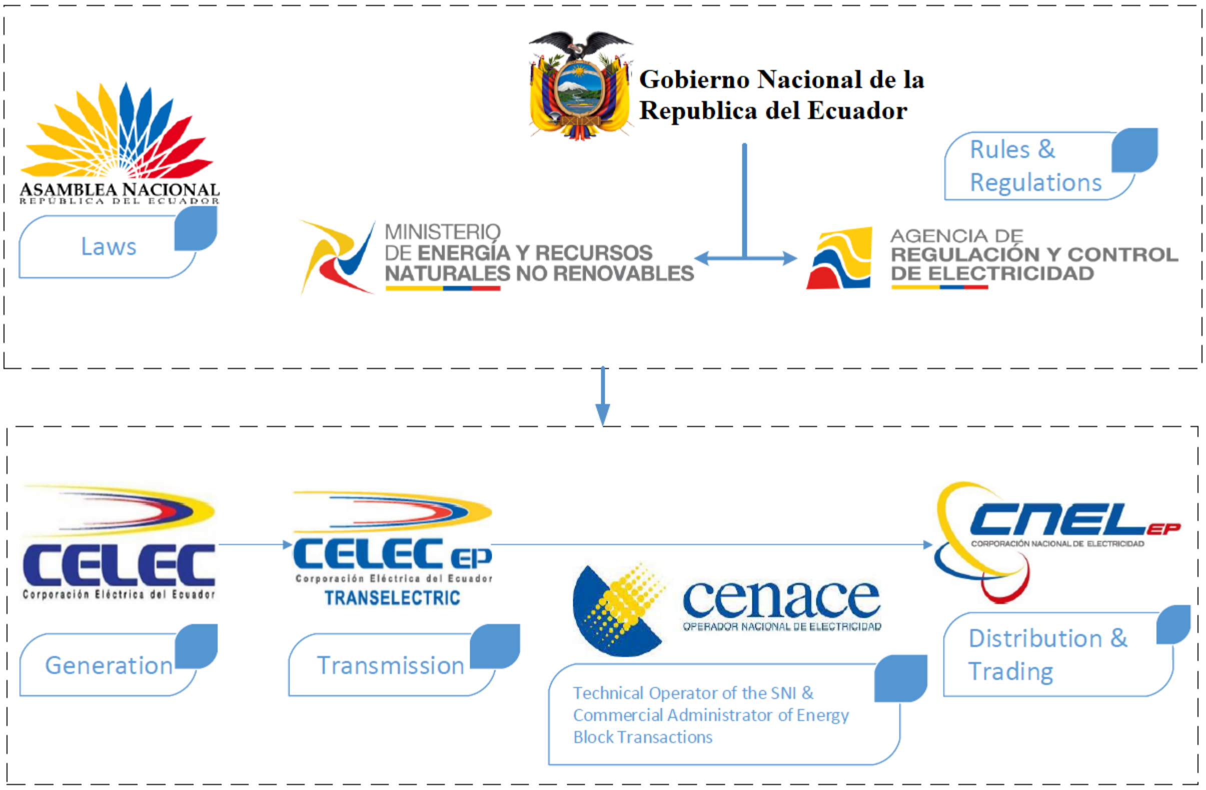

Figure B1: Structure of the electricity sector in Ecuador

National Interconnected System (SNI): It consists of generation facilities, or delivery points of electricity, and the national transmission system, which has power lines of 138 kV, 230 kV and 500 kV; Ecuador has electric interconnection with Peru and Colombia for the purchase/sale of energy (CELEC EP, 2019). The main generator company is public and is the Ecuadorian Electric Corporation (CELEC). The only transmission company is CELEC TRANSELECTRIC. Some power companies, called Generators, are purely generators. Other companies, which main role is in electricity distribution, also have generation capacity (called Distributors). Finally, there are companies identified as Auto-generators that are mostly private. In Chapter Four of this dissertation it is presented the electricity generation per system and per energy source in 2017. Besides the SNI, there are some power plants unincorporated (No Inc.) which serve for local supply (ARCONEL, 2018).

As for distribution, there are only public electricity companies in charge of concessions. Ecuador's main electricity company is the National Electricity Corporation (CNEL). In Guayaquil, the company in charge of supplying electricity to end user is CNEL Guayaquil

The electricity public service law (LOSPEE)

The objective of this law is to assure the electricity supply by the public service. It defines the responsibility of the State to plan, execute, regulate, control and manage the public electric service (AN, 2015). This law also defines the role of the following organizations:

- **Ministry of Energy:** Nowadays the Ministry of Energy and Non-Renewable Natural Resources (MERNNR). One of its tasks is to develop the Electricity Master Plan (PME), as well as the National Energy Efficiency Plan (PLANEE).
- **Electricity Regulation and Control Agency (ARCONEL):** It is the technical administrative body responsible for regulating and monitoring activities related to the public electricity service and the general public lighting service.
- **National Electricity Operator (CENACE):** Responsible for operating the National Interconnected System (SNI) and managing commercial transactions of energy blocks.

Electricity Master Plan (PME): PME reports the current status of the electric sector and its main indicators, performs growth forecast scenarios for power generation, and estimates loads for transmission and distribution system, rural electrification and street lighting (MEER, 2016b). The last available version is PME 2016-2025.

Figure B2 shows electricity losses along the supply chain and Figure B3 shows the electricity coverage. Both figures set a comparison with Latin America countries for both parameters. It can be seen that Ecuador is close to the average regarding coverage and, comparatively, has good figures regarding losses.

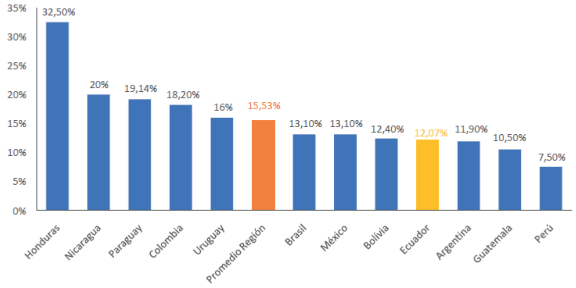

Figure B2: Electricity losses in Ecuador and Latin America
Source: **(MEER, 2016b)**

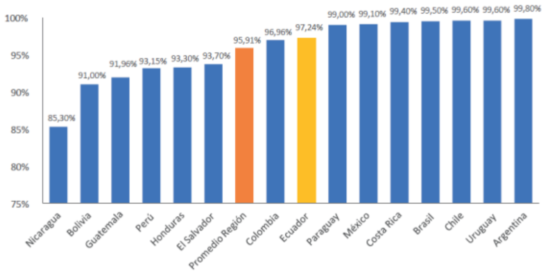

Figure B3: Electricity coverage in Ecuador and Latin America
Source: (MEER, 2016b)

Figure B4 shows the growth of total electricity consumption from 2007 to 2016 in Ecuador. In this period, the average growth rate was 0.86 GWh/year. Figure B5 shows the shares of electricity consumption by different socio and economic sectors; the largest consumer of electricity is the residential sector, although in recent years the industrial sector has shown significant growth.

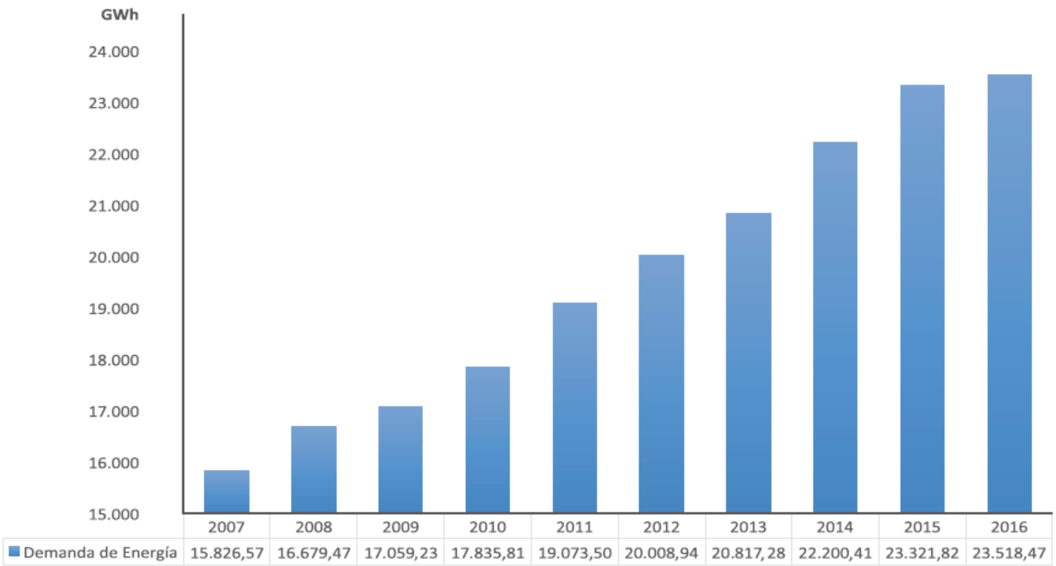

Figure B4: Total electricity consumption in Ecuador, from 2007 to 2016
Source: (MEER, 2016b)

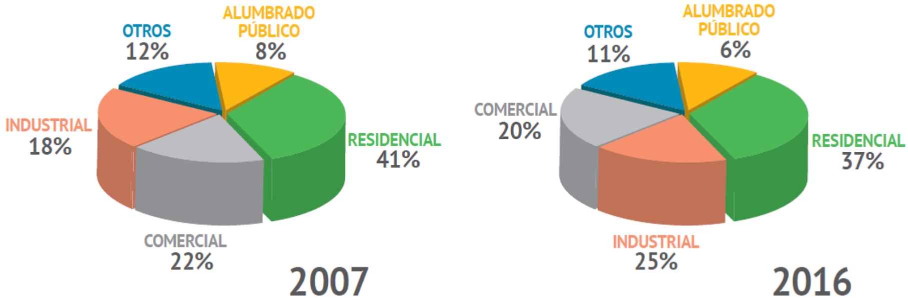

Figure B5: Shares of electricity consumption by socio-economic sector in Ecuador
Source: (MEER, 2016b)

The forecast of electricity demand until 2025, presented in the PME 2016–2025, is shown in Figure B6. Residential sector is the one that leads the growth in the electricity demand, with an estimated increase of 30.5%, closely followed by the industrial sector, as is shown in Table B1. Figure B7 shows the estimated shares of consumption in 2025. On the other hand, Figure B8 presents the estimated residential demand from 2016 to 2025; it can be seen that residential demand would grow 3.3% on average per year. The considered average annual GDP growth in PME 2016–2025 was 3.4%, which corresponds to the average growth for the period 2007-2016, expressed at 2007 constant values.

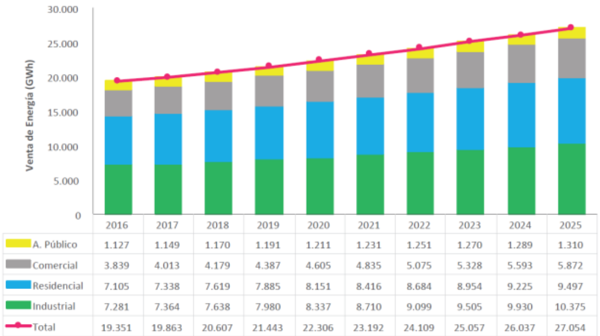

Figure B6: Forecast of electricity demand until 2025
Source: (MEER, 2016b)

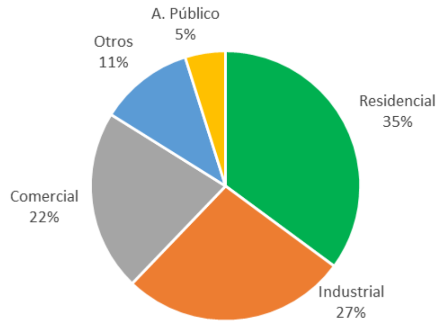

Figure B7: Shares of electricity demand in 2025
Source: (MEER, 2016b)

Table B1: Electricity consumption (GWh) between 2016 (actual) and 2025 (estimated) by consumption sectors

Year	Residential	Industrial	Commercial	Others	Public lighting
2016	6,704	4,546	3,654	1,927	1,054
2025	9,497	7,324	5,872	3,051	1,310
Increase	2,793	2,778	2,218	1,124	256
Share in the total increase of electricity demand	30.5%	30.3%	24.2%	12.3%	2.8%

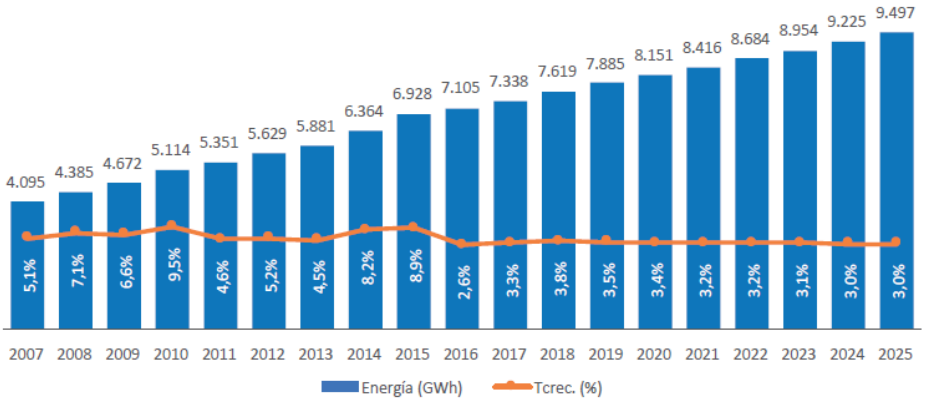

Figure B8: Residential electricity consumption and forecasted demand, in GWh
Source: (MEER, 2016b)

Energy efficiency law (LOEE)

This law came into force in March 2019 (AN, 2019). Its aim is to promote the efficient and sustainable use of energy in order to - according to the text - increase the country's energy security and promote the competitiveness of national economy, contributing to climate change mitigation and ensuring people's rights to live in a healthy environment and take decisions based on information. The law establishes the creation of the National Energy Efficiency Committee (CNEE), which will be responsible for running the national systems of energy efficiency indicators and implementing the guidelines of the national energy efficiency plan (PLANEE). One main task of CNEE is the development of a regulated energy-intensive equipment list, being the standardization to be defined by technical regulations of National Institute for Standardization (INEN).

National Energy Efficiency Plan (PLANEE): The objective is to increase efficiency in the energy supply and end-use sectors by implementing energy efficiency programs and projects in order to reduce imports of petroleum products, contributing to climate change mitigation and creating an energy efficiency culture (MEER, 2016c).

Residential, commercial and public sectors in PLANEE: In this sense, PLANEE focuses on increasing the energy efficient use in residential, commercial and public buildings, and develop a building regulation with energy efficiency guidelines. The specific objectives are the creation and strengthening of replacement and S&L programs for high-energy consumption appliances and the implementation and application of the guidelines presented in the Energy Efficiency Chapter of the Ecuadorian Construction Standard (NEC, 2018). The main initiatives reported (MEER, 2016c) are resumed below:

- Efficient residential lighting. Through this initiative, from 2008 to 2014 16 million incandescent bulbs were replaced by compact fluorescent lamps (CFLs). The estimated result is 287 GWh/year savings.
- Efficient public lighting. Between 2012 and 2014 100 W sodium vapor luminaires replaced 175 W mercury vapor luminaires (61,610 units), with estimated 20 GWh/year in electricity savings.
- Program for the replacement of energy inefficient equipment. Between 2012 and 2016 95,652 refrigerators were replaced, resulting electricity savings equivalent to 38 GWh/year.

- Efficient cooking and water heating program (PEC). It started in 2014 and the aim is to replace LPG for electricity for cooking and water heating in the residential sector.
- Energy efficiency program in the public and residential sectors (SECURE). It started in 2015 and the aim is to increase the use of efficient electrical appliances in the residential and public sectors through the promotion and dissemination of devices labeled by the Maximum Energy Efficiency Distinctive (DMEE). This label is for equipment that has the highest energy efficiency levels on the market (MEER, 2016a; Subsecretaria del Sistema de la Calidad, 2017).

With these programs there was a decrease in electricity consumption at peak hours (19:00-22:00). The peak shaving was estimated at 362 MW, saving more than $ 720 million due to installation of new infrastructure. Figure B9 shows the estimated power reduction in peak demand by 2016 due to energy efficient programs (MEER, 2016c).

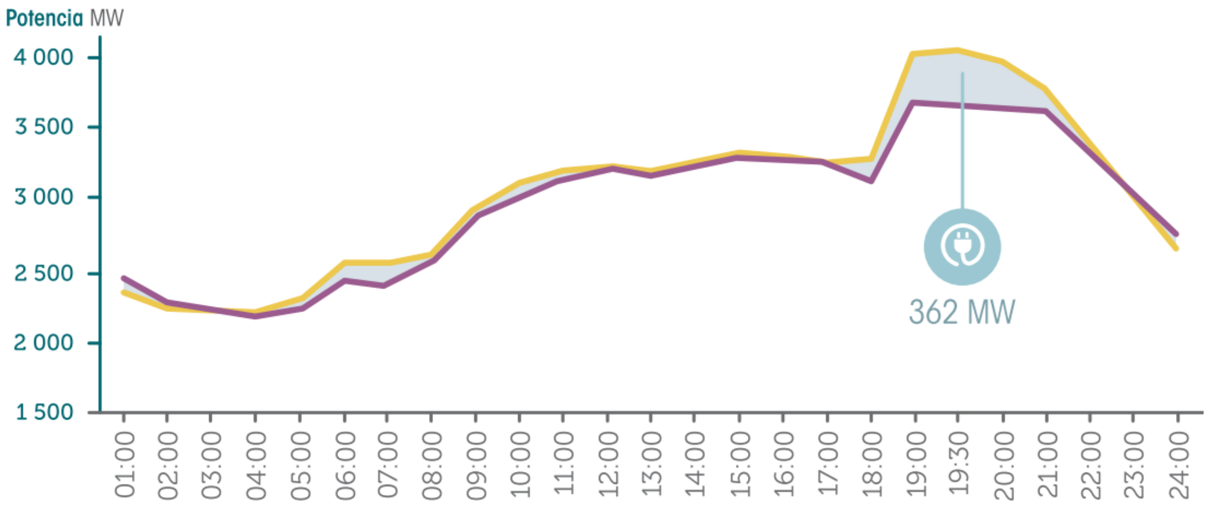

Figure B9: Power reduction in peak demand by 2016 due to energy efficient programs
Yellow line represents the power required to meet the peak demand in Ecuador, violet line represents the power required after the introduction of energy efficiency policies described above. **Source:** (MEER, 2016c)

APPENDIX C – Comparison of perspectives

A full regulatory impact study should consider different stakeholders in the analysis. Table C1 presents concerns about setting stricter energy efficiency standards, and how stakeholder perspective analysis can be done.

Table C1: Perspective of involved stakeholders

Involved Stakeholders	Concerns	Elements of Analysis
Consumer	Concerns about affordability, price increases for energy-consuming products, and efficiency standards that do not result in sufficient savings.	Life-Cycle Cost (LCC) Payback Periods
Public Sectors	Concerns about energy security and mitigation of GHG emissions. Tradeoffs between financial impacts and energy savings.	National Energy Savings: Primary energy savings (PES), electricity savings (ES) and peak load shaving. Net Present Value (NPV): National financial impacts. Greenhouse Gas Emissions Mitigation—Assessment based on national energy savings and forecasting of electricity generation mix.
Manufacturers and Private Sectors	Concerns about trade barriers, adaptation time and investment costs. Energy-efficiency regulations limit the range of products that may legally be produced or imported.	Profitability and Cash flow Impacts on employment and production capacity

APPENDIX D – Binary Integer Linear Programming

An air conditioner is composed of different components, being the main heat exchangers, compressor and expansion valve. These components can be enhanced with various technologies to increase overall AC energy efficiency. This efficiency is measured through the energy efficiency ratio (EER).

A base design of an AC is presented in Table D1. Table D2 shows a list of more efficient components and the predicted impact of them on global energy consumption and manufacturing costs. These impacts are estimate in comparison to the base design.

Table D1: Parameters assumed for the base design

EER_o (W/W)	3.02
Cooling Capacity (kW)	3.5
Manufacturing production cost[s](USD)	180

[a] **Source:** (Letschert et al., 2019)

Table D2: Components that would result better performance of ACs

Components	Description	Incremental Manufacturing Cost %	Energy Savings from Baseline %
Compressor 1	3.0 EER compressor with FSD	4.0	5.5
Compressor 2	3.2 EER compressor with FSD	19.0	10.5
Compressor 3	3.4 EER compressor with FSD	35.0	15.0
Compressor 4	3.6 EER compressor with FSD	85.0	20.0
Compressor 5	Alternating current compressor with VSD (Inverter AC)	49.0	23.5
Inverter DC	Direct current compressor with VSD	89.0	25.5
All DC	VSD for fans and compressor	126.0	29.0
Heat Exchanger 1	UA of both heat exchangers increased 20%	14.0	7.5
Heat Exchanger 2	UA of both heat exchangers increased 40%	54,0	13.5
Heat Exchanger 3	UA of both heat exchangers increased 60%	92.0	18.0
Heat Exchanger 4	UA of both heat exchangers increased 80%	105.0	21.0
Heat Exchanger 5	UA of both heat exchangers increased 100%	163.0	24.0
TXV	Thermostatic expansion valve	37.0	5.0
EXV	Electronic expansion valve	63.0	9.0

Source: (Letschert et al., 2019

Several designs correspond to the combination of different component options. Each project or design will have a corresponding level of energy efficiency, but only viable projects should be considered, i.e. projects that comply with the regulation (greater than or equal to the established standard). Section 4.4.1 sets out the different MEPS to be evaluated.

The selected designs, besides being viable, should be those that minimize manufacturing costs. Because of these conditions, the following binary integer generator linear programming problem is solved:

Minimize the manufacturing cost function determined by Equation D1.

$$Min\colon Cost = C_1 * X + C_2 * Y + C_3 * Z \qquad \text{Eq. D1}$$

Being $C_1, C_2, C_3 \in \mathbb{R}^{1xn}$ the cost matrices of the components and $X, Y, Z \in \mathbb{R}^{\mathrm{nx1}}$ the matrices of elements restricted to:

$$x_i \in \{0,1\};\ i = 1,\ 2, \dots\ 7$$
$$y_i \in \{0,1\};\ i = 1,\ 2, \dots\ 5$$
$$z_i \in \{0,1\};\ i = 1,\ 2$$
$$\textstyle\sum_{i=1}^{7} x_i = 1;$$
$$\textstyle\sum_{i=1}^{5} y_i = 1;$$
$$\textstyle\sum_{i=1}^{2} z_i = 1;$$

In the matrix X are the compressors, in Y the heat exchangers and in Z the expansion valves. Equation D2 corresponds to the constraint related to energy efficiency standards, where the EER of the different designs must be higher than or equal to the EER established by the MEPS.

$$EER_{design} = \frac{Cc}{E} \geq EER_{MEPS}; \qquad \text{Eq. D2}$$

Where Cc represents the cooling capacity and E the energy consumption of a certain design. The energy consumption of the design base E_0 is determined by Equation D3 and depends on the energy efficiency level EER_0 showed in Table D1 and the Cc.

$$E_0 = \frac{Cc}{EER_0}; \qquad \text{Eq. D3}$$

The matrices $E_{S1}, E_{S2}, E_{S3} \in \mathbb{R}^{1xn}$ represent the impacts on energy consumption. Equations D2 and D3 are combined to obtain the final constrain related to energy efficiency, Equation D4, shows the final expression.

$$\frac{Cc}{EER_0} - E_{S1} * X + E_{S2} * Y + E_{S1} * Z \leq \frac{Cc}{EER_{MEPS}}; \qquad \text{Eq. D4}$$

The solutions are presented in Table D3. Where the components are heat exchangers (HE), compressors (CP) and expansion valves (EV). Base design component means that optimization selects the base component as the optimized design solution.

Table D3: Solutions of the optimization

Design	MEPS	Compressor	Heat Exchanger	Expansion Valve	Purchase Cost (USD)	EER
Design #1	3.4	CP 1	HE 1	Base Design Component	423	3.47
Design #2	3.6	CP 2	HE 1	Base Design Component	465	3.68
Design #3	3.8	CP 5	Base Design Component	Base Design Component	510	3.95
Design #4	4.3	CP 5	HE 1	Base Design Component	558	4.38
Design #5	4.7	CP 5	HE 1	TXV	684	4.72
Design #6	5.0	CP 5	HE 1	EXT	773	5.03
Design #7	5.2	CP 5	HE 2	TXV	821	5.21
Design #8	5.8	CP 5	HE 4	TXV	996	5.98

APPENDIX E – Energy efficiency indicators and decomposition analysis

In a world increasingly concerned with energy security, socio-economic impacts of high-energy prices and climate change, countries seek to improve the way they use energy. Improving energy efficiency is often the most economical, proven and easily available way to meet this goal. For this reason, many countries develop policies and measures to promote energy efficiency as a priority. Establish and maintain successful energy efficiency policies require good quality, timely, comparable and, above all, disaggregated data in order to build solid indicators, which allows measuring and communicating the policy progress in correctly and easily way (IEA, 2014b).

Energy indicators describe energy consumption, interactions among economic and human activity, and CO_2 emissions. Usually, they will refer to ratios but, in some cases, they are expressed in absolute terms. In general, energy efficiency indicators demonstrate if one thing is more energy efficient than another, or if there is any improvement after performing an action, showing to policy makers where energy savings can be made. In addition to providing information on trends in past energy consumption, energy efficiency indicators can also be used to model and forecast energy demand (IEA, 2014a).

As mentioned in previous sections, several factors drive energy demand. In isolation, energy efficiency indicators provide partial information of these drivers in energy end uses and, for this reason, it is necessary to separate the impact of changes in activity, economic structure and other exogenous factors that influence this demand. Decomposition, or factorization analysis, quantify impacts of different driving factors to know the real impact of the policy on energy intensity.

The disaggregation level required to analyze energy efficiency policies or build energy efficiency indicators goes beyond energy balances, since the data presented in balances fails to distinguish particular characteristics in final sectors and energy end uses or the variables that affect them. Disaggregate the information contained in the balances requires financial, human resources, and time; therefore, it is important for countries to prioritize which sectors or energy end uses will be prioritized (IEA, 2014b).

Energy indicators for space cooling in the residential sector

The IEA developed a hierarchical pyramid system to describe the degree of disaggregation of indicators and data requirement (IEA, 2014c): the closer to the base, higher is the level of disaggregation. Figure E1 shows the indicators for air conditioning in the residential sector. The letter C in the Figure E1 refers to cooling, the numbers refers to the pyramid's level and the last lowercase letter refers to the type of activity. Real energy efficiency indicators need more disaggregated energy and activity data to be meaningful.

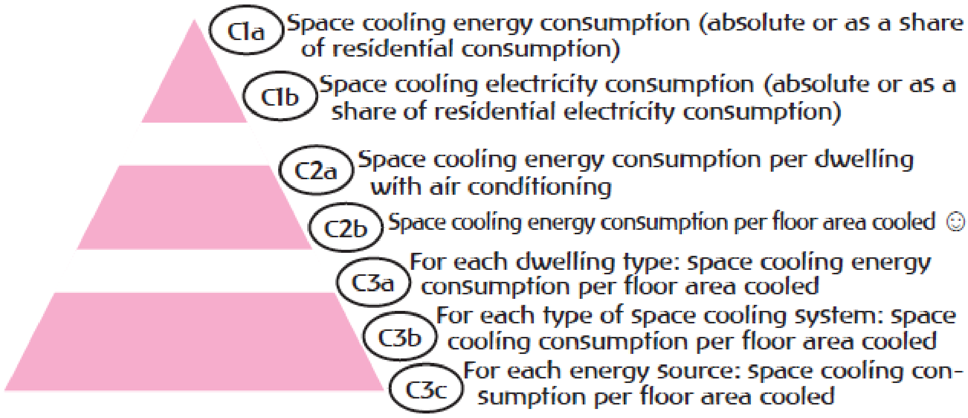

Figure E1: Energy indicators for space cooling
Source: (IEA, 2014c)

Index decomposition analysis for energy demand

Index decomposition analysis (IDA) is an analytical tool that was proposed in the late 1970s to study the impacts of structural change and sectoral energy intensity change on energy use trends in industry. Since then there are multiple areas that apply this methodology, including energy demand and supply, energy-related gas emissions, material flows and dematerialization, national energy efficiency trend monitoring, and cross-country comparisons (Ang, 2004). This methodology is based on defining a governing function relating the aggregate (to be decomposed) to a number of pre-defined factors of interest. With the governing function defined, various decomposition methods can be formulated to quantify the impacts of changes of these factors on the aggregate, but the method choice affects the numerical results obtained despite the fact that the meanings of components are not method dependent.

Two main blocks classify the decomposition methods: methods linked to the Laspeyres index, based on the percentage change concept, and methods linked to the Divisia index, based on logarithmic change concept. Table E1 presents several index decompositions methods; a complete benchmarking and formulation of these methodologies is presented in (Ang, 2004; IEA, 2014b). The method choice in energy decomposition analysis follow four important criteria:

- The index method must have an insignificant or no residual term (perfect decomposition).
- The index method must be applicable to all sectors and sub-sectors so that they can all be interpreted in the same way, making it possible to aggregate the results of sub-sectors.
- The index method must be time reversible, in order to the estimated value from year 0 to year T be the same as the estimated value from year T to year 0, in absolute terms.
- The interpretation of the index must be straightforward (i.e. the results must be easy to understand).

Table E1: Index decomposition methods

Classification	Index	Perfect decomposition	Sub-sectors additive	Time reversible	Easy to understand
Divisia index based	The logarithmic mean Divisia method I (LMDI-I)	Yes	Yes	Yes	Moderately
	The logarithmic mean Divisia method II (LMDI-II)	Yes	No	Yes	Moderately
	Simple average/arithmetic mean/ Divisia (Törnqvist)	No	No	Yes	Moderately
Laspeyres index based	Simple Laspeyres	No	Yes	No	Very easy
	Refined Laspeyres	Yes	Yes	No	Moderately
	Fischer Ideal	Yes	No	Yes	Moderately
	Adjusted Parametric Divisia Method (PMD)	No	Yes	Yes	Difficult
	Paasche	No	Yes	No	Very easy

Source: **(IEA, 2014b)**

APPENDIX F – ANOVA for AC diffusion model

ANOVA

	fd	*SQ*	*MQ*	*F*	*F crit*
Regression	1	51,72	51,72	219,98	1,38765E-13
Error	24	5,64	0,24		
Total	25	57,37			

	Coefficients	*Standard error*	*Stat t*	*value-P*	*95% inferiors*	*95% superiors*
Intersection	3,33	0,21	15,94	0,00	2,90	3,76
Slope	-1,70E-03	1,15E-04	-14,83	1,39E-13	-1,94E-03	-1,47E-03

SUMMARY OF RESULTS

Regression Statistics	
R multiple	0,95
R-Square	0,90
R-square adjusted	0,90
Standard error	0,48
Sample	26