Master Thesis

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MODELING PATHWAYS
for residential energy demand in megacities

The case of the Mexico City Metropolitan Area

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Details

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Abstract

Potential future medium and long-term developments of residential energy demand in large urban agglomerations and their impact on greenhouse gas (GHG) emissions are often poorly understood. The purpose of the thesis is to improve the understanding on how the residential sector in the Mexico City Metropolitan Area (MCMA) may develop under the absence of national and local energy-efficiency policies and measures. Modeling and scenario techniques are used for the investigation on future residential energy demand. This investigation is centered on the impact of demographic and economic developments on household energy demand. In addition, this project also investigates an alternative scenario for a more sustainable future in which currently best available technologies are used. This scenario reveals how the residential energy demand could be greatly reduced by implementing comprehensive energy efficiency policies and overcoming market barriers.

To this end, a bottom-up model for the residential sector in the MCMA was developed and implemented. The designed model adapts modeling techniques developed by other researchers. The resulting final energy demand is subdivided into standard end-use services of households. The model is set to adjusted gas and electricity sales data for the year 2010. Future developments of appliance stocks and energy intensities are projected separately for each end-use service. The impact of energy demand developments on carbon dioxide (CO_2) emissions was estimated through the integration of energy supply scenarios.

As outcome from the modeling work, scenarios suggest that in the absence of additional residential sector policies beyond those in place today, energy demand in the MCMA in 2010 could rise by 23% by 2030. In contrast, the outcome from the alternative scenario indicates that the strict implementation of currently best available technologies in 2018 could decrease the energy demand of the sector by 49% by 2030 in relation to the year 2010. Furthermore, a conducted sub-scenario to the alternative scenario demonstrates that theoretically residential energy consumption in 2010 could be reduced up to 60% in the case that all old, inefficient appliances could be exchanged by 2030. Combining designed energy demand scenarios with energy supply scenarios, it was estimated that CO_2 emissions in 2010 caused by activities of households in the MCMA could be reduced by 75% in 2030. This is done through energy-efficiency improvements of household equipment and the integration of large shares of renewable energies into the electricity grid.

Declaration of authorship

I state and declare that this thesis was prepared by me and that no means or sources have been used, except those, which I cited and listed in the References section. The thesis is in compliance with the rules of good practice in scientific research of Carl von Ossietzky Universität Oldenburg.[1]

Schorndorf, 1st of September 2015

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[1] https://www.uni-oldenburg.de/uni/amtliche_mitteilungen/dateien/AM2002-04_Leitlin.pdf

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Abbreviations and acronyms

A-	Accelerated	
ANCE	Independent Certification Laboratory in the electric sector	Asociación Nacional de Normalización y Certificación del Sector Eléctrico
BAU	Business-As-Usual	
BAT	Best-Available-Technology	
BSRIA	Building Services Research and Information Association	
BUENAS	Bottom-Up Energy Analysis System	
C40	C40 Cities Climate Leadership Group	
CAM	Metropolitan Environmental Commission	Comisión Ambiental Metropolitana
CAME	Megalopolis Environmental Commission	Comisión Ambiental de la Megalópolis
CCFL	Cold Cathode Fluorescent Lamp	
CEPAL	Economic Commission for Latin America and the Caribbean	Comisión Ecónomica para América Latina y Caribe
CFE	Federal Electricity Commission	Comisión Federal de Electricidad
CFL	Compact Fluorescent Lamps	
CICC	Inter-Ministerial Committee on Climate Change	Comisión Intersecretarial de Cambio Climático
CLASP	Collaborative Labelling and Appliance Standards Program	
CONAPO	Mexican National Population Council	Consejo Nacional de Población
CONAVI	National Housing Commission	Comisión Nacional de Vivienda
CONUEE	Mexican National Commission for Energy Efficiency	Comisión Nacional para el Uso Eficiente de Energía
COP	Conference of Parties	
CRT	Cathode Ray Tube	
DEA	Danish Energy Agency	
DF	Federal District	Distrito Federal

DLR	German Aerospace Centre	Deutsches Zentrum für Luft- und Raumfahrt
DOF	Federal Official Gazette	Diario Oficial de la Federación
e	Electric	
ECLAC	(see CEPAL)	
EF	Energy Factor	
Eff.	Efficiency	
ENACC	National Strategy for Climate Change	Estrategía Nacional de Cambio Climático
ENIGH	Survey of National Household Incomes and Expenditures	Encuesta Nacional de Ingresos y Gastos de los Hogares
ENUT	National Survey of Time of Use	Encuesta Nacional de Uso de Tiempo
FEECM	Trust fund of studies about Mexico City	Fideicomiso de estudios estratégicos sobre la Ciudad de México
FIDE	Foundation for Electrical Energy Savings	Fideicomiso para el Ahorro de Energía Eléctrica
FL	Fluorescent Lamps	
g	Gas	
GaWC	Globalization and World Cities Research Network	
GDF	Government of the Federal District	Gobierno del Distrito Federal
GDP	Gross Domestic Product	
GEA	Global Energy Assessment	
GHG	Greenhouse Gas	
GIZ	German Federal Enterprise for International Cooperation	Deutsche Gesellschaft für Internationale Zusammenarbeit
GLS	General Lighting Service Lamp	
GNESD	Global Network on Energy for Sustainable Development	
GPC	Global Protocol for Community-Scale Greenhouse Gas Emission Inventories	
GRP	Gross Regional Product	
HH	Household	

HP	Heat Pump	
ICLEI	Local Governments for Sustainability	
ID	Income Distribution	
IEA	International Energy Agency	
IGECEM	Institute for Information and Geographic Investigation, Statistics and Cadastral of the State of Mexico	Instituto de Información e Investigación Geográfica, Estadistica y Catastral del Estado de México
IGES	Institute for Global Environmental Strategies	
IIASA	International Institute for Applied System Analysis	
IL	Incandescent Lamps	
INECC	Mexican National Institute for Ecology and Climate Change	Instituto Nacional de Ecología y Cambio Climático
INEGI	Mexican National Institute of Statistics and Geography	Instituto Nacional de Estadística y Geografía
Inst.	Instantaneous	
IPCC	Intergovernmental Panel on Climate Change	
LBNL	Lawrence Berkeley National Laboratory	
LCD	Liquid Crystal Display	
LEAP	Long-Range Energy Alternatives Planning	
LED	Light-Emitting Diodes	
LEDS	Low Carbon Development Strategy	
LFL	Linear Fluorescent Lamps	
LGCC	Climate Change General Act	Ley General de Cambio Climatico
LPG	Liquefied Petroleum Gas	
MARKAL	Market Allocation	
MCMA	Mexico City Metropolitan Area	Zona Metropolitana del Valle de México
MCPV	Survey of the Mexican Population and Housing Census	Muestra del Censo de Población y Vivienda

MEPS	Minimum Energy Performance Standards	
NAMA	National Appropriate Mitigation Actions	
NG	Natural Gas	
NMX	Mexican Standards	Normas Mexicanas
NREL	National Renewable Energy Laboratory	
NOM	Official Mexican Standards: Energy Efficiency (ENER) Water (CNA)	Norma Official Mexicana para eficiencia energetica
NYC SAC	New York City Solar America City	
OEA	Other Electric Appliances	
OECD	Organization for Economic Co-operation and Development	
ONU-Habitat	United Nations Human Settlement Programme	Programa de las Naciones Unidas para los Asentamientos Humanos
OLED	Organic Light-Emitting Diode	
PACCMUN	Municipal Climate Action Plan	Programa de Acción ante el Cambio Climático Municipal
PAMS	Policy Analysis Modeling System	
PDP	Plasma Display Panel	
PEACC	State Action Plans on Climate Change	Programa Estatal de Acción ante el Cambio Climático
PECC	Special Climate Change Program	Programa Especial de Cambio Climático
PEMEX	Mexican Petroleum Company	Petróleos Mexicanos
PND	Mexican National Development Plan	Plan de Nacional de Desarrollo
PPP	Purchasing Power Parity	
ProAire	Program to improve air quality management	Programa de gestión para mejorar la calidad del aire
PROCALSOL	Program for the Promotion of Solar Water Heaters in Mexico	Programa para la Promoción de Calentadores Solares de Agua en México

PRONASE	National Program for Sustainable Energy Use	Programa Nacional para el Uso Sustentable de la Energía
PVE	National Program for Housing	Programa de Vivienda Ecologica
R & R/F	Refrigerator and Refrigerator/Freezer	
RE	Recovery Efficiency	
REDUCE	Residential EnD-Use model for City Emission reductions	
REEPS	Residential End-Use Energy Planning System	
RTCC	Responding To Climate Change News	
SEDEMA	Secretary of the Environment for Mexico City	Secretaría del Medio Ambiente Ciudad de México
SEDESOL	Secretary of Social Development	Secretaría de Desarrollo Social
SENER	Secretary of Energy	Secretaría de Energía
SWH	Solar Water Heater	
TV	television	
UEC	Unit Energy Consumption	
UN DESA	United Nations Department of Economic and Social Affairs	
UNEP	United Nations Environment Programme	
UNDP	United Nations Development Programme	
USA/US	United States of America	
US DOE	United States Department of Energy	
US EIA	United States Energy Information Administration	
US EPA	U.S. Environmental Protection Agency	
UNFCCC	United Nations Framework Convention on Climate Change	
VIP	Vacuum Insulation Panel	
WEC	World Energy Council	
WEM	World Energy Model	

WHAM	Water Heater Analysis Model
WRI	World Resource Institute

Nomenclature

Symbol	**Unit**	**Description**
α	-	Constant
β	-	Constant
age	years	Age of appliance
age_o	years	Average lifetime of an appliance
AP_R	-	Annual retirement probability
d	-	Income decile
delay	years	Time households wait to purchase an appliance
DO	persons	Dwelling occupancy: average amount of persons per household
ED	J	Energy demand
FP	appliances	First purchases
HH	households	Number of households
HWD	l/(day*HH)	Daily hot water demand per household
HWDP	l/(day*persons)	Daily hot water demand per person
I	10 thousands PPP US dollar in 2010	Monthly household income from work
lt		Maximum lifetime
n	years	Certain year in the projection
P_R	-	Retirement probability
PStock	appliances	Projected stock
Rep	appliances	Replacements
UEC	J or Wh	Unit energy consumption
S	appliances/HH	Saturation: average number of appliances per household
S_{max}	appliances/HH	Maximum Saturation
Sh	appliances	Shipments: number of new purchases
Stock	appliances	Actual stock

Units of measure and conversion factors

Area	dm^2	square decimeter	
	m^2	square meter	
	km^2	square kilometer	
	sq. ft.	square foot	1sq. ft. = 0.0929 m^2
Emissions	tCO_2	tons of carbon dioxide	
	$MtCO_2$	million tons of carbon dioxide	
	$MtCO_2e$	million tons of carbon dioxide equivalent	
Energy	kJ	kilojoule (1 joule * 10^3)	
	GJ	gigajoule (1 joule *10^9)	
	PJ	petajoules (1 joule*10^{15})	
	kWh	kilowatt-hour	
	GWh	gigawatt-hour	
Power	W	watt	
	kW	kilowatt (1 watt * 10^3)	
	MW	megawatt (1 watt * 10^6)	
	GW	gigawatt (1 watt * 10^9)	
	MW_{th}	megawatt thermal	
	kBtu/hr	thousand British Thermal Units per hour	1 Btu/hr = 0.293071 MW
Volume	m^3	cubic meter	
	l	liter	1 l = 0.001 m^3
	gal	gallon	1 gal = 0.003785 m^3
Mass	kg	kilogram	
Speed	m/s	meter per second	
Time	a	year(s)	
Temperature	K	Kelvin	
	°C	degree Celsius	1 °C = 274K
Monetary	USD	US dollar	
	$ thousand	1 US dollar * 10^3	
	MXN	Mexican peso	
Efficacy	lm/W	lumen per watt	
	W/dm^2	watt per square decimeter	

Key terminology

Base year	Historical year marking the transition from energy estimates based on energy data to modeling-based estimates.
Best-available technology (BAT)	Most energy-efficient technologies on the market.
Building sector	Residential and commercial sector
Energy efficiency	Amount of energy required to provide a certain service.
Energy intensity	A measure where energy is divided by the number of a certain appliance type (e.g. water heater) or group of appliances (e.g. cooking equipment).
Energy factor (EF)	A measure used in the United States for the overall energy conversion efficiency of domestic appliances and equipment.
Energy efficiency labels	Informative labels attached to commercialized products to inform consumers about the energy performance of the product in form of energy use, efficiency or energy cost. A label can approve either that the product meets a certain criteria (endorsement labels) or allow for a comparison of the product performance with others (comparative labels).
Energy-efficiency standards	Regulations and procedures stipulating the energy performance of commercialized products. Standards can include well-defined protocols to estimate accurate and comparable energy performance of the product and target or mandatory limits for energy performance based upon a specific protocol.
Gini coefficient	Measurement for income distribution. The coefficient ranges between 0 to 1, with 0 representing an equal distribution and 1 representing perfect inequality.
Gross Domestic Product (GDP)	Market value of all goods and services produced within a country.
Gross Regional Product (GRP)	Market value of all goods and services produced within a region.

Purchasing Power Parity (PPP)	Technique used to equalize the purchasing power of different currencies.
Solar Fraction	Ratio between the amount of energy provided by the solar system to the total energy required for a certain application.

1 Introduction

1.1 Background of the thesis

Climate change is a defining global challenge for humanity in the 21st century. Global awareness of the causes and impacts is rising, and national and international efforts attempt to limit global warming. At the United Nations Framework Convention on Climate Change (UNFCC) Conference of the Parties in Cancun, Mexico in 2010 (COP16), governments agreed to the goal holding the increase of global average temperature, compared with pre-industrial levels, below 2 degree Celsius (°C) and consider lowering it to 1.5 °C in the near future (United Nations, 2011). With this agreement, they try to prevent extreme, pervasive and irreversible impacts of climate change for society and ecosystem. The need for action is clear, as the IPCC predicts an increase in 2100 from 3.7 °C to 4.8 °C relative to pre-industrialized levels, in the case that no additional mitigation measures are taken (IPCC, 2014).

Residential buildings represent a major energy-consuming sector in the economy with around one-third final energy consumed. Thus, this sector is a significant contributor to greenhouse gas (GHG) emissions. Over the last six decades the world has gone through a process of fast urbanization, from less than one-third urban population in 1950 to 54% in 2014 (UN DESA, 2014a). The dramatic increase in urban population also led to a growth of size of cities, especially, in developing countries (Figure 1-1). The new phenomenon of cities has been conceptualized under the term megacities.[2]

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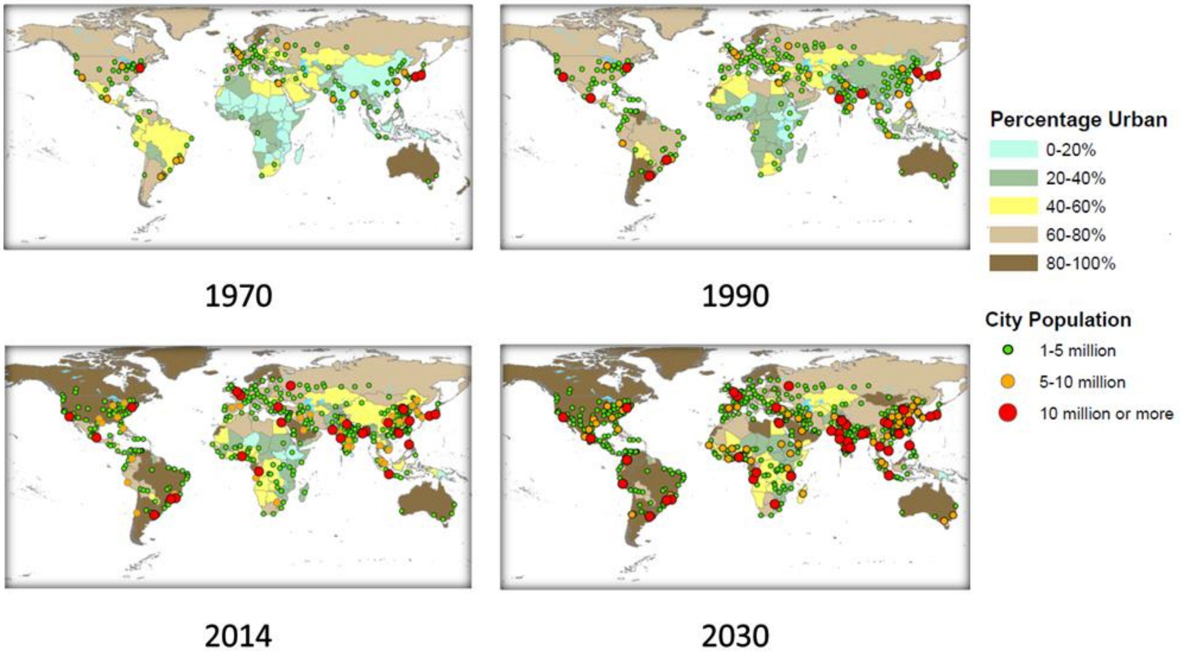
[2] The United Nations defines megacities as metropolitan areas (urban agglomerations or regions) with a population size of at least 10 million inhabitants (UN DESA, 2014a). However, there is also a range of other criteria that could be applied to define megacities.

Figure 1-1: Urbanization and emergence of urban agglomerations 1970-2030 (UN DESA, 2014b)



For many years, researchers, governments and organizations have been working on the design of potential and more sustainable pathways for energy demand. Most of these studies look at the development of whole world regions and/or nations. Only very few studies analyze energy systems at a lower geographical entity such as a city.

Energy demand in households considerably differs between locations according to various factors, including level of development, building characteristics, climatic conditions, access to energy carriers and user behavior among others. Research on energy systems at a regional or local level allows to narrow down variations of energy demand, to consider local characteristics and dynamics, as well as local policies and measures. The consideration of latter is increasingly important as cities stake out a major role in climate change action. Studies that do not only integrate local policy, but also provide guidance for local policymaking are required. The analysis of potential pathways of energy demand in cities can contribute to the understanding of possible future global and national energy trends, and improve the identification of opportunities for energy efficiency policies and measures.

Especially the so-called megacities are of interest for regional analysis due to their often large proportion on national population and economic output, as well as their association with extreme growth dynamics. Knowledge of characteristics and future trends of residential energy demand in these large urban agglomerations is often very limited. Reasons lie in uncontrolled and irregular growth, multi-jurisdictional governance structures and lack of reliable statistical data. This makes policy and research more difficult.

Mexico has communicated ambitious goals for climate change action and the country is the first developing nation that enacted a comprehensive climate change law. By 2050, Mexico wants to reduce 50% of its GHG in relation to the year 2000 (INECC, 2012a). Energy efficiency in buildings has been recognized as one important area of climate change action. In Mexico, around 15% of final energy is consumed in households (SENER, 2011a). With around two thirds of Mexico's population living in urban areas and 60% in metropolitan areas (ONU-Habitat, SEDESOL, 2011) these are key drivers for residential energy demand in Mexico. Furthermore, they are also fundamental for effective climate change action in the residential sector.

Mexico's most important political, economic, financial and educational center is the Mexico City Metropolitan Area (MCMA). Around 18% of Mexico's population lives in the area (CONAPO, et al., 2012) and one fourth of economic output is produced there (INEGI, 2015b and IGECEM, 2013). In spite of its importance for national energy demand, data and knowledge on energy consumption, its composition and potential future development in the metropolitan area is missing. This starts with the absence of official energy balances for Mexico City or the MCMA, meaning that even knowledge on current energy consumption and supply by sector is limited. However, this knowledge, as well as insights into characteristics of energy demand, such as fuel types and technologies used by households, are essential to identify opportunities for climate change action and estimate potential impacts of residential energy demand policies and measures. Although population growth in the MCMA slowed down over the last years, a still increasing number of households and their incomes may boost future energy demand with consequences of higher levels of air pollution from local gas combustion and additional requirements for local or imported electricity production. In contrast, to meet national climate change targets, residential energy demand would actually need to be substantially reduced.

1.2 Research description and thesis structure

Objective of the thesis is to improve the understanding of how residential energy demand in the MCMA could develop in the future and what would be its impact on national CO_2 emissions. To this end, a residential energy demand model for the MCMA is developed and two different development pathways for the residential energy sector in the MCMA investigated.

The scenario work shall provide answers to the following two main research questions:

- How will residential energy demand and corresponding CO_2 emissions in the MCMA develop under the absence of national and local energy-efficiency policies and measures?
- How much could the strict implementation of currently best available technologies (BATs) in the residential energy sector of the MCMA reduce energy demand and corresponding CO_2 emissions?

The development of an energy model contains a number of steps including the selection of adequate modeling techniques, the decision on considered driving forces, the definition of system boundaries and the implementation of the model. Furthermore, for the scenario design, currently implemented energy efficiency policies in Mexico need to be analyzed and available most energy-efficient technologies in the residential sector identified.

The present thesis is arranged in three main parts: background, methodological approach, and presentation of results, conclusions and outlook.

The background chapter contains an overview on current scientific practices in the field of energy modeling and scenarios including a review on modeling techniques and important residential energy demand drivers. The middle part of the chapter deals with the MCMA and provides a description of current climate change and energy efficiency policies at a regional and national level in Mexico. The chapter closes with a comparison of currently available technologies to meet different end-use services of households in terms of their energy efficiency levels.

The methodology chapter describes in detail the developed residential energy demand model for the MCMA and underlying assumptions of the designed scenarios. Furthermore, relevant data sources are named and discussed.

Finally, in the last part of the thesis results of the modeling and scenario work are presented. Based on those, in chapter six conclusions and recommendations for residential energy policy are derived. The thesis closes with an outlook on needs for further research.

2 Background

2.1 Energy modeling and scenarios

2.1.1 Introduction

The goal of sustainable energy systems requires the analysis of future developments in energy demand and available political options to reduce GHG emissions. The energy sector needs long-term planning due to the long lifetime of energy infrastructure and buildings (Ürge-Vorsatz, et al., 2012). Energy consumption and GHG emissions are the result of complex dynamic systems driven by a variety of forces such as demographic and socio-economic changes and technological developments. The future evolution of energy systems and emissions is subject to many uncertainties and therefore difficult to predict. For many years, researchers, governments and organizations have been working on the development of techniques to get insights into possible evolutions of energy systems. Important tools for the analysis have been energy models and scenarios.

Energy models are in principle simplified images of the energy system build though methodologies from mathematics and computer science (Bungartz, et al., 2014). As modeling is a process of abstraction, energy models only include certain aspects of an energy system (Van Beek, 1999). They are never a complete replication of the reality. Researchers use scenarios as tool to account for uncertainties in future developments.

Scenarios represent alternative images of how the future may look like under certain given conditions (IPCC, 2000). They should not be understood as a forecast. Model developers design scenarios by taking decisions regarding underlying forces driving energy demand, political factors and the type of modeling tool they use. These decisions are guided by the model purpose and well performance (high accuracy), but are also subject to constraints on resources, including time, knowledge and data (DEA, et al., 2013). Thus, the interpretation and comparison of results from scenarios based on energy models has to be done always in the context of underlying model assumptions. For scenarios on megacities, in addition underlying definitions of city boundaries and measurement standards are important.

Uncertainties associated with energy models and scenarios can be distinguished between “data uncertainties”, “modeling uncertainties” and “completeness uncertainties” (Functowicz & Ravetz, 1990). Data uncertainties are related with the quality or adequacy of the input data for the model. Uncertainties of the model arise from approximations of the formal representation of dependencies, or from a lacking understanding of the phenomena modeled. Finally, completeness uncertainties arise through omissions due to incomplete knowledge. The uncertainties of outputs with respect to its input (e.g. gross domestic product (GDP)) are assessed in sensitivity analyses, showing how robust model outputs are (DEA, et al., 2013).

The following chapters shall provide the reader with some background on characteristics of residential energy demand, as well as existing modeling techniques. Aim is to give an overview of scientific knowledge and practice, which has been the basis for the development of an appropriate modeling approach for the MCMA.

2.1.2 Residential sector characteristics

The residential or household sector covers all activities related to private dwellings. Energy demand of households is a derived demand from the need of people for certain services, such as comfort and hygiene, preparation and preservation of food, entertainment and communication. Typically, residential energy demand consists of space heating/cooling, water heating and domestic electricity consumption (Kriström, 2008). It does not cover energy consumption for transmission of energy to households, nor personal transport. In many studies the residential and service sector are collectively referred to as “building sector”.

The building sector is the largest end-use sector consuming around 35% of global final energy and is responsible for around one third of global energy-related GHG emissions, when indirect emissions attributed to electricity and heat generation are considered (IEA, 2013b). Residential energy demand accounts for around three-quarter of total energy consumption in the building sector (IEA, 2013b). Energy demand in urban areas differs from those in rural areas regarding structure and magnitude. While in developing countries per capita energy consumption and GHG emissions in cities are higher than national average, it is exactly the opposite in developed countries (Seto, et al., 2014). Besides, urbanization, culture, lifestyle, climate, economic development, ownership, age and location of buildings also explain differences between energy consumption of buildings (Ürge-Vorsatz, et al., 2012).

An important characteristic of residential energy demand is its close connection with capital goods, more precisely domestic appliances and buildings. This connection has implications on the speed with which energy-efficient technologies, which require less energy to provide the same service, diffuse into the stock, and so policy measures make an impact. To accelerate the diffusion of energy-efficient appliances policy measures may also focus directly on this issue. In Mexico, a substitution program for old refrigerators and air conditioners, as well as incandescent lamps (IL) for more efficient ones was successful to achieve fast improvements (CICC, 2012). In literature (e.g. Oswaldo, et al., 2014; Ürge-Vorsatz, et al., 2012), the described characteristic is often mentioned in correlation with a "lock-in risk", as GHG emissions are locked over the lifetime of the good and cannot be reduced anymore in a cost-effective way. The Global Energy Assessment (Ürge-Vorsatz, et al., 2012) for example estimates that by 2050 the size of the lock-in risk is around 79% of 2005's global heating and cooling final energy in buildings, in the case that building codes are introduced universally, retrofits are accelerated, but policies will not ask for state-of-the-art efficiency levels.

2.1.3 Driving factors

The type and level of service, as well as the quantity and type of energy required by households varies considerably. Beside differences between households, there are also changes over time. Elements that contribute to changes of energy demand and GHG emissions are referred to as "drivers" in this document. The identification of drivers is not simple, and there is neither a unique method to identify drivers for energy demand, nor the relation between cause-and-effects is always clear. This has to do with the fact that energy demand is a result of human activities and thus a complex network of interactions. Literature on drivers for residential energy demand is rich with contributions from engineers, economists, social scientists and other researchers. Studies identified a large number of drivers for residential energy demand. The Global Energy Assessment (Ürge-Vorsatz, et al., 2012) points out several factors as major contributors to changes in building energy demand: population development, urbanization, shift from traditional to commercially available energy carriers, income, level of development, cultural features, level of technological development, individual behavior, and financial aspects of technologies and energy carriers. The list does not cover all drivers identified by researchers, but includes the most recognized ones. It is not possible to go here in depth about all factors. Thus, in the following those drivers are discussed, which are seen most important by literature and seem especially relevant for megacities and the MCMA. By name, these are demographic changes, income growth related to economic developments and technological advancement.

Existing energy demand models (e.g. World Energy Model (WEM): IEA, 2014b) recognize population developments and dwelling occupancy as two important drivers for projections. Megacities experience drastic population growths during their development (UN DESA, 2014a) due to natural growth, but especially migration and changes of city boundaries (Kraas, et al., 2014). Thus, population is an important driving force particularly for energy demand in megacities. However, capturing the real population size of megacities can be an issue, as not all immigrants are always registered in the city (Phdungsilp, 2006). There are additional demographic factors with an impact on energy demand such as changes in the age structure (Fan, et al., 2006).

Economic growth is a key driver for most energy models (Mundaca & Neij, 2009). The relationship between economic activity and energy consumption has been well studied by researchers (e.g. Ozturk, et al., 2010 and Campo & Sarmiento, 2013). In the residential sector, income is linked with economic growth, and thus often expressed through measures of GDP or Gross Regional Product (GRP) for cities (Seto, et al., 2014). Megacities contribute significantly to national and international economic growth (PricewaterhouseCoopers LLP, 2008), and show large income disparities (Kraas, et al., 2014). Recent studies (Gertler, et al., 2012 and Wolfram, et al., 2012) point out that not only economic growth rates, but also to which extent low-income groups benefit from the growth plays an important role in projecting energy demand of the household sector especially in developing countries. They state that increases in income that lead to the purchase of energy-using assets for the first time in households have much higher impacts on energy consumption than those when the asset is already available. Therefore, conventional models that do not consider income distributions may underestimate the energy growth in developing countries and megacities. Due to the typical large interconnection of the megacity economy, projections of GRP may depend to a large extent on expectations of national and international economic developments. Energy projections based on GDP are quite sensitive, as economic development is very uncertain (DEA, et al., 2013). In addition, GRP estimates for megacities may be challenging for two reasons: a) megacities often have large informal sectors, which are not included in official statistics of GDP or labor (Daniels, 2004) and b) boundaries of the city may not correlate with statistical units (Cattan, 2007). Beside its impact on energy consumption, economic growth may also have an impact on the fuel choice of households (Barnes, et al., 2005). Finally yet importantly, households respond to price changes of energy carriers and appliances, while price elasticities are normally larger for the long-term than short-term (Kriström, 2008).

Energy use in households is connected with domestic appliances, which provide a certain service consuming energy (electricity, thermal energy) (Kriström, 2008). The increase in energy-efficiencies of appliances is a major target of climate change and energy policies, as it allows energy and GHG reductions without constraints in services. Countries have implemented different kinds of policies in the sector, such as building codes or incentives (Nejat, et al., 2015). Megacities have constraints, but also opportunities for the implementation of low-carbon technologies (Grubler, et al., 2012). Possibilities to reduce GHG emissions by technological change are discussed in depth in chapter 2.3. Energy efficiency gains can lead to shifts in consumption patterns, as they provide the same level of service using less energy, what makes the service cheaper (Aydin, et al., 2014). If consumers find services cheaper, they might opt to use the service more (e.g. decrease the set point of the thermostat for an air-conditioner) or purchase larger appliances (e.g. a television with a larger screen area). Real energy savings can therefore be lower than estimated based on technology improvements, what is known under the term "rebound effect" (Greening, et al., 2000). The impact of the rebound effect varies significantly between technologies, regions and sectors, and evidence of its possible magnitudes is sparse (IEA, 2013b).

2.1.4 System boundaries

Essential for the analysis of megacities is a clear definition of city boundaries, as it can substantially influence on results. This task is not simple, as it is often not clear where a metropolitan area begins and ends. In addition, due to their dynamic, boundaries of megacities often change over time (Cattan, 2007). There is no common approach used to define metropolitan areas, but literature names a number of methods to establish boundaries of an urban area. In most cases, there are also country specific criteria defined by domestic institutions (CONAPO, et al., 2012).

Three common types used in literature to define boundaries of urban areas are:

- **Administrative boundaries:** denoting political or territorial boundaries (Aguilar & Ward, 2003 and Hartshorne, 1933);
- **Functional boundaries:** referring to connections or interconnections between areas related to e.g. economic activity (Douglass, 2000 and Brown & Holmes, 1971); and
- **Morphological boundaries:** defined according to characteristics of land use, land cover or the environment of construction (Benediktsson, et al., 2003).

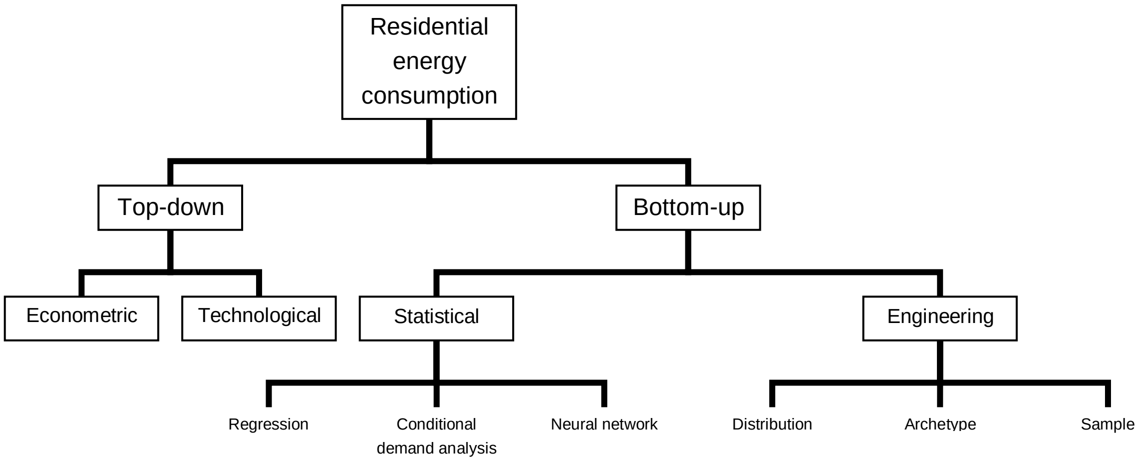
A criterion that should also be taken into account defining system boundaries of megacities for modeling purposes is for which coverage required data is available. Megacities often have multi-jurisdictional governance structure and statistical data for the metropolitan area as a whole often does not exist. (Cattan, 2007)

2.1.5 Modeling techniques

Over time a great variety of methodological approaches and hybrid forms of residential energy demand models have been developed. Therefore, it is not possible to strictly classify energy demand models. Based on a literature review Van Beek (Van Beek, 1999) identified nine different ways to classify energy models: purposes of energy models, model structure, analytical approach, underlying methodology, mathematical approach, geographical coverage, sectoral coverage, time horizon, and data requirements. It is not possible to discuss here in depth all characteristics and differences of energy models. Therefore, for more information it is referred to relevant literature (Van Beek, 1999; Bhattacharyya & Timilsina, 2010 and Messner & Strubegger, 1999). However, in the following some aspects of modeling techniques are highlighted.

A typical categorization of energy demand models is the differentiation between bottom-up and top-down models. The terminology refers to the hierarchal position of used input data in comparison to the sector as a whole. Based on a literature review on residential energy demand models Swan and Ugursal (Swan & Ugursal, 2009) distinguished the two approaches further into sub-groups (Figure 2-1). Top-down models correlate energy consumption to macroeconomic variables such as energy prices or GDP (econometric model) or to broad characteristics of the housing stock, for example housing construction/demolition rates or appliance ownership trends (technological model). In comparison, bottom-up models calculate energy consumption for individual or grouped end-uses or houses and then extrapolate it to represent a certain area. They either use statistical methods (statistical model) or engineering methods (engineering model) to project energy demand. An advantage of top-down approaches is that they use to provide a more complete representation of macroeconomic trends and feedbacks, while the bottom-up approach gives a more detailed representation of the energy system (DEA, et al., 2013). There are also hybrid models that attempt to use the advantages of both approaches (e.g. WEM: IEA, 2014b).

Figure 2-1: Modeling techniques for residential energy demand (Swan & Ugursal, 2009)



Mundaca and Neij (Mundaca & Neij, 2009) identified four methodological categories of residential bottom-up energy-economy models: simulation, optimization, accounting and hybrid models. In simulation models, the energy system is illustrated based on logical linkages between user-behavior and drivers (e.g. Residential End-Use Energy Planning System (REEPS) or WEM). Accounting models or spreadsheet models require users to define outcomes beforehand and then account for flows of energy (e.g. Long-Range Energy Alternatives Planning (LEAP) and Bottom-Up Energy Analysis System (BUENAS)). Optimization models attempt to find solutions based on a least-cost approach concerning technology choice and include constraints of markets and by policy (e.g. Market Allocation (MARKAL) model generator and PRIMES Energy System Model). Finally, hybrid models merge approaches and make use of different characteristics.

Energy scenarios are often distinguished between normative and descriptive scenarios (IPCC, 2000). Normative scenarios are value-based and teleological. The desired or undesired outcome is given and the path to it is explored. In contrast, descriptive scenarios have no preconceived end-point and explore the route into the future.

Scenario development related to energy and climate change policy typically includes the development of a baseline scenario (or reference scenario) and one or various mitigation scenarios. There are no commonly agreed definitions of these terms. Typically, baseline scenarios describe GHG emission developments in the absence of future, additional policies to mitigate climate change (DEA, et al., 2013). In contrary, mitigation scenarios project future GHG emission based on a defined set of new mitigation efforts and policies (DEA, et al., 2013).

2.1.6 Current research

Most investigations on energy and GHG emission scenarios carried out focus on a global or national level. Examples with integral analysis of energy systems are IEA, 2014a; WEC, 2013; Greenpeace, et al., 2012a and DLR, 2010. For governments energy scenarios are of importance for domestic planning purposes or as part of international agreements. There are also studies that did an in depth analysis of possible low-carbon and energy-efficient developments for the residential sector directly or in form of a sub-sector of the building sector. Very comprehensive studies with global coverage have been done by the International Institute for Applied System Analysis (IIASA) and the International Energy Agency (IEA):

- The Global Energy Assessment (GEA) launched in 2012 under the coordination of the IIASA includes a chapter with an in-depth analysis of the global energy-end use in the building sector and pathways for its sustainable transition. The GEA in particular highlights the important role of systemic solutions. (see Ürge-Vorsatz, et al., 2012)
- The IEA published several studies concerning sustainable buildings. As part of the "energy technology perspective series", the IEA examined innovations in the building sector and developed global strategies and scenarios to 2050 (see IEA, 2013b). Other publications deal with political pathways for energy efficiency in buildings (see IEA & UNDP, 2013, IEA, 2010a and IEA, 2010b).

Scenarios on energy consumption and GHG emissions at a city level are still scarce. A reason for this is the lack of city scale data (Grubler, et al., 2012). However, efforts are undergoing to improve the available amount and quality of city data. Examples are IIASA work on a global database on urban energy consumption (Schulz, 2010) or the implementation of a Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) in collaboration between C40 Cities Climate Leadership Group, the World Resource Institute (WRI) and ICLEI Local Governments for Sustainability to achieve global standardized reporting on GHG emissions of cities (Fong, et al., 2015). Some energy system analysis research for cities has already taken place, and it is expected that research efforts will be intensified over the next years.

In the following, some studies shall be highlighted:

- "Risk Habitat Megacity" was a joint research initiative between six German research institutes under the Helmholtz Association and six Chilean organizations, which analyzed sustainable development options for Santiago de Chile (Krellenberg, et al., 2010). Scenarios were developed for different thematic fields including energy and assessed according to sustainability indicators (Simon, et al., 2012).

- The Economic Commission for Latin America and the Caribbean (CEPAL, Spanish acronym) has studied strategies for sustainable development in megacities of Latin America (Samaniego & Jordán, 2013). The study also included the analysis of the building sector in six megacities.
- Energy use of households in Asian Megacities was studies by the Institute for Global Environmental Strategies (IGES). A bottom-up end-use model was developed to predict trends in energy demand considering lifestyle factors, as well as architectural and energy device characteristics (Matsumoto, et al., 2003). In addition, research was carried out on policies and barriers for sustainable energy consumption over all sectors (Dhakal, 2004).

2.2 Mexico City Metropolitan Area

2.2.1 Profile

The MCMA is the dominating center in Mexico regarding political, economic, financial and educational activities. The city is globally interconnected and of major importance for national and regional development (ECLAC, et al., 2010 and GaWC, 2014). When Mexico started its process of urbanization at the beginning of the 20th century, Mexico City was the principle destination for internal migration (ONU-Habitat, SEDESOL, 2011). The city started to grow fast and sprawl from the Federal District (DF, Spanish acronym) into the State of Mexico and Hidalgo forming a metropolitan area of nowadays 7,866 square kilometer (km²). With more than 20 million inhabitants (CONAPO, 2010) the MCMA is currently the fourth largest urban agglomeration in the world (UN DESA, 2014a). Along with the development of Mexico City, also neighbor cities started growing. Thus, today the MCMA is surrounded by five other metropolitan areas with an increasing economic interconnection between each other forming the "megalopolis of the Centre Region"[3] (Figure 2-2). The megalopolis concentrates around 30% of the Mexican population, and holds around 42% of the national GDP (ONU-Habitat, SEDESOL, 2011), respectively 18% and 25% for the MCMA alone (CONAPO, et al., 2012; INEGI, 2015b and IGECEM, 2013).

The MCMA lies in a valley in the high plateaus at the center of Mexico surrounded by mountain ridges (Ciudad de México, 2015). In its natural state, the valley was covered by lakes (Ciudad de México, 2015). The metropolitan area is situated in the tropical zone at an altitude of 2,240 meter above sea level (MexicoCity, 2015). Thus, seasonal variations in temperatures are small and average temperatures vary in the major part of the city between 11°C and 20°C (INEGI, 2013a). Due to unfavorable topographic and metrological conditions, as well as high emissions from vehicles, industry and domestic gas usage, air pollution is a great problem for Mexico City and the whole region. Since the 1970s, the problem has been recognized from politicians and a number of successful programs and plans have been established to reduce emissions such as the program to improve air quality management (ProAire, Spanish acronym) (CAM, 2011).

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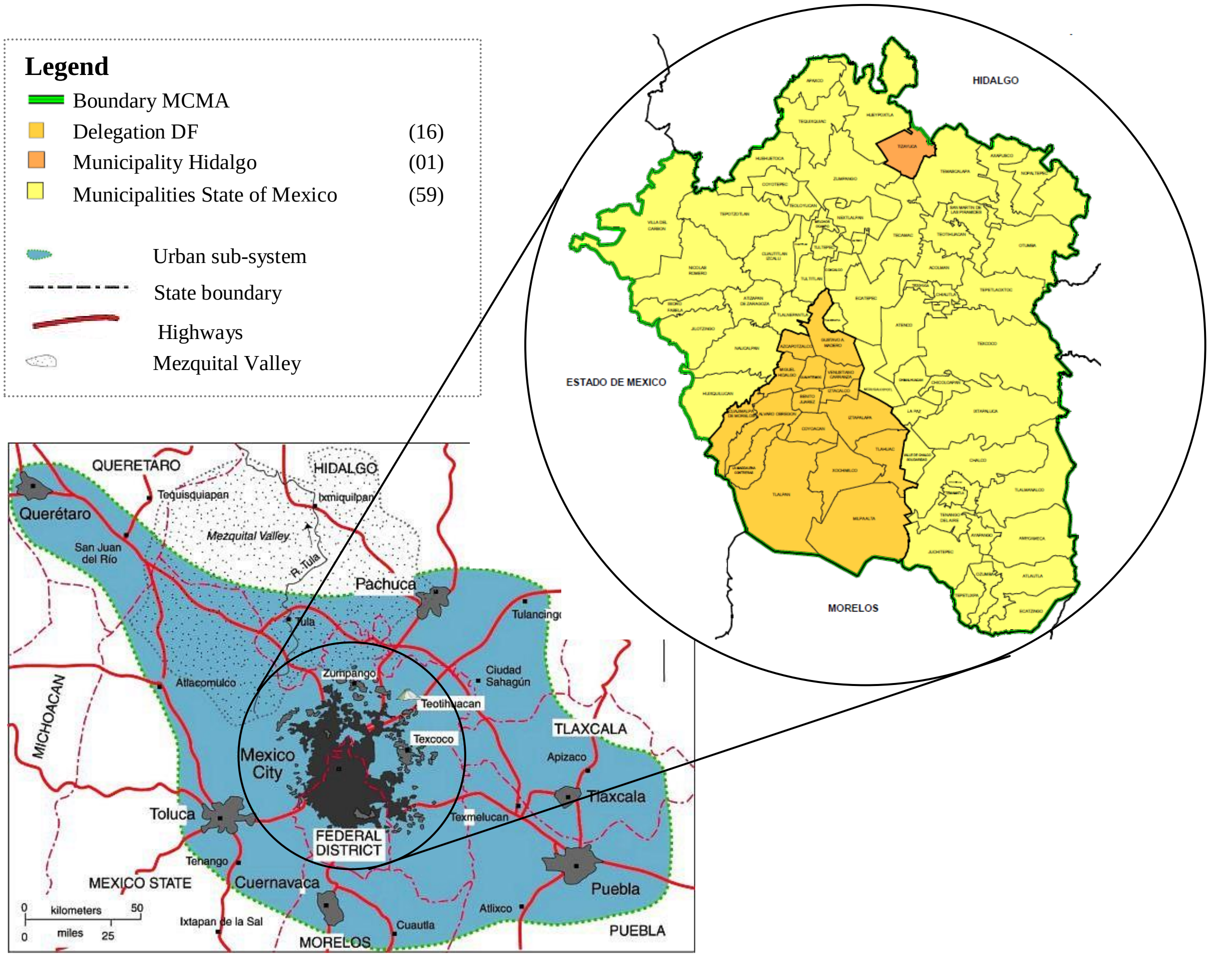
[3] The term megalopolis is used for sets of connected metropolitan areas, which form part of a polynuclear urban areas (ONU-Habitat, SEDESOL, 2011).

Figure 2-2: Mexico City Metropolitan Area within the Megalopolis of the Center Region Chart adapted and modified from (Geo-Mexico, 2010 and FEECM, 2000)



2.2.2 Residential energy demand

The MCMA is well developed in terms of access to energy carriers and use of modern fuels. Almost all households in the MCMA have access to electricity, apart from some few exceptions (Table 2-1). Traditional fuels, such as biomass play a tangential role for domestic energy consumption. Only around 1% of the households in the MCMA use biomass, coal or fuels other than gas or electricity for cooking (INEGI, 2010a). The MCMA faces some problems of water scarcity, a typical problem of megacities, what may get worse with increasing impacts from climate change (Lanko, 2010).

Table 2-1: Access of households to basic services in the MCMA in 2010 (INEGI, 2010c)

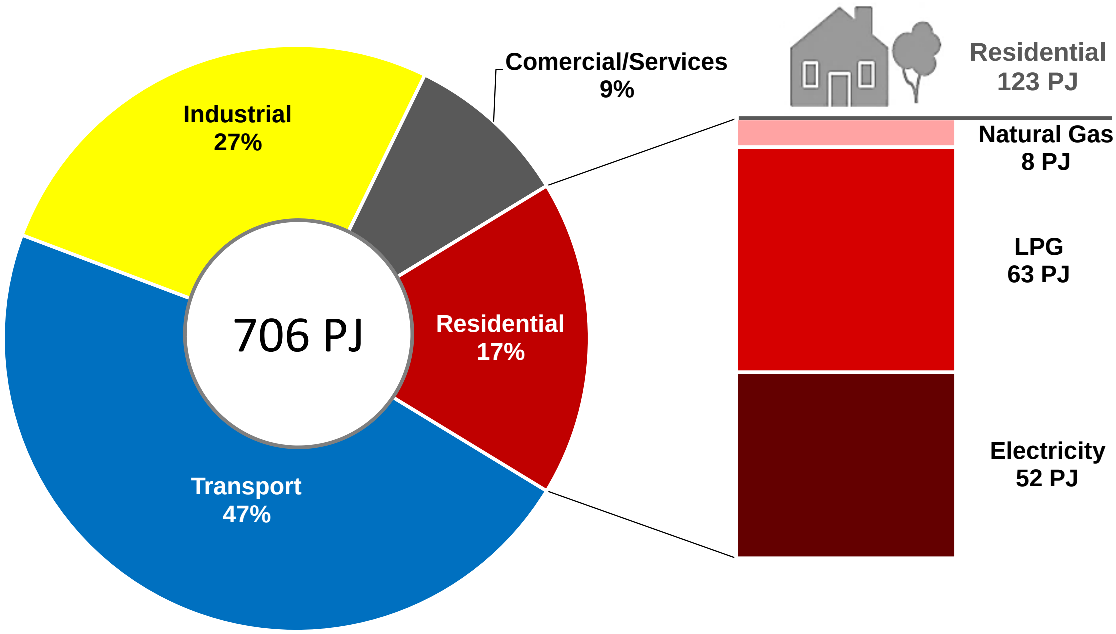
	DF	MCMA	National
Electricity	100%	100%	98%
Water access inside the housing or terrain	97%	96%	92%
Daily water supply*	82%	72%	N/A

*of those households with water access inside the housing or terrain

After extraordinary population growth rates in the MCMA during the period 1950-1980, demographic expansion slowed down and fall below 1% in the 21st century (UN DESA, 2014a). The population development is a result of a slowdown of migration from urban to rural areas, as well as the fact that the Mexican population is no longer only concentrated in the MCMA, but in several large cities (ONU-Habitat, SEDESOL). The MCMA is often classified as a global city with high service levels and foreign direct investments (OECD, 2004). However, its productivity and competiveness in comparison to other metropolitan areas is low (OECD, 2004). Real GDP per capita (excluding Tizayuca, Hidalgo) grew in average by 1.2% in the period 2003-2011, also due to the economic crisis in 2008/2009 (INEGI, 2015b and IGECEM, 2013).

Local and federal environmental governments started in 1989 to develop biannual emission inventories for the MCMA under the main objective to guide air pollution policy (SEDEMA, 1998). The inventory from 2010 (SEDEMA, 2010) estimates that activities in the MCMA are responsible for around 9% of national CO_2 equivalent (CO_2e) emissions made of 54.7 million tons of carbon dioxide equivalent ($MtCO_2e$) emitted within the borders of the MCMA and additional 9.9 million in other parts of the country. It also states that around three quarter of electricity consumed in the MCMA is imported. The portion of residential energy demand on total energy consumption varies considerably between megacities (WEC, 2010). Considering gas and electricity sales in the MCMA, primary energy consumption is estimated to around 123 petajoules (PJ) for the residential sector, accounting for 17% of total energy consumption in the MCMA in 2010 (SEDEMA, 2010) (Figure 2-3).

Figure 2-3: Primary energy demand by sector in the MCMA in 2010
Own graph based on (SEDEMA, 2010)



Energy use in households in the MCMA is divided into gas, mainly liquefied petroleum gas (LPG), and electricity (Figure 2-3). Typical end-uses relying on gas are water heating and cooking (INEGI, 2010a). Domestic appliances, lightning and electronics are the basis for electricity consumption. The saturation of households in the MCMA with appliances increased over the last years. The largest raises in saturation for the period 2000-2010 show computer with 156% and washing machines with 17% (INEGI, 2000 and INEGI, 2010a). Due to the pleasant temperatures over the year, there is almost no demand for heating and cooling in the MCMA (see INEGI, 2010a).

2.2.3 Institutional framework

Mexico is a federal republic. It has a democratic and representative government system. The Mexican Constitution divides public power into three levels: the federal (central) government, 32 federal entities and around 2,500 municipalities. Executive, legislative, and judiciary branches are separated in their function. Over the last 20 years, Mexico has gone through a process of decentralization (OECD, 2003). In this way, state and local governments gained on political and economic autonomy.

Today, the MCMA is not an administrative unit, but rather defined by its functional and socioeconomic interconnection (CONAPO, et al., 2012). The governance and administration of the MCMA is quite complex with various governmental units coming together. The legal status of the Federal District (Mexico City), as the capital of the country, is different from those of the rest of the Mexican states. It has different responsibilities, revenue opportunities and no own constitution (OECD, 2004). The complex institutional structure of the MCMA is an important obstacle for regional planning.

The need for regional cooperation has been recognized and led to the creation of plethora regional coordination and planning institutions, the creation of regional trusts and other coordination mechanisms, as well as federal programs targeting the metropolitan area (OECD, 2004). Examples for a coordination body are the sector-specific metropolitan commissions. One of them was the Metropolitan Environmental Commission (CAM, Spanish acronym), which was replaced in 2013 by the Megalopolis Environmental Commission (CAME, Spanish acronym) now including the whole megalopolis with 16 delegations from the Federal District and 224 municipalities (Se Responsable, 2013). The Commission worked successfully in the coordination, planning and execution of measures to reduce air pollution, such as the program "Hoy No Circula" (No driving day) (CAME, 2015). Beside the large amount of bodies and planning attempts, their success for coordination seems quite limited thus far. Main reasons are a missing shared "metropolitan vision" and the financial disequilibrium between the different actors in the region (OECD, 2004).

Energy policy in Mexico is in principle responsibility of the national government. Possibilities for federal and municipal governments to influence energy consumption of households at a regional level are quite limited. State programs can include energy aspects, when they are connected to climate change mitigation and adaption. The legal framework for energy policy in the residential sector in Mexico is given by the Ley for Climate Change General Act, the Law on Sustainable Energy Use and the Housing Act (Florián, et al., 2013). The National Development Plan (PND, Spanish acronym) 2013-2018 sets criteria and principles for sector, state and municipal planning with the goal of a peaceful, inclusive and prosper Mexico with quality education and taking global responsibility.

2.2.4 Climate change policy

In 2009, Mexico communicated that the country is planning to reduce 30% of its GHG emissions by 2020 in relation to a baseline scenario (UNFCCC, 2014). Furthermore, in the long term Mexico is planning to reduce 50% of its GHG emissions by 2050 in relation to the year 2000 (INECC, 2012a). This goal is seen to be consistent with international efforts to stabilize atmospheric GHG concentrations below 450 parts per million (ppm) (DEA, et al., 2013). According to plans from the Mexican National Institute for Ecology and Climate Change (INECC, Spanish acronym) GHG emissions in the building sector shall be reduced by 53% (17 $MtCO_2e$) up to the year 2020 and 72% (27 $MtCO_2e$) up to the year 2030 in relation to a baseline scenario (INECC, 2010). With that, the building sector shall contribute to around 5-7% of overall emission reductions (INECC, 2010).

With the publication of the Climate Change General Act (LGCC, Spanish acronym) in 2012, these targets, as well as Mexico's goal to reach 35% clean energy in electricity production by 2024, became legally binding (INECC, 2012a). Mexico is the first developing country that enacted a comprehensive climate change law. The LGCC provides for two fundamental instruments to orientate and arrange public climate change policy. The first one is the National Strategy for Climate Change (ENACC, Spanish acronym) providing a medium and long-term guidance for policy at federal, state and municipal level. The second one is the Special Climate Change Program (PECC, Spanish acronym), a framework program, which establishes strategies, goals and lines of action for mitigation, adaption and crosscutting policy in line with the ENACC. Lines of action to reduce GHG emission for or related to the residential sector in the current PECC 2014-2018 include the promotion of energy efficiency through Official Mexican Standards (NOM), the promotion of distributed energy generation, the strengthening of programs for solar water heaters, the boost to realize National Appropriate Mitigation Actions (NAMA) for housings, and the development of programs for domestic refrigerators.

The inter-ministerial Commission for Climate Change (CICC, Spanish acronym) organizes the activities of the different agencies of the Federal Public Administration (APF, Spanish acronym) regarding climate change mitigation and adaptation. At a regional level, the different states establish local offices of the CICC, which coordinate appropriate public policies, design or modify their laws to contain climate change issues aligned with provisions from the Federal Government. They also work on State Action Plans on Climate Change (PEACC, Spanish acronym). All three states forming the MCMA have concluded PEACCs. In addition, the Federal District has a state committee on climate change and a local law on climate change. Some municipalities have a Municipal Climate Action Plan (PACMUN, Spanish acronym) in addition to the federal one.

Although the MCMA is interconnected in many aspects, there is no common and widely shared 'vision' or action related to climate change in the metropolitan area. The

Federal District, as the capital of the country, has been a pioneer in climate change action among states in Mexico in the past.

In recent years, Mexico made various efforts to develop strategies and actions for low-carbon development, which support the achievement of the set goals. These included the development of national emission baseline scenarios and the identification of cost-effective mitigation potentials for different sectors. GHG emission abatement cost-curves developed by Mc Kinsey & Company have provided the basis for the selection of mitigation measures (compare Mc Kinsey & Company, 2009). The National Institute for Ecology and Climate Change (INECC before INE, Spanish acronym) analyzed the most important strategies and measures in the medium-term in the base document for a Low Carbon Development Strategy (LEDS) in Mexico (INECC, 2012c).

2.2.5 Energy policy

The conservation of energy and the promotion of an increasing use of renewable energy resources are part of national strategies in Mexico for more than 15 years. Since then, Mexico is quite active in the implementation of policies to accelerate the use of energy-efficient domestic appliances. The Mexican Secretary of Energy (SENER) is the leader in political decisions according to energy efficiency, while the execution and supervision of the measures, projects and programs is responsibility of the National Commission for Energy Efficiency (CONUEE, Spanish acronym) and the Trust Fund for Electricity Savings (FIDE, Spanish acronym).

In consistence with the PND, the SENER is responsible to develop the sectorial program for energy (PSE, Spanish acronym) and establish the commitments of federal dependencies and organisms related to energy. Additionally, congruent to the PSE, a framework program for energy efficiency, the National Program for Sustainable Energy Use (PRONASE, Spanish acronym) is implemented. Lines of actions of the current PRONASE 2014-2018 include the development of operational programs for the adaption of energy-efficient technologies, thermic insulation, solar water heaters, and the regulation of energy efficiency requirements.

Three core elements of recent energy policy in the building sector in Mexico are energy performance standards and labels, solar water heaters and sustainable buildings. Each discussed in more detail in the following.

Standard and labelling program

The implementation of energy performance standards and labels is very advanced in Mexico. Regulations from the United States of America (USA) have served as role model for Mexican programs and standards were often harmonized to those (Harrington & Damnics, 2004). There are two types for each, energy efficiency labels and standards, established in Mexico.

Labelling programs (Harrington & Damnics, 2004):

- **Comparative label:** a mandatory label implemented by the CONUEE showing energy savings relative to minimum energy performance standards (MEPS) (see standard below); and
- **Endorsement label:** the "seal FIDE" ("Sello Fide", Spanish) is a voluntary label implemented by FIDE.

Standards according to the Federal Law of Metering and Standards (SE, 2015):

- **Official Mexican Standards for Energy Efficiency** (**NOM-ENER**, Spanish acronym)**:** are mandatory standards including MEPS and test procedures to determine the performance of products; and
- **Mexican Standards** (**NMX**, Spanish acronym)**:** voluntary standards.

Typically, it needs about two years to enact a new standard in Mexico (CONUEE, 2012). Obligatory energy efficiency labels are required for domestic water heaters, washing machines, refrigerators and freezers, air conditioners, building envelopes and window characteristics (CONUEE, 2014). Table 2-2 provides an overview of NOM-ENERs that came into force by 2013. Mexico has laboratories and procedures in place to ensure compliance with energy efficiency certificates and performance standards (CONUEE, 2012). Some impacts of the standard and labelling program in Mexico are highlighted in the following.

Table 2-2: Overview of Official Mexican Standards for the residential sector 1995-2013 (SENER, 2014)

Appliance type	Into force for first time	1st actualization	2nd actualization	3rd actualization
Water heaters	07/05/1997	28/02/2001	07/11/2011	
Washing machines	11/05/1997	28/10/2000	03/06/2010	04/02/2013
Refrigerators & freezers	01/01/1995	01/08/1997	16/05/2003	16/05/2012
Cook stoves	14/12/2013			
Compact fluorescent lamps	23/06/1998	24/12/2008	10/03/2013	
Lamps for general usage	04/02/2011			
Air conditioners	08/02/1998	05/11/2002	21/08/2007	
Split air conditioners	01/09/2011			
Room air conditioning	01/01/1995	24/06/2001	31/01/2009	
Thermal insulation products	24/10/1998	12/02/2012		
Building envelope	07/12/2011			
Glass for buildings	17/04/2013			

The standard for water heaters establishes MEPS for thermal efficiencies of gas water heaters. Thermal efficiencies of storage water heaters, the most common type in Mexican households, increased over time from 74% to 80% in 2010 (SENER, 2010). Standby heat losses are not regulated, as overall efficiencies are not considered in the standard. However, it is reported that tank insulations improved anyway (SENER, 2010). Likewise the energy efficiency standards, there are also standards to regulate water consumption in housings (NOM-CNA, Spanish acronym).

Energy efficiency programs for refrigerators & freezers led to dramatic increases in efficiencies of around 62% in the period 1994 to 2005 and for washing machines 72% for the same period. Improvements even exceeded requirements of MEPS, what may be an indicator for the orientation of manufactures to the US and Canadian market rather than only the Mexican market. Test procedures for refrigerators and freezers are harmonized with the USA giving the advantage that consumption values between both countries can be compared directly and do not require normalization. (Sánchez Ramos, et al., 2006),

The latest Mexican standard for domestic refrigerators (NOM-015-2012) requires in average 25% higher efficiency levels than standards of other Central American countries. In the past, Mexican refrigerator standards have been harmonized with the USA. The current standard in Mexico lies about 20% below energy efficiency requirements of the new US standard from 2014. However, it is probable that Mexico will harmonize its standard in the near future. (UNEP & CLASP, 2015)

In 2011, a new standard for lamps for general use, the NOM-28-ENER-2010, came into force. The standard established the gradual phase-out of ILs in the residential sector. In Mexico, ILs could be commercialized until December 2011 in case of lamps with 100W or more power, until December 2012 for lamps of 75W and until December 2013 for lamps of 60W and 40W according to the standard. To support the standard, a campaign promoting energy-efficient lighting was initiated and a program was implemented to facilitate marginalized groups the acquisition of energy saving lamps (DOF, 2009). In addition, there is a standard for compact fluorescent lamps (CFL), last time updated in 2013.

Currently, there is no official compulsory standard for solar water heaters (SWH) in Mexico, but a Technical Report on Residential Solar Thermal Systems and several Mexican Norms, which are voluntary (CONUEE, 2014). In addition, a training standard for thermosiphon systems in single-family homes has been introduced (CONOCER, 2014).

Solar water heating

The SWH market in Mexico exhibited strong growth over the last years, increasing from an operating capacity of 723.8 megawatt thermal (MW_{th}) by the end of 2008 to 1,755 MW_{th} by the end of 2013 (Weiss & Mauthner, 2010; Mauthner, et al., 2015). The United Nations Environment Program (UNEP) assessed the market readiness for SWHs regarding policies, finance and investment, business, and quality control infrastructure across various countries including Mexico. The study (UNEP, 2014) assessed the enabling environment for SWHs in Mexico to be strong and likely ready to attract investment (score 3.9/5). Barriers identified included the lack of a formal target for SWH market penetration and existing heating fuel subsidies in Mexico. Another study (UNDP, 2009) recognized high initial costs, lack of consumer awareness, missing quality control and trust in the product and its installation, as well as a lack of suitable and attractive financing mechanisms as main obstacles. However, it has also been shown that solar water heating is already economic viable in Mexico in many cases (CONUEE, et al., 2007).

Several initiatives and programs have been implemented in Mexico to maintain and accelerate the growth of the SWH market. Examples are the Program for the Promotion of Solar Water Heaters (PROCALSOL, Spanish acronym) 2007-2012 from CONUEE (CONUEE, et al., 2007) and Solar Water Heating Market Transformation and Strengthening Initiative 2008-2012 from UNDP (UNDP, 2009).

For PROCALSOL recently a follow-up program has started, the PROCALSOL 2014-2018. The new program tries to promote SWHs through the creation of a new subsidy scheme, a new compulsory standard regarding the performance of SWHs, as well as standards for the training of installers. Target of the program is an increase in the domestic SWH market by 20% yearly up to the year 2018 (Epp, 2013).

The investment in SWHs for residential houses in Mexico is supported by the Green Mortgage Funds (Hipoteca Verde) from the Institute for the National Housing Fund for Workers (Infonavit, Spanish acronym) for the implementation of ecological technologies in housings. In 2012, the Green Mortgage Funds provided financing for around 100,000 square meter (m^2) of glazed collector area representing a share of 53% on the total national installation in that year (Epp, 2013).

Sustainable Housing

The National Housing Commission (CONAVI, Spanish acronym) is the coordinative organ of federal policies in the building sector (Florián, et al., 2013). The national framework program for the building sector is the National Program for Housing (PVE, Spanish acronym).

Building codes in Mexico are established at a federal or municipal level and can contain energy codes. CONAVI published in 2010 the second edition of a regulatory model for building codes in Mexico, which includes a chapter for sustainable energy use and supply in buildings (CONAVI, 2010). The Federal District is the only state that counts with a certification scheme for sustainable buildings applying criteria in the areas of energy, water, waste, quality of life and social responsibility, as well as environmental impact (SEDEMA, 2008). For energy, the program promotes energy savings in electricity and the installation of SWHs.

Concerning financing of purchase, construction, and renovation of houses, the Infonavit plays an important role, supporting around one third of all home mortgages in Mexico (Lastras, 2012). The agency provides low-interest loans for investments in ecological technologies such as solar water heaters or fluorescent lamps (Infoanvit, 2015a). Since 2011, the implementation of ecological technologies is a requirement for all credits for housings by the Infonavit (Infonavit, 2015b). In addition, CONAVIs program “That’s your home” (“Esto es tu casa”, Spanish name) providing subsidies to low-income groups includes since 2009 criteria for energy efficiency in housings.

NAMAs are planned for the time period 2012-2020 supplementing on-going initiatives for sustainable housing in Mexico from CONAVI.

2.3 State of the art outlook for technologies in the residential sector

2.3.1 Content

In the following, a general overview on currently most common technologies used by households, as well as available more energy-efficient alternatives, is presented. The alternative energy demand scenario in the thesis applies the here identified energy saving opportunities under the consideration of regional specifications.

The review is limited to those technologies using modern fuel types, as traditional fuels play a minor role in households in the MCMA. Furthermore, energy saving opportunities for space heating and cooling are not discussed, due to their low relevance for the MCMA.

2.3.2 Water heating

Water heating is a major energy consumer in the residential sector with large potentials for technical improvements (IEA, 2013b). Conventional storage water heaters and instantaneous water heaters working either with gas or with electricity dominate the global market for water heating technologies (BSRIA, 2014). While storage water heaters have hot water ready stored in a tank at any time, instantaneous water heaters produce hot water on demand using a gas burner or electric heating coil (US DOE, 2013a). Thus, instantaneous water heaters tend to have higher energy efficiencies by eliminating standby heat losses associated with a tank and often substantially reducing pipe losses (IEA, 2013b). Gas water heaters have normally lower rated energy efficiencies than electric ones, due to the combustion efficiency of gas and higher tank losses, but are more energy-efficient looking at the source efficiency, which takes into account all consumed primary energy (NREL, 2013).

Major technologies for water heating to reduce energy consumption are condensing water heaters for gas heating, heat-pump water heaters for electric heating and solar thermal water heaters. Condensing water heaters improve the energy efficiency of storage and instantaneous gas water heaters by about 10-30% capturing the latent heat of the combustion gas before it exits (NREL, 2010). Another promising technology with raising popularity are heat pumps, although their share on the market is still low (IEA, 2013b). They operate on an electrically driven vapor-compression cycle removing heat from the ambient air to water in a tank and achieve an energy factor (EF) between 2 to 3 depending on the unit (Hepbasli & Kalinci, 2009). Finally, solar domestic water heaters offer great potentials for energy savings and are already widely used in a number of countries. They can be stand-alone systems or be combined with a backup system consisting of any of the previously described technologies. In general, solar water heating systems are small systems with a collector area of between 3 to 6 m² and a storage tank of 150-300 liters, designed to provide between 30% to almost 100% of the demand, depending on collector size, storage volume and climate (IEA, 2012). Common market barriers for energy-efficient water heaters are high initial costs, poor customer awareness and lack of trained installers (NREL, 2013). Table 2-3 presents an overview of typical efficiencies, lifetimes and costs of different domestic water heating systems in the US market based on estimations from the US Energy Information Administration (US EIA).

Table 2-3: Comparison of typical energy efficiencies, lifetimes and costs of various residential water-heating technologies in 2013 on the example of the US market (US EIA, 2015)

	Gas Storage	Electric Storage	Instantaneous*	Heat Pump	Solar
Typical capacity	40 gal	50 gal	178 kBtu/hr	50 gal	42-63 sq.ft.
Energy Factor	0.62	0.92	0.82	2.0	2.5**
Lifetime	6-20 a	6-20 a	8-30 a	6-20 a	20 a
Installing cost	0.99-1.02 $ thousand	0.61-0.67 $ thousand	1.43-1.93 $ thousand	1.61-2.33 $ thousand	7.60-10.00 $ thousand
Annual maintenance cost	14 $	6 $	85 $	16 $	25 $

* mainly gas-fired water heaters
** Solar Fraction = 0.5

Other considerations to save energy include the reduction of hot water demand or use. An example for a typical conservative measure is the installation of low-flow fixtures for showers and taps (faucets) (Australian Government, 2014). In households where dishwashers and washing machines are connected to a central hot water system, the purchase of more energy efficient appliances will also reduce demand (US DOE, 2012).

2.3.3 Cooking

Cooking is a large energy use in the residential sector, but with rather low capacities for energy savings through technology improvements. It is expected that no great technological changes in modern forms of cooking will take place. (IEA, 2013b)

An analysis for the European Union outlines energy saving potentials on a life cycle basis for ovens of 10-39% to be cost effective and 15-41% to be achievable with best practice technologies. Considered improvements for gas ovens included better thermal insulation, pre-heating of ventilation air with a heat exchanger, reduced thermal mass and a third glass sheet on the door. For electric ovens better insulation, introduction of reflecting layer, electronic temperature control and door glazing leaded to reduced energy consumption. For hobs, only marginal improvements could be identified. (Mudgal, et al., 2013)

A prototype of an electric saucepan with an integrated heating element, thermal insulation and an “intelligent” controller and timer, the so-called EffiCooker, promise energy savings in the range of 28% to 81% compared to conventional equipment (Schjær-Jacobsen, 2013).

Regarding the cooking method, gas hobs and ovens are normally more energy-efficient comparing the primary energy consumption than induction or electric ones, but typically less energy-efficient looking at the appliance efficiency (Adria & Bethge, 2013).

In general, modifications in cooking habits may be more promising to reduce energy consumption than technical improvements (Hager & Morawicki, 2013).

2.3.4 Lighting

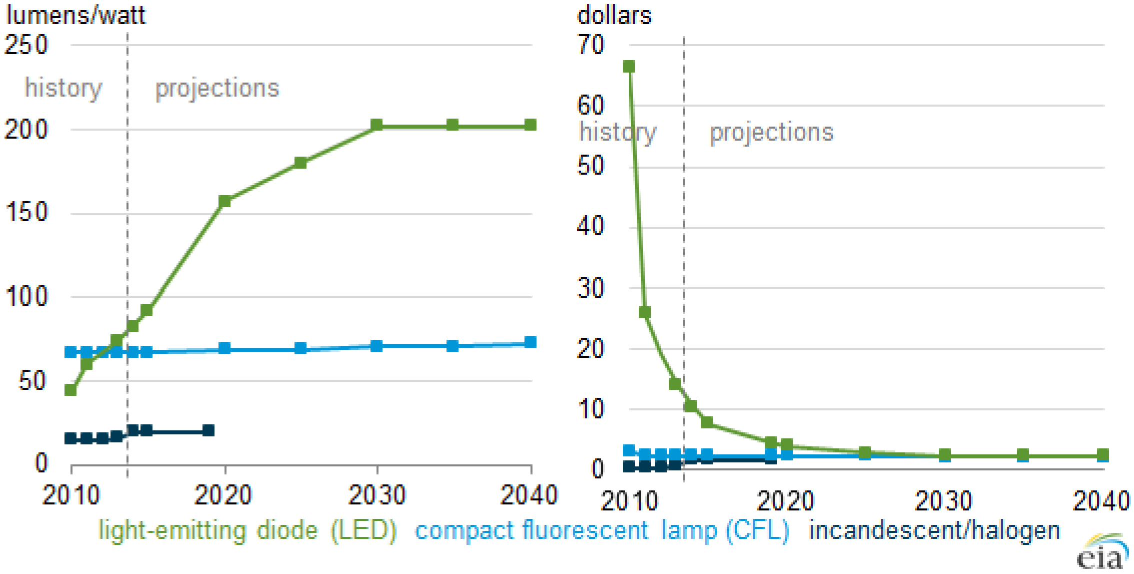
Lighting is also a major energy consumer, representing roughly 15% of global electricity use in the residential sector. There are significant technical potentials to reduce energy consumption from electric lighting with high efficient lamps, light control systems and improved building designs. (IEA, 2013b)

Electric lamps for residential application produce light typically through one of the following processes: incandescence, gas discharge or electroluminescence (IEA, 2013b). Conventional ILs, also called General Lighting Service Lamps (GLS), have dominated the lighting market for many years and still do in many countries due to their low purchase price and for a long time unmatched quality of light (IEA, 2006 and US DOE, 2004). These lamps produce visible light though an electric current, which is led through a tiny coil or filament of tungsten wire that starts glowing when it is heated (US DOE, 2013b). The luminous efficacy and lifetime of ILs is quiet low and new upcoming lighting technologies beat conventional GLS by far (Halonen, et al., 2010). Tungsten halogen lamps are a derived form of conventional GLS and achieve some small advances in luminous efficacy and lifetimes due to the use of halogen gas insight the bulb (Halonen, et al., 2010).

Much higher improvements are possible with gas discharge lamps, typically fluorescent lamps (FL), and solid-state light-emitting diodes (LED). FLs are low-pressure gas discharge light sources, producing light mainly by fluorescent powders which get activated by ultraviolet radiation created by discharge in mercury (Halonen, et al., 2010). In the residential sector both, linear fluorescent lamps (LFL) and CFLs, are used with last one gaining increasing popularity due to an experienced sharp price drop in the past and their similar form to ILs (IEA, 2006). In recent years, many governments have passed measures to replace conventional ILs with CFLs, as they only require around one-quarter to one-third of electricity to produce the same amount of visible light (IEA, 2013b). A major market barrier for CFLs is their higher initial costs in comparison to ILs (Lefèvre, et al., 2006) although they are normally more economical on a life cycle basis, due to lower energy consumption and longer lifetimes (IEA, 2006). Other market barriers are consumer awareness and distrust of consumers in the technology, as CFLs had at the beginning of their commercialization some quality and suitability issues to overcome (Lefèvre, et al., 2006).

A promising and rapidly developing technology in terms of luminous efficacy and costs are LEDs (IEA, 2006). These lamps are p-n junction semiconductors that emit light by electroluminescence from an electric field (Halonen, et al., 2010). The key differences of LEDs to other lighting technologies is their small size, emittance of light in a specific direction and low heat losses, what makes them so energy-efficient (US DOE, 2013b). There is already a variety of LED products commercially available for applications in the residential sector and product tests showed that LEDs achieve good results for light colour, colour rendering and brightness (Schäppi & Bogner, 2013). The US EIA states that LEDs are already the most energy-efficient technology at the market with around 83 lumens per watt (lm/W) for a typical lamp, in comparison to 67 lm/W for a CFL providing the same amount of light (US EIA, 2014). The agency further predicts halving of costs as efficacies almost double by 2020 (RTCC, 2014).

Figure 2-4: Average lighting efficacies and costs per bulb for different technologies (US EIA, 2014)

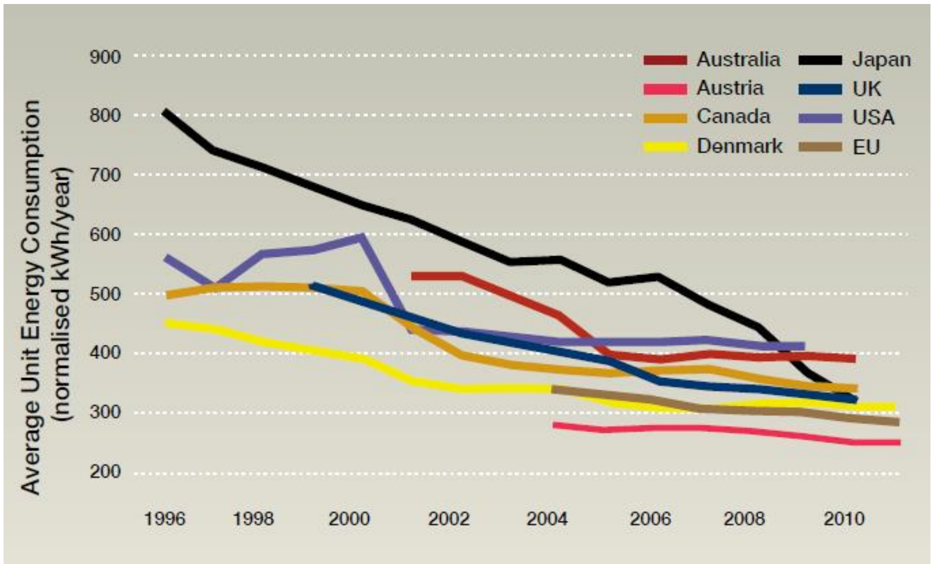


2.3.5 Refrigeration

Domestic refrigerated appliances can be categorized into three groups: refrigerator/freezer combinations, refrigerators only and with freezer compartments and freezers only (IEA 4E, 2014a). Technologies across the different categories are very similar working typically on an electrically driven vapor-compression refrigeration cycle (IEA, 2013b).

Over the past decades, energy efficiency of refrigerated appliances improved significantly, where energy efficiency regulations played a major role (IEA, 2013b). Figure 2-5 shows developments of normalized (accounting for differences in test temperatures) unit energy consumptions (UEC) of refrigerator/freezer combinations for several countries. In 2010, their energy consumptions were in the range of 250-400 kilowatt-hours (kWh).

Figure 2-5: Trends in normalized UECs for refrigerator/freezer combinations (IEA 4E, 2014b)



Several low-cost technologies for refrigerated appliances are available to improve their energy efficiency. Depending on how far energy efficiency policies already advanced in countries, the Lawrence Berkeley National Laboratory (LBNL) (Letschert, et al., 2012) estimated a cost-effective potential for energy reductions from refrigerators of 4-71%. Options to improve the design of refrigerated appliances include thicker insulation, increased surface area for evaporators and condensers, higher efficiency compressors, thermostatic controls, use of vacuum insulation panels (VIPs) and optimized capillary tube characteristics (Shah, et al., 2014).

2.3.6 Televisions

Today, liquid crystal display (LCD) televisions dominate the global market accounting for about 80% of sales in 2010 (NPD DisplaySearch cited in IEA, 2013b). They are gradually replacing conventional cathode ray tube (CRT) technologies at an accelerated rate although these maintain popular in some emerging markets (NPD DisplaySearch cited Park, et al., 2011). Another market transition, which takes place, is from cold cathode fluorescent lamp (CCFL) backlit LCD televisions to higher efficient light-emitting diode (LED) backlit LCD televisions (NPD DisplaySearch cited Park, et al., 2011). The development is driven by a movement from analogue to digital televisions as well as energy-efficiency standards and an advancing LED technology (Park, et al., 2011). Plasma televisions have small portions of sales, and are mainly present in the market for large screen sizes (IEA, 2013b).

Screen sizes and time of use have considerable impacts on annual electricity consumption from televisions. For instance, a growth in screen size diagonal of 40% equates roughly double the screen size area, and 60% increase in electricity consumption in on-mode (IEA 4E, 2010). However, in recent years, the growth in screen size slowed down to around 3% for LCD and 2% for plasma in the period 2007 to 2009 (IEA 4E, 2012a). Other technology trends just started towards 3D-televisions and smart televisions, increasing power consumption and changing user behavior (Park, et al., 2013).

The design of televisions has a major impact on their efficiency (Table 2-4). The least efficient technology is CRT televisions although they normally consume less energy than LCDs and plasma display panel (PDP) televisions due to smaller screen sizes. The use of LED backlit screens instead of CCFL backlit screens increases television efficiency of about 0.6 watt per square decimeter (W/dm²) (Park, et al., 2011). Trends in LED-LCD technologies suggest that efficiency levels of one W/dm² are achievable (IEA, 2013b). For instance, reflective polarizing filters could reduce energy consumption by around 20-30% of LCD televisions (Fraunhofer IZM, 2007). The organic light-emitting diode (OLED) technology promises to be more energy-efficient than LED-LCD televisions due to the low backlight to screen efficiency of the LCD technology (Park, et al., 2011). So far, OLED televisions face some technical obstacles and are still more expensive than LEDs (IEA, 2013b).

Table 2-4: Screen sizes, on-mode powers and energy efficiencies by television type in 2010 (Park, et al., 2011)

Technology	Average size [dm²]	Average on-mode power [W]	Average energy efficiency [W/dm²]
LED LCD	39	67	1.7
OLED	6	11	1.8
PDP	59	120	2.0
CCFL LCD	31	72	2.3
CRT	13	55	4.2

Furthermore, power management can reduce energy consumption although its impact is rather low. Examples are ambient light and occupancy sensors (Park, et al., 2013) or standby power control (CONUEE & GIZ, 2009).

In the past, energy efficiency and product labelling programs have been effective to increase energy efficiencies of televisions (IEA, 2013b).

2.3.7 Other electric appliances

Other electric appliances with a significant share on energy demand of households are washing machines and computers.

Typically, a washing machine consumes around 0.5 kWh per washing cycle (IEA 4E, 2012b). Opportunities to reduce energy demand from washing machines include reduction of system losses through efficient central water heating, cold washing, machine efficiency improvements (10-15% possible), and in the long-term advanced washing technologies such as ultrasonic washing (IEA, 2013b). Energy consumption of domestic laundry dryers was in Europe, the USA, Canada and Australia around 0.7 kWh per kg clothes in 2011 (IEA 4E, 2012c). Heat pump cloth driers and in some cases, a switch from electric to gas appliances can achieve energy savings (IEA, 2013b).

Energy demands for desktop computers vary significantly between regions (IEA, 2013b). Table 2-5 shows that current BATs for desktop and notebook computers are considerably more energy-efficient than the global average of the stock.

Table 2-5: Estimated energy consumptions per year from computers (IEA, 2013b)

	Desktop				Notebook			
	Annual TEC [kWh/a]	Idle mode [W]	Sleep mode [W]	Off Mode [W]	Annual TEC [kWh/]	Idle mode [W]	Sleep mode [W]	Off Mode [W]
Base case	270	75	3.8	1.0	68	23	1.8	1.2
BAT case	50	13	1.7	0.8	20	7	0.9	0.4

Note: screen energy demand is included for notebooks but not for desktops

3 Methodology

3.1 Development of the energy demand model

3.1.1 Model overview

REDUCE (Residential EnD-Use model for City Emissions) is a new energy demand model developed by the author for the residential sector in the MCMA. Main goal of the model is to provide a tool, which allows quantifying the impact of future developments of key drivers and especially improvements in energy efficiencies on residential energy demand and CO_2 emissions.

REDUCE is a bottom-up model combining accounting and simulation techniques. Residential energy demand in the model is subdivided into standard end-uses including water heating, cooking, lighting, refrigeration, washing machines, televisions, computers, and other electric appliances. Space heating and cooling are no separate categories in REDUCE due to their insignificant shares on energy demand in the MCMA. Energy demand is modeled with an annual time resolution. REDUCE is implemented in the Excel environment and is arranged in spreadsheets.

The model determines energy demand as a product of activity and energy intensity levels (Equation 3-1). A number of existing bottom-up models uses this approach and the idea for it was taken from them. Examples are the BUENAS (McNeil, et al., 2012) and the WEM (IEA, 2014b).

Equation 3-1: Basic equation for energy demand

$$Energy\ demand = Activity * Intensity$$

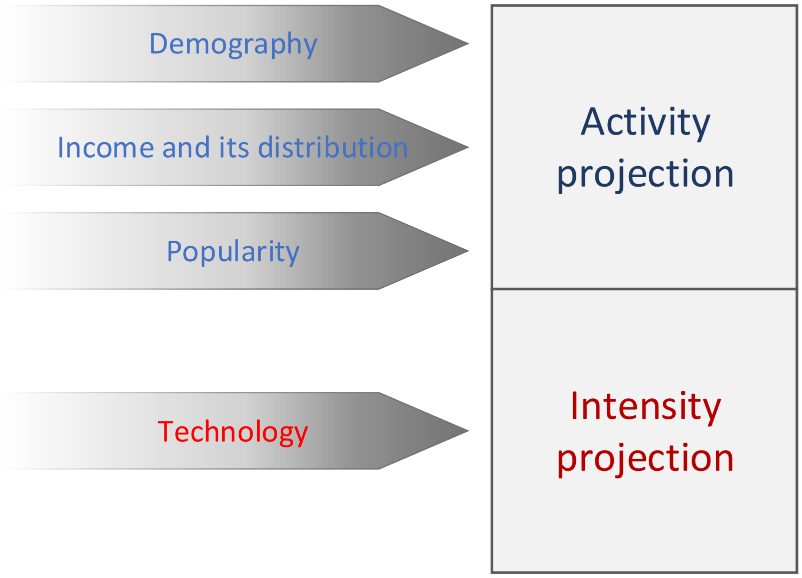
In REDUCE the “activity” level of an end-use refers to the average amount of appliances owned by households to provide the service. Each end-use is represented by one appliance type. The energy “intensity” level of an end-use is the average energy consumption of households for the service divided by its activity level.

Four types of forces drive residential energy demand in REDUCE (Figure 3-1):

- **Demography:** Population size and dwelling occupancy rate in the MCMA;
- **Income and its distribution:** Total income of households in the MCMA and its distribution over income classes;
- **Popularity:** Popularity of appliances independent from household income;
- **Technology:** Types and energy efficiency levels of appliances used by households to satisfy their needs for services.

The named drivers are considered to be the most important ones for residential energy demand in the MCMA and were selected based on a literature review (chapter 2.1.3). While the first three have an impact on activity levels of end-uses in the model, the latter one drives energy intensities. An exception is the end-use water heating. For this particular end-use, demography and income additionally drive energy intensities.

Figure 3-1: Driving forces in REDUCE



Furthermore, REDUCE connects the residential sector with the energy supply sector to allow the modeling of emissions caused by activity from households. The model focuses on CO_2 emissions, which are responsible for around 90% of the GHG emissions in the energy sector (IEA, 2013a). These are calculated using energy source-dependent emission factors expressing the amount of emitted CO_2 per unit energy consumed (Equation 3-2).

Equation 3-2: Basic equation for CO_2-emissions

$$CO_2\ emissions = Energy\ demand * Emission\ Factor$$

3.1.2 End-use coverage

In the following the coverage of end-uses in REDUCE is specified.

- **Water heating:** covers all services, which require hot water in a household (shower, hand washing, etc.) and are satisfied through a domestic water heater. The end-use does not include the use of biomass for water heating.
- **Cooking:** contains services for the preparation of food using any kind of cooking equipment.
- **Lighting:** is a service provided through lighting bulbs to illuminate rooms or areas outside but belonging to the house.
- **Refrigeration:** covers the refrigeration of food in electric refrigerator/freezer combinations, refrigerators only or refrigerators with freezer compartments. Refrigeration in freezer only units could not be included in this end-use, due to a lack of data, but is covered by other electric appliances.
- **Washing machines:** represents the service of cloth washing through electric washing machines. The end-use does not cover the use of cloth driers, which are also included in other electric appliances.
- **Televisions:** include the use of televisions in households.
- **Computer:** covers services provided through domestic computers.
- **Other electric appliances:** contains services from small electric appliances, as well as freezers only, cloth driers, fans and dishwashers.

While in many cities space heating and cooling consume large amounts of energy, their significance for the MCMA is rather low due to the favorable climatic conditions in the region. Heating and cooling degree-days for the MCMA were calculated via a web tool using methodological data from the Mexico City Airport for the period 06/2012-05/2015 (BizEE Software, 2015). For the mentioned period, Mexico City had in average 112 heating degree-days per year (base temperature 12°C) and 12 cooling degree-days per year (base temperature 26°C). Although climate change will increase temperatures in the city by 0.5-1.25 °C in winter and 1-1.5 °C in summer by 2030 (Rodríguez, et al., 2014), cooling demand is still expected to be not significant in comparison to other end-uses.

3.1.3 Definition of system boundaries

The MCMA also called Metropolitan Zone of the Mexican Valley (Zona Metropolitana del Valle de Mexico, ZMVM, Spanish) cuts across administrative boundaries, incorporating municipalities from three Mexican states. The core of the metropolitan area is Mexico City (Federal District).

An interinstitutional cooperation between the Secretary of Social Development (SEDESOL), the National Population Council (CONAPO) and the National Institute for Statistic and Geography (INEGI) developed and applied criteria for the territorial delimitation of metropolitan areas in Mexico (CONAPO, et al., 2012). Their definition was taken to define the system boundaries in REDUCE.

The definition is summarized in the following according to (CONAPO, et al., 2012):
A metropolitan area is a set of two or more municipalities, where a city of more than 50 thousand inhabitants is located, which urban area, functions and activities exceed the boundary of the municipality originally containing the city, incorporating as part of it or through its direct influence neighbor municipalities predominant urban with a high degree of socioeconomic integration. Moreover, those municipalities are included in the metropolitan area, which are relevant for planning and urban policy through their particular characteristics. In addition, metropolitan areas are also defined as municipalities with cities of more than one million inhabitants, as well as cities with more than 250 thousand inhabitants, which share a process of conurbation with the United States of America.

According to this definition, the MCMA consists currently out of 16 delegations from the Federal District, 59 municipalities from the State of Mexico and one municipality from the state Hidalgo (CONAPO, et al., 2012). Table 8-1 in the Annex provides a full list of all municipalities by name forming the MCMA.

3.1.4 Simulation of the appliance turnover

An important purpose of REDUCE is the possibility to simulate the impact of energy efficiency improvements on energy demand. Therefore, the model takes into account variations in UECs of appliances depending on their year of purchase. The number of purchased appliances by households in a certain year multiplied by their average UEC is the energy demand from purchases of that year. The model than simulates their aging over the projected time horizon. Each projected year appliances increase by one year in their age and hence also in their probability to be replaced. Energy demand *ED* in a projected year is calculated as the sum over all energy demands from appliances of different ages from recently purchased to the end of their lifetime *lt*. The relation is described in Equation 3-3, where *Stock(age)* represents the number of appliances at a given age *age* and *UEC(age)* their average consumption at that age.

Equation 3-3: Energy demand per end-use

$$ED = \sum_{age=0}^{\mathrm{lt}} Stock(age) * UEC(age)$$

UECs of appliances are completely externally defined (exception is water heating) and an input parameter for the model, while the appliance stock is a simulation result. Explanations follow in chapter 3.1.5 and 3.1.6.

The methodology to calculate the amount of new purchases in any year is based on considerations of the BUENAS and the Policy Analysis Modeling System (PAMS), which both use in principle the same analytical framework developed by the LBNL and the Collaborative Labelling and Appliance Standards Program (CLASP) (McNeil, et al., 2012 and McNeil, et al., 2007).

The number of shipments (appliance purchases) *Sh* in any year *n* consists of first purchases *FP* and replacements *Rep* (Equation 3-4).

Equation 3-4: Shipments in a certain year (McNeil, et al., 2007)

$$Sh(n) = FP(n) + Rep(n)$$

First purchases refer to households, which obtain an appliance for the first time. They are described in a given year as the difference between the projected appliance stock *PStock* and the actual stock *Stock* adjusted by some delay *delay* (Equation 3-5). The projected stock is a simulation outcome driven in REDUCE by economic, demographic and popularity projections. The delay can be interpreted as the number of years households wait after income increases to do the purchase. In REDUCE it is assumed to be two years.

Equation 3-5: First purchases in a certain year (McNeil, et al., 2007)

$$FP(n) = \frac{PStock(n) - Stock(n)}{delay}$$

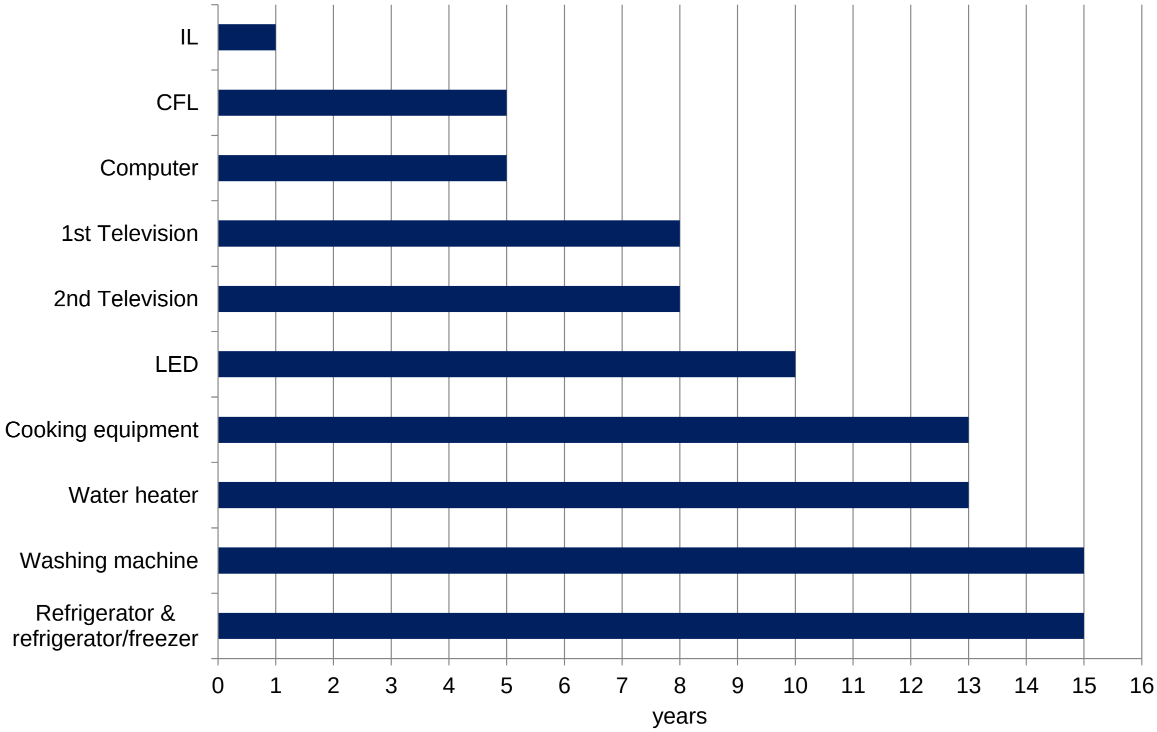
Replacements are estimated in terms of a retirement probability P_R that depends on the age of appliance (Equation 3-6). In the function age_o is the average lifetime of the appliance, and D_{age} the mean deviation of replacement ages, set to two years (McNeil, et al., 2007).

Equation 3-6: Probability for appliance retirement (adopted from McNeil, et al., 2007)

$$P_R(age) = \frac{1}{1 + e^{(age_o - age)/D_{age}}}$$

The number of years during which an appliance is in use, known as its lifetime, determines how long it takes until the stock is completely exchanged by new appliances under normal market conditions. Figure 3-2 presents assumed average lifetimes in the model for each appliance type.

Figure 3-2: Assumptions on average appliance lifetimes (Letschert, et al., 2012)



The number of replacements in a certain year for an appliance type is calculated as product of its stock and the annual retirement probability AP_R (Equation 3-7). The latter one is a measure of normalized increase in retirement probability when an appliance becomes older (Equation 3-8).

Equation 3-7: Product replacements in a certain year (adopted from McNeil, et al., 2007)

$$Rep(n) = \sum_{age=1}^{lt} Stock(n-1, age-1) * AP_R(age-1)$$

Equation 3-8: Annual retirement probability (McNeil, et al., 2007)

$$AP_R(age) = \frac{P_R(age) - P_R(age-1)}{1 - P_R(age-1)}$$

3.1.5 Activity levels

The activity level of each end-use is represented by one appliance type. These are water heater, cook stove, lighting bulb, refrigerator, washing machine, television and computer.

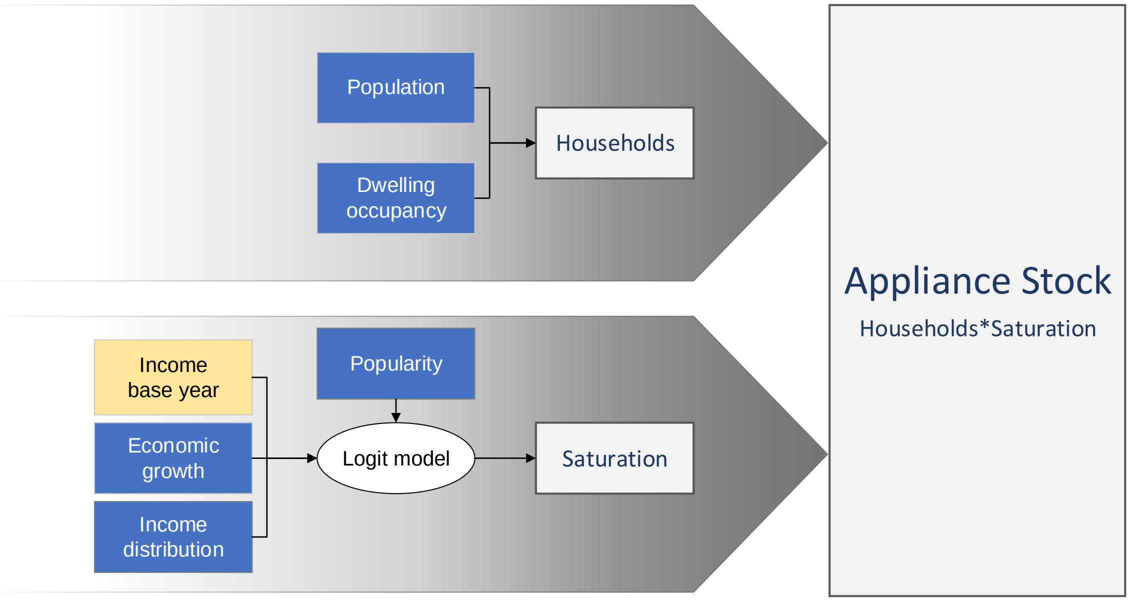
Demographic developments, economic growth and increasing popularity are the three forces in REDUCE driving activity levels of end-uses. The appliance stock of an appliance type in a certain year *n* is the product of number of households *HH* in the MCMA and appliance saturation *S* in that year (Equation 3-9). Saturations express the average amount of appliances a household owns of a certain type.

Equation 3-9: Appliance stock

$$Stock_n = HH_n * S_n$$

Figure 3-3 presents an overview on the used methodology for activity projections.

Figure 3-3: Methodology for activity projections in REDUCE



The number of households in the MCMA is calculated from the MCMA's population size and dwelling occupancy (Equation 3-10).

Equation 3-10: Number of households

$$Number\ of\ households = \frac{Population\ size}{Dwelling\ occupancy}$$

The LBNL developed a methodology to forecast ownership of appliances based on income developments and applied it to improve electricity demand projections at global, national and regional level (see McNeil & Letschert, 2005 and McNeil & Letschert, 2010). The methodology was selected to model saturations of appliances for the MCMA, as it considers income distributions.

The relationship between appliance saturations and income levels follows typically an S-curve and is parameterized from the LBNL by a logit model (McNeil & Letschert, 2005). This means that appliance saturations for low-income groups accelerate rapidly with raising incomes, then slow down and finally taper for high-income groups. While the LBNL later added urbanization and electrification as parameters to explain country differences, here the basic form is used without these parameters (Equation 3-11). The appliance saturation S is described by the maximum theoretical ownership rate S_{max}, income I and two free parameters, where α is a constant proportional to income and β modifies the shape of the curve.

Equation 3-11: Basic equation for appliance saturation (McNeil & Letschert, 2005)

$$S = S_{max} * (1 - e^{-\alpha * I})^{\beta}$$

To consider the impact of variations in saturation levels according to income, these are calculated for different income groups (McNeil & Letschert, 2005). For REDUCE income deciles I_d were chosen, as it's a common subdivision used by income statistics in Mexico. Finally, the average saturation of an appliance type is the average over all deciles (Equation 3-12).

Equation 3-12: Average appliance saturation (adopted from McNeil & Letschert, 2005)

$$\bar{S} = 0.1 * \sum_{d=1}^{10} S_{max} * (1 - e^{-\alpha * I_d})^{\beta}$$

A classification of appliances into income dependent and income independent types for the MCMA, as well as the determination of regional values for α, β and S_{max} for the equations was done by the author using microdata from two national household surveys in Mexico from the year 2010.

Survey descriptions:

- **Survey of the Mexican Population and Housing Census** (**MCPV**, Spanish acronym)**:** INEGI carries out a national population and housing census every ten years with a recount in between after five years (INEGI, 2015a). The census collects data at individual, household and complete house level. Together with the census, INEGI also conducts a survey consisting of an amplified questionnaire giving a deeper insight into demographic and socioeconomic characteristics as well as living conditions of the Mexican population (INEGI, 2011a). Typically, the survey covers around 10% of the Mexican households and allows estimations of variables with a geographical disaggregation to municipalities (INEGI, 2011b). Results and micro data of the survey are public information and can be accessed through the homepage of INEGI.[4]
- **Survey of National Household Incomes and Expenditures** (**ENIGH**, Spanish acronym)**:** The survey is carried out by INEGI each two years (INEGI, 2015d). Goal of the survey is the collection of data regarding income and expenditure structures of Mexican households (INEGI, 2011d). In addition, it also provides information on the available infrastructure and equipment in households (INEGI, 2011d). The number of households questioned for the survey is smaller than for the MCPV, why the ENIGH only has a national coverage and in some cases federal entities. The same as for the MCPV, results and microdata from the ENIGH are publically available at the homepage from INEGI.[5]

The MCPV could be used at the geographical level of the MCMA, while evaluations based on the ENIGH were carried out only at the level of the Federal District assuming its representativeness for the MCMA. Identified income-dependent appliance types for the MCMA include water heaters, lighting bulbs, refrigerators, washing machines, second televisions and computers. Income-independent appliance types are cook stoves and first televisions. The parameters α and β in the Equation 3-12 were determined specifically for the MCMA via a nonlinear regression analysis in SPSS[6] using microdata of the surveys for

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[4] http://www.inegi.org.mx/est/contenidos/Proyectos/ccpv/

[5] http://www.inegi.org.mx/est/contenidos/Proyectos/encuestas/hogares/regulares/enigh/

[6] SPSS is a software package from IBM for statistical analysis:
http://www-01.ibm.com/software/uk/analytics/spss/

household income and availability of appliances (INEGI, 2010a). An inconvenience of the data from the surveys was that they only ask for household income based on any kind of work. Not included are pensions, income supports from the government, or monetary transfers from relatives. On the other hand, it considers income through irregular work. In REDUCE, maximum saturation levels for appliances were set equal to calculated saturations of the 10th income decile in 2010. The results for determined parameters of equations by each appliance type are presented in the Annex in Table 8-28. For the end-use lighting, the function describes the number of rooms. The amount of lighting bulbs is calculated based on a factor of two bulbs per room calculated from the ENIGH.

To evaluate the goodness of the logit model, determined appliance saturations per income decile from the model were compared with those directly calculated from the survey in 2010 (Table 3-1). Results show that in most cases deviations of income deciles lie between 1-2% with a maximum of 7%. An exception is second televisions were the fit shows larger deviations and hence the function does not represent so well the real situation in Mexican households. However, the function was still used for modeling.

Table 3-1: Deviations between survey and model results for appliance saturations by income decile in 2010

	Deviation of total saturation	Average deviation of income deciles	Maximum deviation of income deciles
Water Heaters	0.2%	1.7%	6.3%
Refrigerators	0.1%	0.9%	2.2%
Washing machines	0.0%	1.0%	1.8%
Computers	0.4%	2.1%	6.9%
Rooms	0.0%	2.1%	6.0%
2nd Televisions	0.7%	10.5%	28.1%

Moreover, the model considers the possibility of changes in popularity through changes in maximum saturation levels. The more popular an appliance become the higher is its saturation in the 10th income decile.

3.1.6 Energy intensity levels

Historic as well as projected energy intensities per end-use are model inputs and externally defined. In REDUCE in some cases energy intensities are equal to UECs, but not in all cases.

Energy intensity definitions in REDUCE for end-use services:

- **Water heating:** UEC of a domestic water heater;
- **Cooking:** Energy consumption for cooking purposes of a household owning a cook stove;
- **Lighting:** UEC of a lighting bulb;
- **Refrigeration:** Energy consumption of a household for food refrigeration using an electric refrigerator/freezer combination, a refrigerator only or a refrigerator with freezer compartments;
- **Washing machines:** UEC of a washing machine;
- **Televisions:** UEC of a television;
- **Computers:** UEC of a computer; and
- **Other electric appliances:** Energy consumption of a household for other electric appliances.

Water heating is the only end-use for which REDUCE considers changes in energy intensity according to income and demographic developments. Although other end-uses also respond to these drivers, it was not possible to do this evaluation for all end-uses due to time and data constraints. However, these drivers have been considered for water heating, as it is the largest end-use in the MCMA with the highest impact on energy demand and CO_2 emissions.

It was assumed that water demand in relation to income follows a logit function like appliance saturations do (Equation 3-13), where $HWDP$ is the hot water demand per person and $HWDP_{max}$ the maximum hot water demand per person.

Equation 3-13: Average hot water demand per person

$$HWDP = HWDP_{max} * (1 - e^{-\alpha * I})^{\beta}$$

For the calibration of the function, data from Quintanilla Martínez (Quintanilla Martínez, et al., 2000) on hot water demand per person and social stratum for the MCMA was used. Determined parameters can be found in the Annex 8.4.2 in Table 8-29.

Furthermore, average hot water demand HWD of a water heater is the sum of hot water demand per person and decile $HWDP_d$ weighted by the corresponding appliance saturations of the decile S_d and finally multiplied by the average dwelling occupancy of an household DO (Equation 3-14).

Equation 3-14: Average hot water demand of a water heater

$$\overline{HWD} = \overline{DO} * \sum_{d=1}^{10} \overline{HWDP_d} * \overline{S_d}$$

3.1.7 Model input parameters

To model residential energy demand and CO_2 emissions a number of externally defined inputs are required in REDUCE.

These are:

- Number of appliances owned by households in the base year;
- Distribution of appliance ages in the stock in the base year;
- Historic annual energy intensities;
- Projections for population and dwelling occupancy;
- Projections for income per income decile;
- Projections for popularities of appliances;
- Projections for future annual energy intensities;
- CO_2 emission factors in the base year; and
- Projections for CO_2 emission factors.

The first three types of input parameters serve the representation of energy demand in the base year. Data input for these parameters is described in chapter 3.2. The next four types of input parameters are required for the projection of energy demand into the future in form of scenarios. Their description is presented in chapter 3.3. The last two types of input parameters are for the energy supply side and are described in chapter 3.4. Additional data to those presented in the text, which served as model input, can be found in the Annex at the end of the thesis.

3.2 End-use representation in the base year

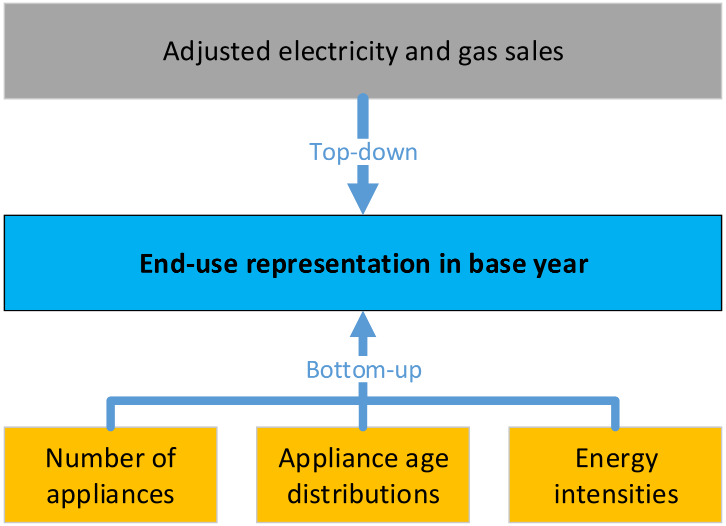
3.2.1 Outline

A base year is a historical year marking the transition from energy estimates based on energy data to modeling-based estimates (DEA, et al., 2013). For the carried out modeling work it was set to the year 2010, as it is the year of the last MCPV.

The estimation of energy demands for standard end-use services for the MCMA in the base year has been a challenge, as reliable data are scare not only at a regional, but also national level. Data is especially missing on market shares and technical parameters of technologies. Therefore, it was necessary at several points to do assumptions on parameters based on data from other countries or in some few cases also own judgement. Whenever it was possible national regulations as well as analysis or data from Mexican organizations were integrated.

Energy demand for each end-use in the base year was estimated via the combination of a bottom-up and top-down approach (Figure 3-4). Via the top-down approach, energy demand by energy source in the MCMA in 2010 was determined. With the bottom-up approach energy demand per end-use was calculated based on Equation 3-3 in chapter 3.1.4 using information on the size of the appliance stock, the age of appliances in the stock and energy intensities according to the year of purchase of appliances. Afterwards, energy intensities of end-uses are adjusted, so estimates from the bottom-up meet those from top-down. Energy intensities were selected, as values for the parameter are more uncertain in comparison to estimates of the stock sizes and age distributions. The calibration of bottom-up estimates improves their quality as well as facilitates the coupling of REDUCE with models treating other sectors.

Figure 3-4: Methodology for the representation of end-uses in the MCMA



3.2.2 Adjusted gas and electricity sales

Reliable data on energy consumption for metropolitan areas in developing countries is not easy to gather for two main reasons: a) statistical or measured units may not fit with the defined system boundaries; b) the irregular sector (illegal electricity connections, illegal gas sales) may be large and not covered by statistics.

In the case of the MCMA, no official energy balance for the region or its federal states exist. Nevertheless, the Secretary of the Environment of the Federal District (SEDEMA, Spanish acronym) develops regularly emission inventories for the MCMA, which are publically available.[7] The inventory from 2010 (SEDEMA, 2010) included beside data on GHG emissions also data on gas and electricity sales reported by the Mexican Federal Electricity Commission (CFE, Spanish acronym) and Mexican Petroleum Company (PEMEX, Spanish acronym). The companies informed that 227.6 million cubic meter (m^3) natural gas (NG) (equivalent to eight PJ final energy), 2.50 million m^3 LPG (equivalent to 63 PJ final energy) and 5,335 gigawatt-hours (GWh) electricity (equivalent to 19 PJ final energy) were sold in the MCMA in 2010. These values do not include the municipality of the state Hidalgo that belongs to the MCMA in the definition used in the thesis as well as illegal sales and electricity connections. Due to the last point, the data could not be used directly to calibrate bottom-up estimates, as illegal connections and sales are responsible for a quite large share of energy consumption in the MCMA. Illegal sales for gas are estimated to account for at least 10% of sold gas in the MCMA (SIPSE Noticias de México,

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[7] http://www.aire.df.gob.mx/default.php?opc=Z6BhnmI=&dc=Zg==

2013). The CFE reported for the distribution area, which covers the MCMA, immense distribution losses of electricity of around 31% in 2009 including so-called non-technical losses referring to losses caused by illegal connections (CFE, 2010). In comparison, at a national level distribution losses accounted only for roughly 12% of electricity consumption (CFE, 2010). Finally, gas consumption was estimated to account for 77 PJ, including 10% of illegal sales and electricity consumption to 25 PJ including 30% of illegal connections (Table 3-2 and Table 3-3).

Table 3-2: Adjusted gas consumption in the residential sector in the MCMA in 2010*
Own estimation based on (SEDEMA, 2010 and SIPSE Noticias de México, 2013)

	Gas demand (sales) [millions m³]	Gas consumption [millions m³]	Final Energy [PJ]
Natural Gas	227.6	227.6	8
Liquefied Petroleum Gas	2.50	2.38	63
Illegal sales LPG (10%)	0.25	0.24	6
Total			**77**

Note: Values exclude the municipality Tizayuca of the state Hidalgo

Table 3-3: Adjusted electricity consumption in the residential sector in the MCMA in 2010*
Own estimation based on (SEDEMA, 2010 and CFE, 2010)

	Final energy [GWh]	Final energy [PJ]
Electricity sales	5,335	19
Illegal connections (30%)	1,601	6
Total	**6,936**	**25**

Note: Values exclude the municipality Tizayuca of the state Hidalgo

3.2.3 Appliance stocks

Numbers of appliances in the MCMA in the base year 2010 were calculated using microdata from the two Mexican household surveys MCPV and ENIGH (for a description of the surveys see the previous chapter 3.1.5).

Appliance saturations for water heaters, cook stoves, refrigerators, washing machines, televisions and computers were directly calculated from the MCPV for the MCMA (Annex Table 8-2). Using population data from the CONAPO and average household sizes calculated from the MCPV, number of appliances could be computed. As the MCPV asks households only about the availability of appliances and not their number, the ENIGH was consulted to define the amount of appliances. The ENIGH is only representative at a national or state level, why its evaluation was done for the DF and later translated to the

MCMA. The evaluation showed that the number of appliances is relevant for lighting bulbs and televisions and can be neglected for other types of appliances. The amount of lighting bulbs was transferred to the MCMA based on the amount of rooms of households and the amount of second televisions based on income relations (Annex Table 8-3 and Table 8-4).

3.2.4 Appliance ages

The age of appliances in the stock in the base year 2010 was estimated mainly based on survey or sale data. This approach has the advantage that it considers historical variations through programs that promoted the substitution of an appliance and/or market fluctuations. Priority was given to local data although such data was not always available. The ENIGH asks in which year households bought for the last time a certain appliance (INEGI, 2011c). Based on this source age distributions of cook stoves, refrigerators, washing machines, televisions and computers were determined for the DF. It was assumed that the distribution from the DF is also representative for the MCMA. Results show two peaks over all four appliance types in 2000 and in 2005. This can be a sign of unreliable answers from households, which just roughly estimated the age of an appliance to 5 or 10 years. However, this source was assessed to be still the best one. For FLs, the age distribution in the stock was approximated through national data on direct sales, as well as results from various programs that distributed such lamps (Andrade Salaverría, 2010). FLs in the MCMA were calculated from this data taking into account its population size, as well as the geographical coverage of programs whenever it was possible. Finally, for water heaters no good local or national data source was available to do an estimation on their age distribution. Therefore, information from the USA was consulted, due to its geographical proximity to Mexico and a large use of gas water heaters (BSRIA, 2014). The LBNL developed survival functions for various appliance types using survey and shipment data (Lutz, et al., 2011). Their results for gas water heaters were used to estimate an appliance age distribution for water heaters in the MCMA. For televisions, two different distributions are used differentiating between a first and second appliance. It is assumed that second televisions are in average twice as old as the first one. This is an estimation based on the judgment of the author. It is founded on the fact that it is quite common that televisions are replaced before the end of their lifetime and then kept as additional appliances. The results for appliance age distributions can be found in the Annex 8.2.2.

3.2.5 Energy intensities

The estimation of the average energy intensities for an end-use service is a complex task, owing to the fact that there are several variations regarding the product characteristics (size, efficiency) and user behavior (time of use). As a result, the quality of estimations on average energy intensities for a region depends mainly on the availability and quality of data.

Average energy intensities in the MCMA were determined and then adjusted to meet top-down estimates for energy demand. Due to a significant absence of data, a large number of assumptions were made.

In 2008, SENER and IEA started a project to strengthen the energy indicators in Mexico, financed by the British Embassy. The project included the development of energy efficiency indicators for Mexico for the period between 2002 to 2008 (published in SENER, 2011b). For the residential sector, the analysis included the end-uses of water heating, cooking, space heating and cooling, lighting, refrigeration and domestic appliances. SENER used a bottom-up approach to estimate energy consumptions of each end-use based on appliance saturations, time of usages and average powers. The study did not take into account changes in UECs between 2002 and 2008 and survivals of appliances. Like noted before, SENER also stated that detailed information on energy consumption in the residential sector in Mexico is missing, and their study had to rely on a series of assumptions.

A calculation of energy consumptions using energy efficiency indicators from SENER showed that the indicators do not fit to the adjusted gas and electricity sales for the MCMA. In principle, there could be two reasons for this difference: a) estimates of SENER rely on assumptions that may not always reflect the reality in Mexico; b) energy intensities in the MCMA actually differ from national averages. Therefore, own estimations on energy intensities for the MCMA were carried out integrating a series of data sources. The results are described in the following and in addition compared to the indicators from SENER. Averages for energy intensities were calculated using the age distributions from the previous chapter. Tables containing estimates on UECs per appliance type and over all years are presented in the Annex 8.2.3. These were used as model inputs.

Gas consumption

Households in the MCMA (excluding the state Hidalgo) consumed 77 PJ of energy using gas in 2010 (estimate from chapter 3.2.2). The consumption was divided into the end-use services water heating and cooking. Own estimations for energy intensities are much lower for both end-uses as those from SENER.

For **water heaters** the author estimated UECs in the range of 21.8 gigajoules (GJ) for the oldest appliances in the stock to 16.5 GJ for the newest ones with an average of 19.1 GJ. In comparison, the energy efficiency indicators from SENER indicate an average UEC for gas water heaters of 25.6 GJ, when local dwelling occupancy and shares between LPG and NG in the MCMA are taken into account. An explanation could be that this value only considers storage water heaters and no other more energy-efficient types of water heaters in Mexican households. No information is available about the share of instantaneous water heaters in the market or in the stock. Therefore, a share of 56% instantaneous water heaters in the stock was assumed with an increasing share on new appliances. Furthermore, a penetration of 0.5% of solar water heaters in the stock was estimated based on national data (SENER, 2014c). Own estimations for UECs for gas storage water heaters were done using the Water Heater Analysis Model (WHAM).[8] Approximations for UECs for instantaneous water heaters rely on the principle of energy conservation and estimates on energy efficiency. Average UECs for solar water heaters were estimated using RETScreen[9]. The reference system for solar water heating contains of a glazed collector with a heat exchanger and storage tank. The system was designed to meet a solar fraction of 70% what is realistic under local conditions in the MCMA. Details about equations, as well as assumptions on input parameters for all three water heater types are presented in Annex 8.5. Major parameters for calculations on water heating energy demand are energy efficiencies and hot water consumption (Annex Table 8-11 and Table 8-13). Assumptions on energy efficiency developments are based on MEPS for thermal efficiencies from NOMs and studies from the US market. Hot water consumption is estimated income dependent based on reported hot water consumption for the MCMA. According to the study (Quintanilla Martínez, et al., 2000), hot water consumption of 50°C varies between 30 and 80 liters per day per person depending on the social stratum.

Energy intensities for **cooking** based on gas was estimated in the range of 1.2 GJ for households with old cooking products to 0.9 GJ for new ones with an average of 1.1 GJ. The same as for water heating, energy intensities were also compared with energy efficiency indicators from SENER. For cook stoves, SENER indicates an average UEC for cook stoves of 6.8 GJ considering local dwelling occupancy and shares between LPG and NG in the MCMA. Moreover, this value is much higher as own estimations, which include

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[8] WHAM is a simplified energy equation taking into account operating conditions and water heater characteristics achieving good approximations as comparisons with detailed simulation models show (Lutz, et al., 1998).

[9] RETScreen Clean Energy Management Software is a free software package developed by the Government of Canada: http://www.retscreen.net/de/home.php

all cooking equipment. Beside the uncertainties in own estimations as well as those from SENER, there may be real differences between national average and local average consumption. For instance, the National Survey of Time of Use (ENUT, Spanish acronym) from 2009 indicates that cooking time in urban households is 7% lower than the national average (INEGI, 2009). However, own estimations for cooking energy intensity rely on data from the USA, as these seem more reasonable for the MCMA due to the low overall gas consumption. In addition, a gradual improvement in efficiencies over the years was taken into account based on the spreading of electronic ignition for cook stoves over the last years (SENER, 2013).

Electricity consumption

6,936 GWh (25 PJ) of final energy were demanded by households in the MCMA (excluding the state Hidalgo) consuming electricity in 2010 (estimate from chapter 3.2.2). The consumption was divided into the end-use services lighting, refrigeration, washing machines, televisions, computers and other electric appliances.

The UEC for a **lighting** point was estimated to be 31 kWh in 2010. In comparison, SENER estimated an UEC of 83.9 kWh. Reason for the large difference is the underlying assumption of time of use. While own calculations are based on 2 hours of time of use per day and unit (Annex Table 8-12), SENER assumes 5 hours. Due to no information was available on how long households use a bulb in the MCMA, the estimation relies on own judgement of the author. Literature (e.g. Andrade Salaverría, 2010, INECC, UNDP, 2012 and Letschert, et al., 2012) suggest a range number of values, while 2 hours are rather found at the lower band of estimates. For the power of lamps, a typical 60 watt (W) IL and 15 W FL was assumed, providing 900 lumens (INECC, UNDP, 2012). The share of FLs in the stock was estimated to be 39% in 2010 based on data from direct sales, as well as reports from lamp distribution programs taking into account also local information (Andrade Salaverría, 2010).

For **refrigerated appliances,** the author estimated average UECs in the range of 828 kWh for the oldest and 337 kWh for the newest ones with an average of 471 kWh. Furthermore, for **washing machines** average UECs are in the range between 103 kWh to 66 kWh, therefore, they were estimated to an average of 76 kWh. SENER calculated average UECs for refrigerators of 978 kWh and 118 kWh for washing machines. The authors estimations, for both refrigerated appliances and washing machines, are based on data reported by an impact assessment of standards and labelling programs in Mexico for the period 1994-2005 (Sánchez Ramos, et al., 2006) and estimates from the LBNL on the effect of recent standards implemented in Mexico on energy consumption (McNeil, et al., 2012). The impact assessment uses efficiency data from the independent certification laboratory (ANCE, Spanish acronym) and shares of different technologies from manufacturers and manufacturer associations. The time of use per appliance is assumed to 9.6 hours per day for refrigerated appliances and 1.7 hours for washing machines (Annex Table 8-12).

Finally, for **televisions** the average UECs for first appliances were estimated to be in the range of 123 kWh to 161 kWh and second appliances 192 kWh to 302 kWh. Furthermore, for **computers** average UECs were assumed to be between 84 kWh and 109 kWh. In comparison, SENER estimated 45 kWh for televisions and did not consider computers. Televisions are the only appliance type where own estimations lie above those from SENER. The reason for the difference is that the authors' calculations assume higher powers for the appliances and take plasma and LCD televisions apart from CRT televisions into account. Estimates of the author are based on a global television study (Park, et al., 2011) and a Mexican study (CONUEE & GIZ, 2009) for computers and televisions including information and data about the computer market in Mexico provided by national associations and chambers of manufacturers. Time of use was assumed to 6 hours for first and to 4 hours for second televisions, and to 3 hours for computers based on the Mexican study.

In the end, **other electrical appliances** were calibrated to the total electricity consumption to 344 kWh per household. Other electric appliances include small electric appliances, as well as freezers only, cloth driers, fans and dishwashers. In comparison, Prognos and the Öko-Institut (Prognos & Öko-Institut e.V., 2009) estimated for Germany an average consumption of 934 kWh per household containing electricity demand for freezers, dishwashers, driers, Video/DVD, Radio-HiFi and small appliances in 2005.

3.3 Scenarios for residential energy demand

3.3.1 Scenario descriptions

The thesis uses two different scenarios to show how energy demand in the MCMA and resulting CO_2 emission could evolve in a medium time horizon from 2010 to 2030. All scenarios are consistent in their assumptions regarding future developments of population size, dwelling occupancy, income and appliance popularity. However, they differ in their assumptions regarding the diffusion of low-carbon and energy-efficient technologies into the market.

Business-as-usual (BAU) scenario

The scenario describes a pathway for residential energy demand, reflecting current trends and policies. It takes into consideration only those technological developments that started before 2015. Additionally, policies and implementing measures that had been formally adopted by 2014 have an impact on residential energy demand in the scenario. Energy or GHG emission reduction targets set by national or local governments, but did not follow in concrete measures are not taken into account. In contrast, the scenario offers a picture of the future where Mexico fails to follow through on climate change policy and markets do not autonomously develop towards low-carbon and energy-efficient technologies. It provides a reference against which alternatives can be measured. The scenario is combined with an energy supply scenario reflecting the continuation of current trends and policies in the power sector.

Best-available technology (BAT) scenario

The BAT-scenario, by contrast, pictures a future where Mexico follows ambitious targets to reduce residential energy demand and CO_2 emissions. In the scenario, national and local governments implement comprehensive policies and measures to force the adaption of current best-available technologies. These may especially include the introduction or update of Mexican standards and the implementation or revision of national or local building codes. It is assumed that best-available technologies and practices become the standard by 2018 for new products. The scenario provides a reference for politicians how far energy demand and CO_2 emissions could be reduced in the residential sector in the MCMA by overcoming market barriers and implementing already available technologies. The BAT-scenario is combined with an energy supply scenario characterized by the integration of large shares of renewable energies into the electricity grid and consistent with the global +2°C target.

Energy demand in the BAU-and BAT-scenario is projected simulating the turnover of appliances under normal market conditions. As BATs implemented in 2018 will not have completely replaced all appliances in the stock by 2030, a sub-scenario for the BAT-scenario was designed. This scenario has the goal to show how far energy demand and CO_2 emissions theoretically could be reduced by the implementation of BATs. The accelerated BAT-scenario (A-BAT scenario) assumes that the complete stock will be exchanged within the period 2018 to 2030. To this end, retirement probabilities for appliances with long lifetimes are increased leading to a larger turnover in the stock.

3.3.2 Demographic projections

Mexico carries out a population and household census each 10 years with a recount in between after 5 years (INEGI, 2015c). Thus, last official statistics for the actual population size in the MCMA are from 2010.

Official estimates for population and dwelling occupancy developments in Mexico come from the CONAPO. The council also developed population projections for the MCMA founded on probable scenarios for fertility, mortality and migration rates for the municipalities forming the metropolitan area (CONAPO, 2013 and CONAPO, 2008). These projections were directly incorporated into scenarios. Projections for household sizes are subdivided by CONAPO up to state level and could not be directly transferred to the metropolitan region. Thus, the average size of households in the MCMA in the base year 2010 was estimated based on the MCPV (INEGI, 2010a). Furthermore, estimates for future developments were done on percentage changes of average dwelling occupancy for projections of the DF from CONAPO (CONAPO, 2014). The number of households in the MCMA is a result of population size divided by dwelling occupancy.

It is expected that the trend of decreasing population growth rates over the last decades for the MCMA continuous with rates falling below 1% after 2010 (Table 3-4). The development is a result of a slowdown of migration from urban to rural areas, as well as the fact that the Mexican population is no longer only concentrated in the MCMA, but in several large cities (ONU-Habitat, SEDESOL, 2011). Household sizes are continuously decreasing, so the number of households in 2010 still grew with around 2%, but will slow down as well over the next years (Table 3-4).

Table 3-4: Projections for demographic parameters and resulting household numbers for 2010-2030 (INEGI, 2010a, CONAPO, 2013 and CONAPO, 2014)

	Scale	2010	2015	2020	2025	2030
Population	millions	20.50	21.34	22.09	22.72	23.25
Dwelling occupancy	-	3.78	3.60	3.45	3.33	3.22
Number of households	millions	5.42	5.93	6.40	6.83	7.22

3.3.3 Income projections

Income deciles were calculated for the MCMA in the base year using microdata from the MCPV. Income distribution was measured via the Gini coefficient. A value of 0.5429 was calculated indication a large gap between rich and poor households in the MCMA. In comparison, the World Bank estimated a Gini coefficient of 0.4716 for Mexico in 2010 (The World Bank, 2015). However, due to the used methodology for the calculation, the value for the MCMA may be overestimated and income in the MCMA is probably more equally distributed than the coefficient suggests. Reason to assume this is that for the calculation only income from work was considered and no other income sources such as pensions, income supports from the government, or monetary transfers from relatives. Therefore, income from low-income groups may be underestimated.

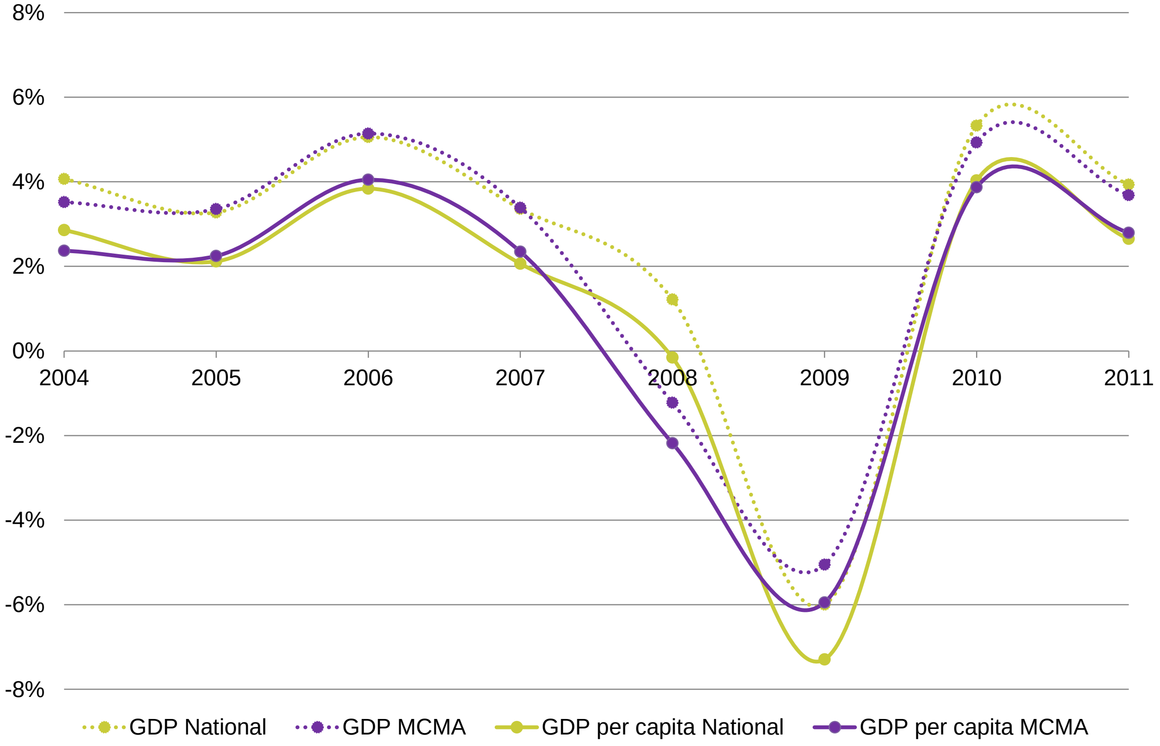
Table 3-5: Annual household income per capita and decile in the MCMA in 2010 (INEGI, 2010a)

	Average [MXN]	Sum [million MXN]	Average [US dollar]	Sum [US dollar]	Share of total income
Decile 1	5,400	11,071	706	1,447	1.2%
Decile 2	10,293	21,103	1,346	2,756	2.3%
Decile 3	13,750	28,189	1,797	3,685	3.0%
Decile 4	17,363	35,597	2,270	4,653	3.8%
Decile 5	21,676	44,441	2,834	5,809	4.8%
Decile 6	26,862	55,071	3,511	7,199	5.9%
Decile 7	34,414	70,555	4,499	9,223	7.6%
Decile 8	45,932	94,169	6,004	12,310	10.1%
Decile 9	69,362	142,204	9,067	18,589	15.3%
Decile 10*	209,540	429,593	27,391	56,156	46.1%
Average	**45,459**	**93,199**	**5,942**	**12,183**	**-**
Sum	**-**	**931,992**	**-**	**121,829**	**100%**
Gini			**0.5429**		

*Monthly household incomes above 999,998 MXN were only counted as 999,998 MXN in the survey what may lead to an underestimation of the decile.

Income developments were projected into the future based on assumptions on economic growth for the MCMA. Economic growth in the MCMA is strongly linked to national (Figure 3-5) and international developments. The national and metropolitan real GDP per capita (prices 2003) grew most of the time between 2-4% in the period 2003-2011. The financial crisis in 2008 led to global regression in 2009, and had a strong impact on the Mexican economy as well. Therefore, it was seen important that economic projections for the MCMA consider the national and international context.

Figure 3-5: Comparison of real GDP growth rates between the MCMA and whole Mexico 2003-2011 (INEGI, 2015b and IGECEM, 2013)



The thesis uses estimates for GDP growth prepared by the Organization for Economic Co-operation and Development (OECD) in its baseline scenario of the Environmental Outlook to 2050 published in 2012 (Manders, et al., 2012). Although there are more current projections developed by the OECD, this one has been chosen, as it is based on prices from 2010 and not as others on prices from 2005.

In the scenario, the OECD expects in principle a continuation of historic trends of global economic developments and decreasing growth rates over the next decades (Manders, et al., 2012). For Mexico, the OECD projects a similar development than the globe with a growth in real GDP by about 3.5% per year from 2010 to 2050 (Table 3-6).

Table 3-6: GDP growth projection for Mexico, baseline scenario from the OECD (Measured in constant 2010 USD) (Manders, et al., 2012)

	2010-2020	2020-2030	2030-2050	2010-2050
Mexico	4.5%	3.6%	2.9%	3.5%
World	4.1%	3.6%	3.1%	3.5%

GDP per capita is a common measure for income developments and is taken as such in the scenarios, while reserving judgement on its appropriateness as development and welfare indicator (see Costanza, et al., 2009). The scenario from the OECD expects an in average growth of GDP per capita for Mexico of 3.7% per year in the period 2010-2020 and 2.9% in the period 2020-2050 (Table 3-7). For the scenarios developed in the presented thesis, continuously decreasing growth rates were estimated based on the OECD projection, to avoid a jump in outcome parameters.

Table 3-7: GDP per capita growth projection for Mexico, baseline scenario from the OECD (Measured in constant 2010 USD) (Manders, et al., 2012)

	2010-2020	2020-2050
Mexico	3.7%	2.9%
World	3.1%	2.7%

3.3.4 Popularity projections

Saturation levels per appliance type in the last income decile were calculated for the MCMA for the years 2000 and 2010 based on the two household surveys MCPV and ENIGH. Historic trends were derived and continued for future projections. Most appliance types already show almost full appliance saturations in the last income decile and did not change anymore from 2000 to 2010. However, for computers and washing machines a trend towards increasing saturation levels were identified, which seems to be independent from income. Their projection is shown in the following table.

Table 3-8: Projected maximum saturation levels for computers and washing machines

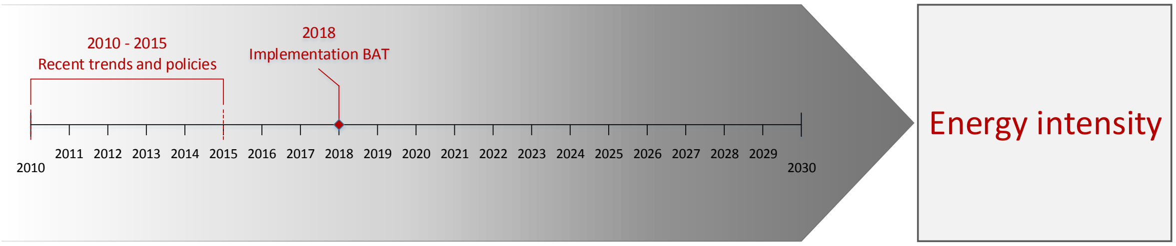
	2010	2020	2030
Maximal saturation computers	82%	97%	97%
Maximal saturation washing machines	87%	89%	91%

Note: Values refer to appliance ownership in the 10th decile.

3.3.5 Energy intensity projections

Energy intensities per product type are projected for two different scenarios, which vary regarding assumptions on low-carbon and energy-efficient technology diffusion into the stock. Both scenarios take into account the most important recent technological trends and policy measures, which had an effect on energy intensities in the residential sector after 2010. In concrete, these include MEPS for various products established by NOM-ENERs, SWH promotion programs and the recent technological transition in the television market. Some of the MEPS implemented between 2010 and 2015 were also taken into account for estimations on energy intensities in the stock assuming an anticipating effect of the announcement of upcoming new standards. Besides, new standards are partly also initiated by existing technological developments. In the case of refrigerators, also developments of the US market were taken into account. Backgrounds to residential energy policy in Mexico were presented in chapter 2.2. While the BAU-scenario assumes that beside the named developments no further technological changes will take place, in the BAT-scenario best-available technologies and practices are implemented by 2018. The selection of BATs for the MCMA is based on the review of current states of technologies from chapter 2.3 and local specifications. Energy demand scenarios are later combined with energy supply scenarios described in chapter 3.4. The corresponding energy supply scenario for the BAT-scenario assumes that by 2025 emission factors for electricity will be lower than for gas due to the large integration of renewable energies into the grid. Therefore, the BAT-scenario assumes a switch from gas to electric appliances. Underlying assumptions for each end-use and scenario are described in the following sections. Assumed developments for UECs can be found in the Annex 8.3.3. Both scenarios do not consider behavioral changes (e.g. time of use) or rebound effects through efficiency improvements.

Figure 3-6: Methodology for energy intensity projections in the scenarios



3.3.5.1 Business-as-usual scenario

Brief descriptions of dominant technologies and main assumptions for each end-use are presented in the black boxes. In addition, below each box some background information is given.

Water Heating

Conventional gas water heaters of storage and instantaneous type dominate the water heating market in Mexico. It is assumed that energy efficiencies for gas water heaters continue to improve up to 2012, due to a recent update of MEPS for thermal efficiencies. A number of programs and initiatives have been implemented to promote solar water heating in the commercial and residential sector in Mexico. However, a boom of solar water heating in Mexico has not yet happened and several market barriers still need to be overcome. The scenario assumes a small increase of the market share of solar water heaters to 2%.

Improvements in energy efficiencies for gas water heaters due to the latest update of the NOM-ENER for residential and commercial gas water heaters were already taken into account for the stock. After 2010, energy efficiencies continue to improve up to an energy factor of 0.61 for storage and 0.84 for instantaneous water heaters. Changes in market shares by technology type are marginal. Solar water heaters increase their market share from 0.5% to 2% at the expense of storage water heaters. The share for solar water heaters is aligned to SENERs base case in the outlook for national gas developments 2013-2027 (compare SENER, 2013).

Cooking

Energy intensities for cooking does not experience any change in the BAU-scenario.

Improvements of energy efficiencies for cooking due to the implementation of a new standard for gas cooking products were not taken into account in the scenario. Main reason is that the energy intensity for cooking was estimated based on average consumption in the USA and data on gas sales in the MCMA. Information about cooking products and their efficiencies in Mexico was not available or did not fit with top-down estimates.

Lighting

Mexico’s update of standards for general lighting in 2011, formalized the path-out of ILs in the residential sector by 2013. Households replaced incandescent bulbs mainly with CFLs. A market transition towards LEDs did not start so far.

The BAU-scenario for lighting simulates the gradual exchange of typical ILs of 60 W for CFLs of 15 W. The latter had an estimated share of 40% in households in the MCMA in 2010. LEDs are not purchased by households in the scenario.

Refrigeration

The scenario assumes energy efficiency improvements for refrigerated products up to 2014 driven by updates of MEPS for domestic refrigerators and freezers in Mexico and the USA.

In the recent achievement scenario the LBNL (McNeil, et al., 2012) assumes a harmonized development of energy efficiency levels of refrigerated products in Mexico and the USA. According to the scenario, their UEC in Mexico decreased by 16% up to the year 2014 in relation to 2005. Although the current standard in the USA from 2014 requires energy efficiencies of around 20% above the last update of the Mexican standard from 2012 (UNEP & CLASP, 2015), the assumption seems reasonable, as historic trends showed how close developments in Mexico are linked with the US market (Sánchez Ramos, et al., 2006).

Televisions

Developments in the globalized television market lead to technology transitions from CRT and Plasma to LCD televisions and from CCFL to LED backlit screens for LCD televisions. The BAU-scenario assumes that the new energy-efficient OLED technology enter into the market in 2015 and dominates it completely by 2026. Average screen sizes for televisions increase slightly, while sizes of OLED televisions grow significantly due to technological development. Changes in average UECs over time are only driven by market shifts between technology types and not by technological improvement. Energy efficiencies of televisions are not regulated in Mexico.

Manufacturing of televisions is highly globalized and concentrated, with five manufacturers holding 60% of worlds television market (Park, et al., 2011) and even 80% in Mexico (CONUEE & GIZ, 2009). Hence, technologies, sizes and efficiencies are very similar across regions (Park, et al., 2011). Main efficiency improvements are expected to come from technology transitions, which will be driven through autonomous market movements (Park, et al., 2013). Projections for energy consumption of televisions in the longer run are highly uncertain, due to the rapid evolution of television technologies and markets.

The BAU-scenario assumes that CRT televisions disappeared from the Mexican market already in 2011 (compare CONUEE & GIZ, 2009), CCFL-LED televisions in 2015 and the Plasma technology will disappear in 2016 (compare DisplaySearch, 2014). Furthermore, it is assumed that OLED televisions entered into the market in 2014 (compare DisplaySearch, 2013). Experts expect that their share on the market does not exceed 1% in 2017 (DisplaySearch, 2014) and grows in average 76% per year in the period 2015-2019 (Infiniti Research Limited, 2015). In the scenario this trend continues, so OLED televisions control the market completely by 2026. This was assumed even in the BAU-scenario due to the fast development of the television market.

The scenario considers an increase in screen size of LCD televisions by 3% per year by 2015 (compare IEA 4E, 2010) and after that a constant average screen size. The assumption is made, as LCD televisions replace gradually plasma televisions in the market of large screen sizes and a consumer trend to larger televisions. The screen size of OLED televisions is expected to grow as well driven by technological development, reaching the level of LCD televisions by 2026.

Energy efficiencies of each technology type are taken from (Park, et al., 2011) for 2010, beside OLED televisions. Here the estimated efficiency for 2014 was used. As it is difficult to say how efficiencies will autonomously develop without policy intervention, the BAU-scenario simplifies this issue and assumes frozen efficiencies of technologies.

Other electric appliances including washing machines and computers

It is assumed that energy efficiencies of washing machines improve by 2014 due to stricter regulations. Besides, UECs for computers and after 2014 for washing machines as well as average energy demand for other electric appliances per household maintains constant in the scenario. A standard for energy efficiencies of computers does not exist in Mexico.

Improvements in average UEC of washing machines due to an update of the Mexican NOM-ENER are estimated based on expectations from the LBNL (McNeil, et al., 2012). Other electric appliances include a range number of different products and also larger consumers such as dishwashers, freezers and fans. Energy intensities for computers and other electric appliances were set frozen due to a lack of information on technology shares and characteristics.

3.3.5.2 Best-available technology scenario

The BAT-scenario takes into account those developments described in the BAU-scenario plus the implementation of best-available technologies and practices by 2018. The transition from gas- to electricity-based water heating and cooking products starts also in 2018 due to their long lifetime, as well as higher appliance efficiencies.

Similar to the previous section, black boxes in the following contain brief descriptions of selected BATs and main assumptions for each end-use. In addition, below each box the reader can find some background information.

Water heating

The scenario assumes a gradual replacement of conventional gas water heaters by solar water heaters with electric backup (70%) and heat pump water heaters (30%). In addition, households purchasing new water heaters also install low-flow fixtures to reduce hot water demand.

The MCMA provides suitable climatic conditions for the installation of solar water heaters (Annex Table 8-32), which is the most energy-efficient technology available for water heating. Besides, solar water heaters are commercially available in the MCMA and subject of financial incentives. The solar water heating system in the BAT-scenario is in principle the same as in the BAU-scenario or the stock, but with an electric instead of gas backup and higher energy efficiency reducing the required collector area due to a reduced water demand (specified in the Annex Table 8-31). However, not all buildings in the MCMA may be suitable for the installation of solar collectors at the building roof. As studies evaluating the potential for solar water heating on roofs in the MCMA are missing, an estimation from the assessment for New York Cities Solar Water Heating Roadmap (NYC SAC partnership, 2013) were taken as reference. The study estimated that around 70% of the residential buildings in New York could be used for the installation of solar collectors. For the remaining 30% the scenario assumes the installation of heat pump water heaters meeting current energy star criteria from the USA with an energy factor of 2.0 (US EPA, 2015). In addition, a simply measure to reduce hot water demand is the installation of low-flow fixtures for showerheads and taps. The BAT-scenario assumes that the measure is implemented together with the purchase of a new water heater. Taking into account information from manufacturers in the MCMA (GDF, 2009), it was estimated that the installation of low-flow fixtures reduces hot water demand by 25%.

In the case, that gas remains the cleaner energy source in comparison to electricity, high energy-efficient condensing water heaters could be an alternative to heat pumps. The currently most efficient ones come from Navien manufactures and reach efficiencies of up to an EF of 0.98 (US EIA, 2015).

Cooking

In the scenario, Mexican households switch from gas to more energy-efficient electric cooking products. Additional energy savings of 10% are assumed to be achievable through improved cooking practices or technological improvements or transitions.

The possibility to switch from gas to electric cook stoves and ovens was assessed based on overall (system) efficiencies. These include beside appliance efficiencies also production and transportation efficiencies. According to the alternative supply scenario, CO_2 emission factors for electricity fall below those for gas by 2025. Taking into account the long lifetime of cook stoves and ovens a switch by 2018 would make already sense assuming similar appliance efficiencies for gas and electric ones. However in addition, electric cooking products are typically more energy efficient than those of gas. In the USA, electric cooktops have an average appliance efficiency of 74% and standard ovens 12.5% (US DOE, 2009). In comparison, appliance efficiencies for gas stove top and standard oven cooking is only 40% and 6% respectively (US DOE, 2009). The same, as for energy intensity estimates in the stock, energy consumption for electric cooking products relies on estimates from US households from the LBNL (US DOE cited in McNeil, et al., 2012). Energy consumption for electric cooking is assumed to be 0.55 PJ/year in comparison to 0.9 PJ/year for gas. Additional reduction potentials under currently best available technologies and practices were conservatively estimated to 10%. These could be achieved either through consumer education towards improved cooking practices or technological improvements (Hager & Morawicki, 2013). For instance, induction cooktops have typically energy efficiencies of around 84-90% (Hager & Morawicki, 2013).

Lighting

After the substitution of ILs for CFLs by the end of 2013, the BAT-scenario considers another technological transition from CFLs to high energy-efficient LEDs. The scenario assumes that CFLs will be replaced completely within five years.

Over the last years, energy efficiencies of LEDs increased significantly and became by date more energy-efficient than CFLs. The trend of increasing efficiencies for LEDs is expected to continue over the next decades. Expected efficiency improvements for LEDs are incorporated into the BAT-scenario and are based on a recent study prepared for the US Department of Energy (Navigant Consulting, 2014).

Figure 3-7: Outlook for average LED lamp efficiency (Navigant Consulting, 2014)

	Unit	2015	2020	2030
Luminary efficacy for general service	lm/W	81	102	131

Refrigeration

The BAT-scenario assumes an additional reduction of UECs for refrigerators and refrigerator/freezer combinations by 30% for new appliances in relation to the level from 2014. The target is oriented on currently most efficient products on the US market.

The scenario assumes the current harmonization of refrigerated products between the Mexican and US market. Although sizes and consumer behavior varies between the countries, energy efficiencies are assumed to be at the same level (see BAU-scenario). Currently most energy-efficient products in the US are recognized by the Energy Star Program as such. Most energy-efficient refrigerator-freezers in 2014 achieved energy efficiencies of 30% above federal requirements (Energy Star, 2013).

Televisions

Televisions in the BAT-scenario will be gradually replaced from 2018 on with energy-efficient LCD and OLED televisions of one W/dm² screen area.

Assumptions on technological transitions and screen sizes in the television market are the same in the BAT-scenario and the BAU-scenario. The difference between the two projections is that energy efficiencies in the BAU-scenario are frozen by technology type and in the BAT-scenario they increase for LED-LCD and OLED televisions to a level of one W/dm² (IEA, 2013b). This means a 40% reduction for LCD and 10% reduction for OLED televisions in comparison to the BAU-scenario.

Other electric appliances including washing machines and computers

No other changes than those declared in the BAU-scenario are assumed.

Although energy efficiencies of other electric appliances are possible, their importance for energy consumption and CO_2 emissions in the MCMA is rather low. In addition, possible energy reductions for other electric appliances are difficult as they cover a range number of appliance types. Therefore, for simplification, energy consumption per household of other electric appliances including washing machines and computers is set constant.

3.3.6 Sensitivity analysis

Input parameters in the model are subject of uncertainties. To provide an indication of the robustness of model outputs with respect to key input parameters a sensitivity analysis was carried out. Sensitivities for parameters were tested for a low and a high scenario with variations for GDP per capita growth, income distribution and dwelling occupancy change. Population was not variated as its projection is much more reliable than those of other parameters are. Projections for population come from official statistics. Main assumptions for each scenario are listed in the following.

Main scenario:

- Real GDP per capita growth rate decreases by 0.04% each year from 3.8% in 2010 to 3.1% in 2030;
- Dwelling occupancy size drops from 3.8 people per household in 2010 to 3.2 people per household in 2030; and
- No change in income distribution takes place over the projection horizon.

Low scenario:

- Real GDP per capita growth rate decreases with 0.15% each year;
- Dwelling occupancy growth rate decreases by 0.2% less than in the main scenario; and
- No change in income distribution takes place over the projection horizon.

High Scenario:

- Constant real GDP per capita growth rate of 3.8% per year;
- Dwelling occupancy rate decreases by 0.2% faster than in the main scenario; and
- Income is more equally distributed measured through a decrease in the Gini coefficient of 25% by 2030 in relation to 2010.

3.4 The energy supply sector

3.4.1 Gas

Gas is an important energy carrier for residential energy demand in Mexico. The national household survey MCPV indicates that households in the MCMA mainly use LPG for water heating and cooking, and only less than 10% have actually access to natural gas supply (Table 3-9). Comparing these two sources, natural gas is a bit more favorable in terms of CO_2 emissions than LPG. Emission factors in Table 3-9 use higher heating values as estimates on water demand and cooking in this document use data from the USA, where higher heating values are used to define energy-efficiency indicators.

Table 3-9: Gas supply structure in the MCMA and emission factors (INEGI, 2010a and World Resources Institute, 2015)

Fuel type	Share [%]	Emission factor* [tones CO_2 per GJ]
LPG	92	0.057
NG	8	0.050

*Higher heating value

In all scenarios, the ratio between LPG and natural gas, as well as emission factors for those are fixed.

3.4.2 Electricity

The MCMA is part of the national electricity grid. Projections for electricity supply for the MCMA are based on national averages and do not consider local specifications. Losses in the transmission and distribution grid (technical losses only) were assumed to 8% based on 2012 level (SENER, 2014b). Scenarios do not consider measures to reduce technical losses in the electricity grid.

In 2012, Greenpeace published in cooperation with DLRs energy scenario group, an outlook for the energy system in Mexico (Greenpeace, et al., 2012b). The study included two different scenarios: a reference scenario (business-as-usual scenario) reflecting a continuation of current trends and policies, as well as an energy [r]evolution scenario, designed to meet the global +2°C target and phase-out nuclear power. Figure 3-8 shows the structure of future electricity generation in both scenarios up to the year 2050. While in the reference scenario increasing energy demand is mainly met by natural gas, the energy

[r]evolution scenario integrates large shares of renewable energies into the grid reaching a share of 93% in 2050.

Figure 3-8: Electricity generation structure under the reference and energy [r]evolution scenario (Greenpeace, et al., 2012b)

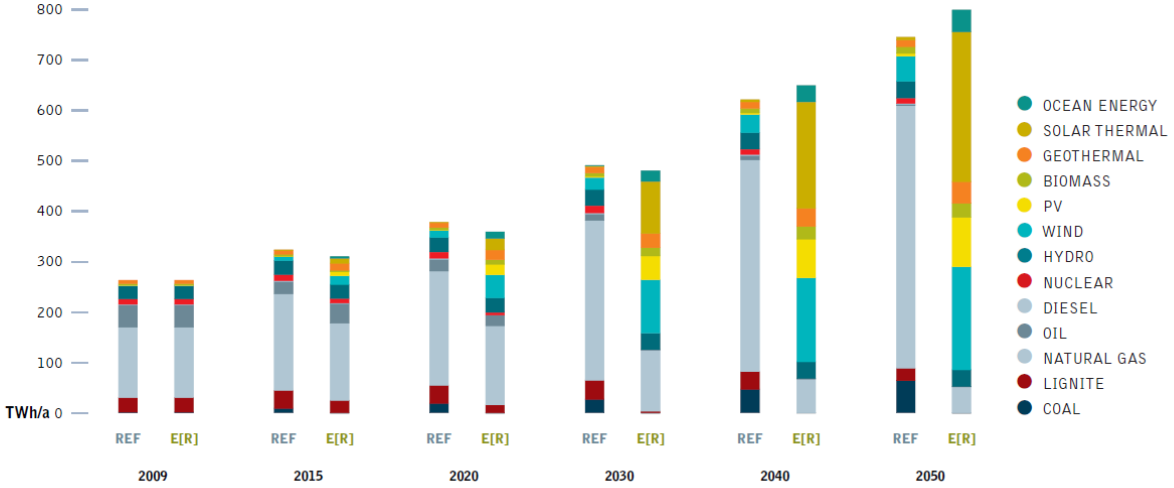


Table 3-10 presents resulting average tones of CO_2 emission per GWh generated electricity in both scenarios up to 2030 including conventional and renewable energy sources. While in the reference scenario emissions per GWh produced only decrease by around 15%, in the energy [r]evolution scenario they decline by 76%. The BAU-scenario for the MCMA uses emission factor trends from Greenpeace reference scenario and the BAT-scenario those of the energy [r]evolution scenario.

Table 3-10: Emission factors for electricity under the reference and energy [r]evolution scenario in tCO_2 per GWh (Greenpeace, et al., 2012b)

Scenario	2009	2015	2020	2025	2030
Reference	458	422	414	400	388
Energy [R]evolution	458	369	258	187	109

In the energy [r]evolution scenario, emission factors fall below those of local gas combustion by 2025 considering distribution and transmission losses. This would mean that electricity becomes a cleaner energy source than gas in terms of CO_2 emissions.

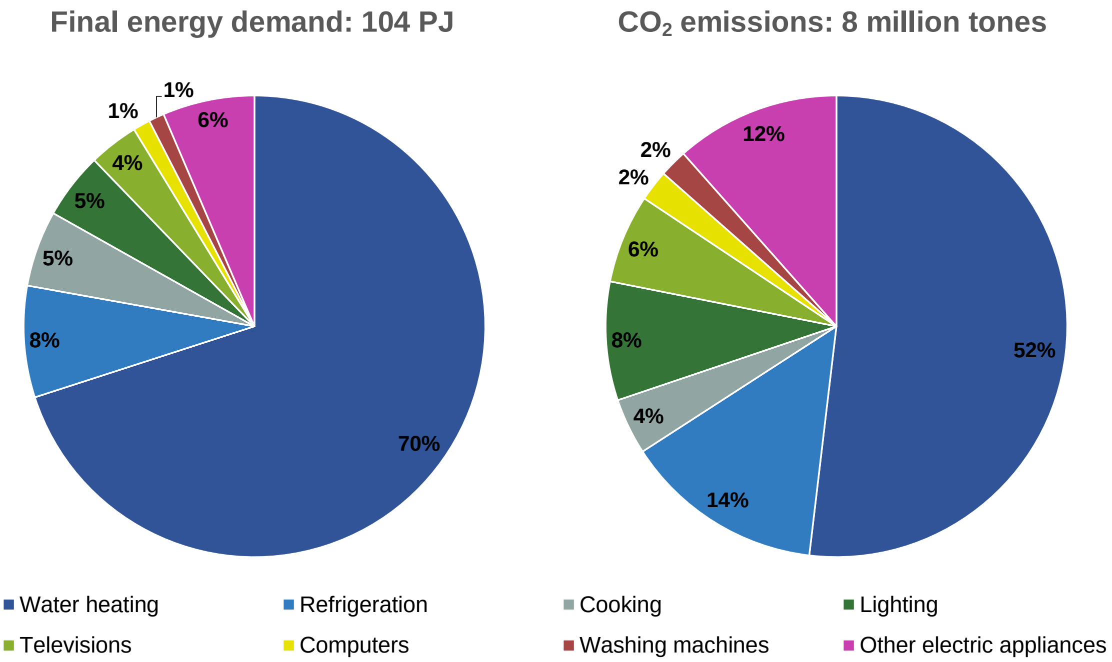
4 Modeling results for the MCMA

4.1 Status of energy demand and CO_2 emissions in 2010

The MCMA’s final residential energy demand is estimated to stand at 104 PJ in 2010 including energy consumption of households that illegally connected to the electricity grid or purchased gas from not registered sources. With the application of emission factors for local gas combustion and the national electricity grid, it was calculated that this demand resulted in a total emission of eight million tons of CO_2 in Mexico in 2010.

Shares of end-use services on household energy demand and CO_2 emissions (Figure 4-1) were estimated based on engineering-based bottom-up calculations. These show that the largest energy consuming end-use in the MCMA by far is water heating. Its share on final energy demand was calculated to around 70% and on CO_2 emissions about 52% in 2010. Other important end-uses identified include refrigeration of food, cooking, lighting, computers and washing machines. Nevertheless, their share in comparison to water heating is much lower. The dominance of water heating for residential energy demand in the MCMA is mainly a result of the large UEC of water heaters and less of their availability in households.

Figure 4-1: Model outcome for residential energy demand and CO_2 emissions by end-use in 2010


Final energy demand: 104 PJ

CO_2 emissions: 8 million tones

A study from the IEA for the building sector in Mexico (IEA, 2013b) estimates that Mexican households consumed around 0.8 EJ final energy in 2010. Hence, the residential energy sector in the MCMA probably accounts for roughly one eighth of national residential energy demand. Furthermore, a comparison between estimations on end-use shares on residential energy consumption from the IEA for Mexico and own modeling results for the MCMA indicates existing regional differences in Mexico. The IEA study estimates shares of end-use services on national residential energy demand in 2010 in the order: 45% water heating, 29% cooking, 15% appliances and other equipment, 7% lighting, 2% space heating and 2% space cooling (IEA, 2013b). Results from the MCPV state that water heaters have a much larger saturation in urban than in rural areas in Mexico. Around 65% of Mexican households in locations with more than 100,000 residents owned a water heater in 2010, in comparison to only 20% in locations of less than 2,500 residents. This tendency does also exist for other appliance types (INEGI, 2013b).

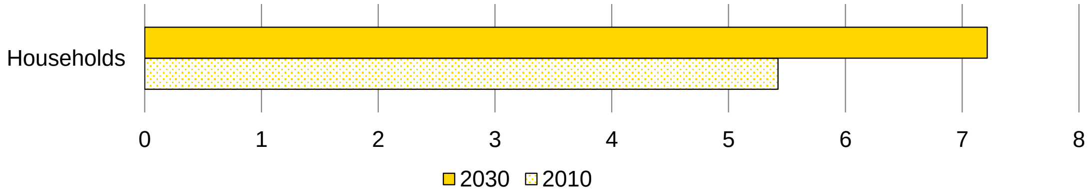
4.2 Pathways for energy demand and CO_2 emissions up to 2030

4.2.1 Activity projections

In the designed model, projections for the MCMA's population size, dwelling occupancy, household income and appliance popularity drive appliance ownership rates in the time after 2010.

The future number of households in the MCMA is calculated from official projections from CONAPO for population growth and dwelling occupancy changes. Modeling results indicate that the MCMA will contain around 7.2 million households in 2030, around 30% more than in 2010 (Figure 4-2). In the time from 2010 to 2030, the growth rate for the number of households in the MCMA is continuously slowing down in the projection, as increases in population growth rates and decreases in dwelling occupancy growth rates level out.

Figure 4-2: Estimated number of households in the MCMA for 2010 and 2030 (in millions)



Real household income per capita in the MCMA almost doubles by 2030 in the scenarios. The estimation is based on expectations from the OECD for economic growth in Mexico. In addition, scenarios assume an increase in the popularity of computer and washing machines over the next decades. Figure 4-3 and Figure 4-4 compare appliance ownership rates of households in the MCMA between the years 2010 and 2030. Appliance ownership rates in the base year are calculated from household surveys; while those for 2030 are simulation outcomes from REDUCE. In 2010, households in the MCMA were almost fully saturated with cook stoves and first televisions. Hence, their appliance stock in scenarios only increases from a raising number of households in the MCMA. In comparison, model results indicate that very large increases in saturation levels can be expected for computers and second televisions. It was estimated that in the MCMA in 2010 only each second household had a computer and 65% a second television. Model outcomes suggest that by 2030 already three forth of the households will have a computer and almost 80% a second television. Furthermore, appliance saturations for water heaters, refrigerators, washing machines and lighting points are increasing as well.

Figure 4-3: Estimated saturation levels of domestic appliances in households for 2010 and 2030

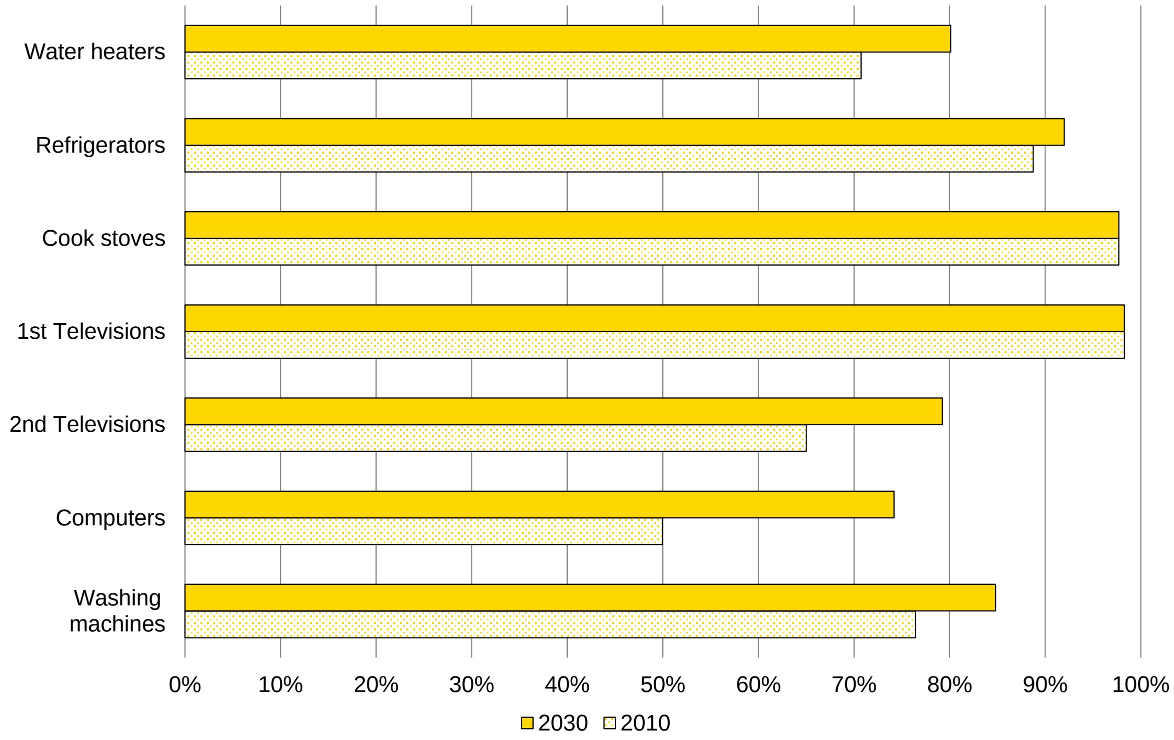
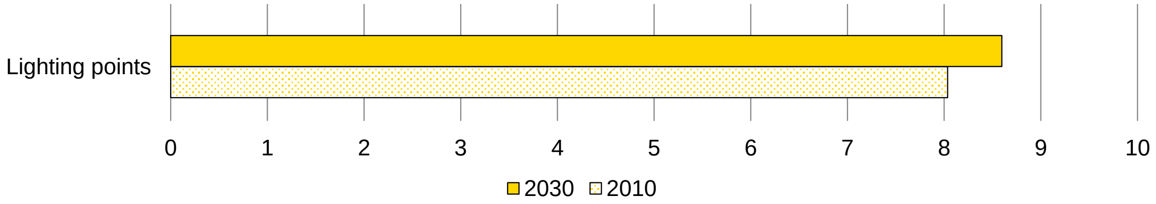


Figure 4-4: Estimated average number of lighting points in households for 2010 and 2030



The previously presented appliance ownership rates are averages over all income deciles. However, income groups contribute differently to their future increase. Table 4-1 shows that in the conducted scenarios the growth in activity levels and hence energy demand are mainly driven by first purchases of appliances from low- and medium-income groups. Functions defined for the MCMA, relating saturation levels with income, indicate that saturation levels of households for water heaters, second televisions, computers and washing machines in the MCMA largely respond to changes in household income. In comparison, they also suggest that the ownership of refrigerators and lighting bulbs, as well as first televisions and cook stoves is little to very little dependent on household income for the MCMA.

Table 4-1: Calculated growth rates for appliance saturations by income decile for the period 2010-2030

Decile	Income share	Water Heaters	Refrigerators	2^{nd} Televisions	Computers	Washing machines	Lighting points
1	1.2%	22%	6%	47%	86%	16%	9%
2	2.3%	20%	5%	41%	78%	15%	8%
3	3.0%	19%	5%	38%	73%	14%	8%
4	3.8%	18%	5%	34%	68%	13%	8%
5	4.8%	17%	4%	31%	62%	12%	8%
6	5.9%	15%	4%	27%	56%	12%	8%
7	7.6%	14%	4%	22%	49%	10%	7%
8	10.1%	11%	3%	16%	41%	9%	7%
9	15.3%	8%	2%	8%	30%	7%	6%
10	46.1%	1%	0%	0%	19%	5%	2%
Total		13%	4%	22%	49%	11%	7%

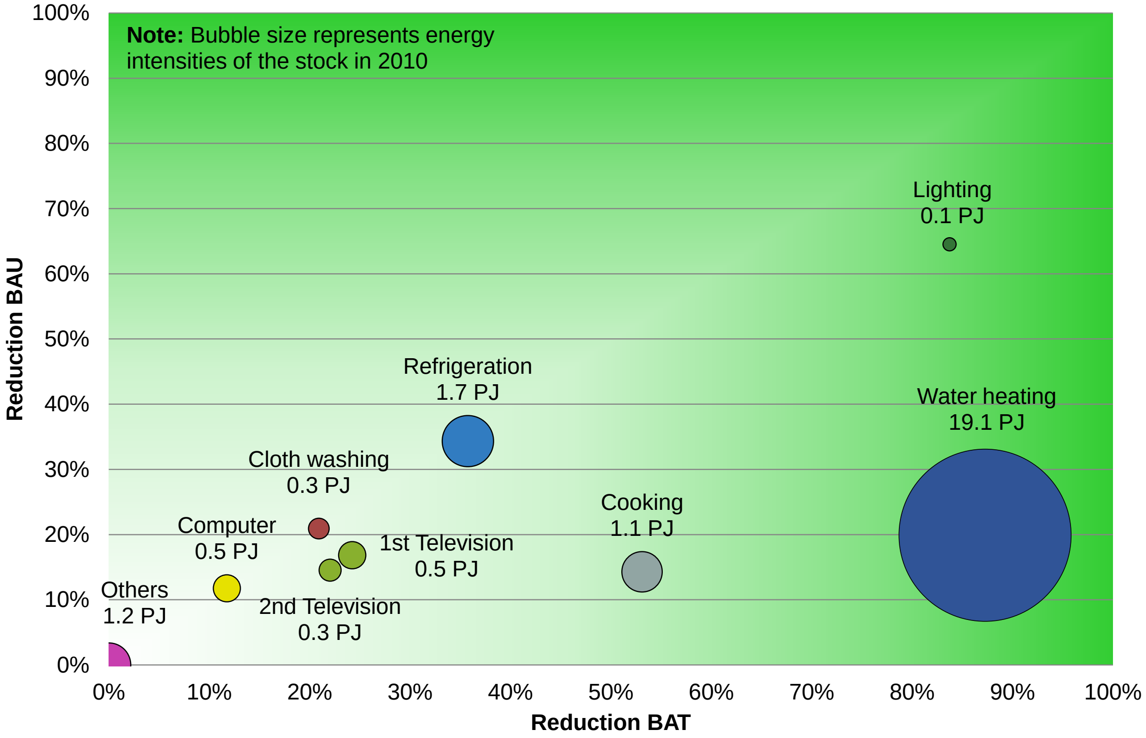
Combining growth rates for household number and appliance ownerships in the MCMA results in forecasts of appliance stocks from 2010 to 2030 (Annex 8.3.2). The largest increase in the appliance stock takes place for computers in the scenarios, due its large income dependence and raising popularity. Their number almost doubles from 2010 to 2030. Furthermore, the stocks of water heaters, washing machines and second televisions increase by around 50-60% and those of the remaining appliance types by about 30-40% up to 2030 in relation to 2010.

4.2.2 Energy intensity projections

Energy intensities of end-uses can vary considerably. Bubble sizes in Figure 4-5 indicate their magnitude in the appliance stock in the MCMA in 2010. Annual values of energy intensities were estimated based on engineering calculations and calibrated to adjusted reports on gas and electricity sales. Therefore, their values are quite uncertain and should be rather interpreted as indicators for magnitudes. The by far most energy intensive end-use in households in the MCMA is water heating. Calculations suggest that the energy intensity of water heating in the stock in 2010 was probably around 19 PJ/year. Moreover, it was estimated that refrigeration of food had an energy intensity of about 1.7 PJ/year and cooking 1.1 PJ/year. Rather small annual UECs were assumed for televisions, computers, washing machines and lighting bulbs.

The thesis investigates two different pathways for energy intensities in the residential sector in the BAU-scenario and the BAT-scenario. The location of bubble sizes in Figure 4-5 indicates the total reduction of energy intensities from the average in the stock in 2010 to those of new purchases in 2030 for each of these scenarios. The higher an end-use is located upwards in the figure the larger is its reduction under the BAU-scenario. The more an end-use is placed to the right of the figure the greater is its drop under the BAT-scenario.

Figure 4-5: Reductions in energy intensities under the BAU-scenario and the BAT-scenario



The figure shows that several end-uses decrease in energy intensities already notable under the BAU-scenario as a consequence of recently implemented policies in Mexico or technological trends. It is expected that the lately passed path-out of incandescent lamps in Mexico will decrease energy intensities of lighting in the MCMA by around 65% as households replace them by more energy-efficient fluorescent lamps. Energy efficiencies of refrigerated products in Mexico improved significantly over the last decades due to three updates of MEPS for residential refrigerators and freezers. Scenarios assume a drop in average energy intensity of 63% from products purchased in 1994 to those in 2014. Furthermore, washing machines also improved considerably under the standard and labeling program in Mexico. Their average UEC decreases by 42% between products purchased in 1994 and 2014 in the scenarios. Reductions in energy intensities under the BAU-scenario also take place for water heating, cooking, televisions and computers.

The figure also shows that additional reductions to those applied under the BAU-scenario are possible in the future. The greatest unexploited potential for energy savings holds water heating. It is estimated that the implementation of solar and heat pump water heaters in combination with hot water demand reductions could reduce the energy intensity of new water heaters to those in the stock by 87%. A significant percentage reduction for energy intensity seems also possible for lighting through the replacement of CFLs for LEDs. Their energy consumption is expected to be half of those of CFLs by 2030. Under the BAT-scenario, energy intensity for cooking halves by 2030 mainly due to a switch of households from gas to electric cooking equipment. However, this makes only sense under the assumed large integration of renewable energies into the electricity grid. Current best-available refrigerated appliances demonstrate that significant reductions in energy intensities for this end-use are possible.

It should be noted that scenarios did not consider increases in user time e.g. for televisions or a rebound effect.

4.2.3 Energy demand scenarios

Combining the projections for activity and energy intensity levels results in future pathways for the MCMA’s final energy demand (Figure 4-6).

Under the BAU-scenario, total final energy demand increases by 23% from 104 PJ/year in 2010 to 129 PJ/year in 2030. End-use services that increase in energy demand under the BAU-scenario include water heating, cooking, televisions, computers, washing machines and other electric appliances. Computer experience the largest percentage change with 98% driven by a fast growing appliance stock. Final energy demand for televisions almost double by 2030 especially due to an increasing number of second televisions in households. Cooking and lighting decrease in energy demand by 5% and 50% respectively under the BAU-scenario. Here, energy efficiency improvements are more significant than their rising appliance stock.

In comparison, in the BAT-scenario, final energy demand decreases by 49% compared to the consumption in 2010 and is expected to reach 53 PJ/year in 2030. The largest drop in energy demand show lighting with 71% and water heating with 66% due to their immense improvements in energy efficiency. Cooking, refrigeration and televisions experience some decrease as well through the implementation of BATs. Energy demands for washing machines, computers and other electric appliances are the same as in the BAU-scenario, as here no measures are integrated in scenarios.

Under the accelerated BAT-scenario, final energy demand drops by even 60% to 42 PJ/year in 2030. The larger decrease in energy demand in comparison to the BAT-scenario is achieved through the acceleration of appliance turnovers. It provides a reference point, how much energy demand could be theoretically reduced. In the scenario water heating, cooking and refrigeration are the end-use services, which further decreases in energy demand in comparison to the BAT-scenario due to the long lifetime of respective appliances.

Figure 4-6: Pathways for final energy demand under the BAU-scenario and the BAT-scenario

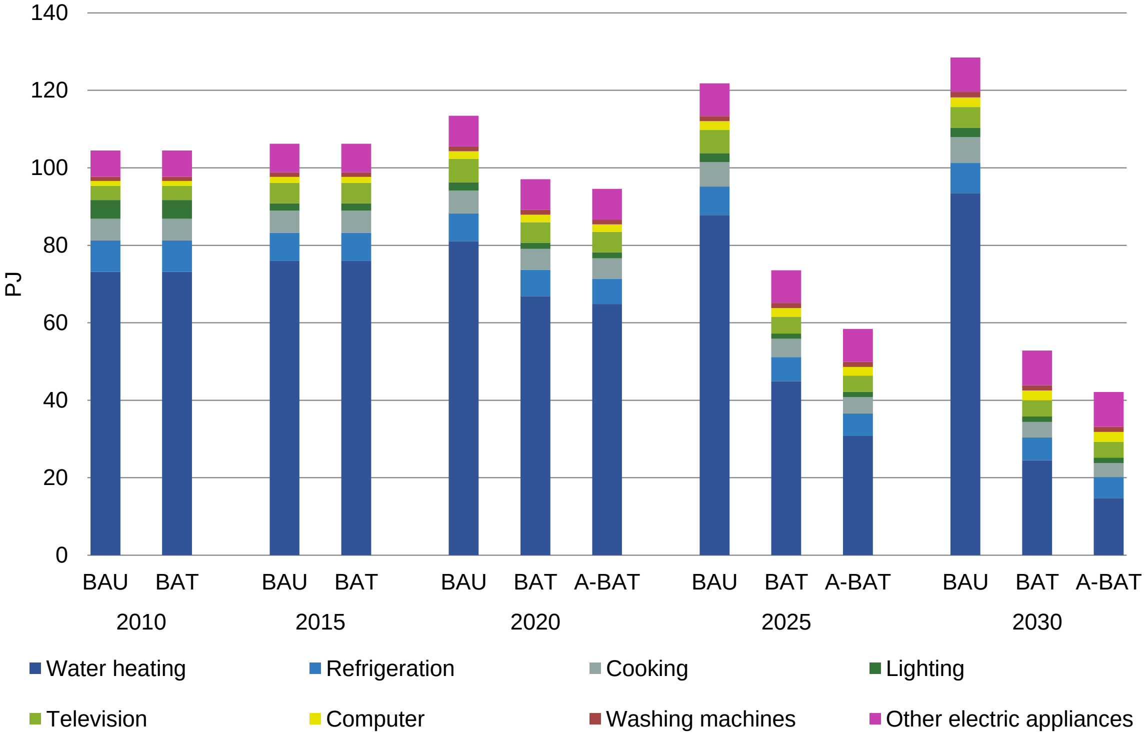
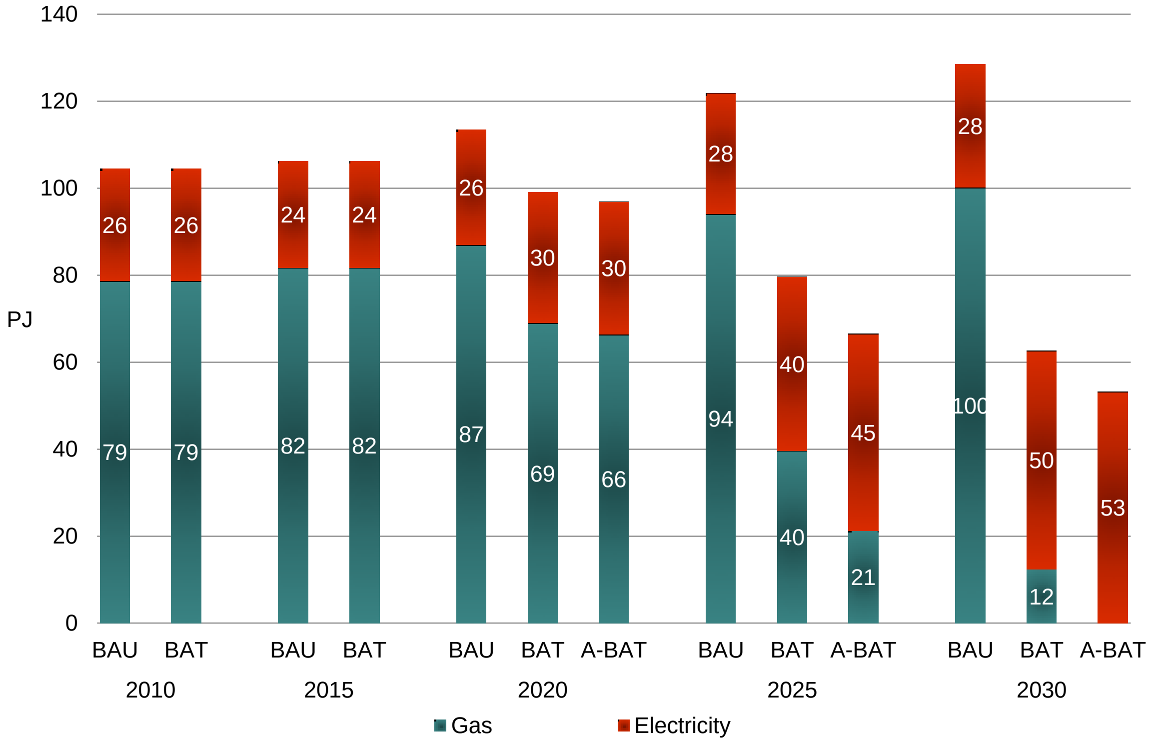


Figure 4-7 shows future developments in gas and electricity demand for the MCMA under the three scenarios. Under the BAU-scenario, final energy demand for gas rises by 27% from 79 PJ/year in 2010 to 100 PJ/year in 2030 driven by growing energy demands for water heating and cooking services. Furthermore, electricity demand increases in the scenario by 10% to 28 PJ/year. Due to fuel switches from gas to electricity for water heating and cooking, final energy demand for gas is reduced by 84% in the BAT-scenario. Old appliances purchased before 2018, which will not be replaced before the end of the projection horizon, cause a gas demand of 12 PJ/year in 2030. In the BAT-scenario, a significant increase in electricity demand is expected by 95% to 50 PJ/year in 2030 in spite of energy efficiency gains, as two large end-uses, water heating and cooking, switch to electricity. Under the accelerated BAT-scenario, cooking equipment and water heaters are completely exchanged by electric ones. In 2030, the residential sector exclusively demands 53 PJ/year electricity in the scenario.

Figure 4-7: Pathways for final gas and electricity demand under the BAU-scenario and the BAT-scenario

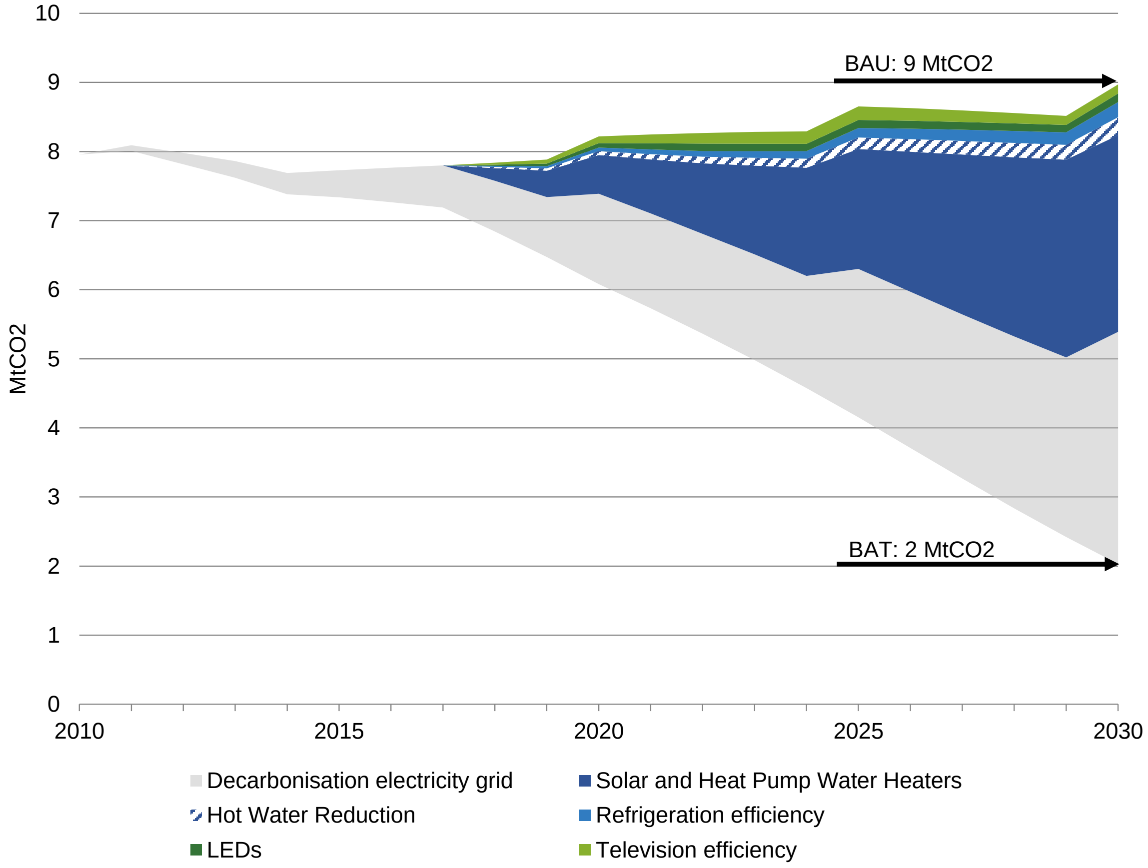


4.2.4 CO$_2$ emission scenarios

CO$_2$ emissions from activities in the MCMA increase in the BAU-scenario by 13% from 8.0 Mt/year in 2010 to 9.0 Mt/year in 2030. In comparison, under the BAT-scenario, CO$_2$ emissions decrease by 75% in relation to 2010 and 78% in relation to the BAU-scenario up to 2030. Annual per capita CO$_2$ emissions of the residential sector drop from 0.4 tons to 0.1 tons. Under the accelerated BAT-scenario, CO$_2$ emissions in 2010 even decrease by 83% to 1.4 Mt/year in 2030 due to the larger drop in final energy demand.

Figure 4-8 shows the contribution of measures taken in the BAT-scenario to CO$_2$ emission savings. Almost half of these reductions are attributable to the decarbonisation of the power sector and the other half to the decrease in energy demand. Hence, both sectors, the residential sector and the energy supply sector, contribute more or less in equal shares to the decrease in CO$_2$ emissions under the BAT-scenario. The electricity supply in the BAT-scenario is characterized by a dramatic increase of the renewable energy market. The replacement of conventional gas water heaters for solar and heat pump water heaters in combination with hot water demand reductions account for around 45% of the 7.0 million tons of carbon dioxide ($MtCO_2$) savings by 2030. Energy efficient lighting, refrigeration and televisions contribute with 11% to reductions. The end-use service cooking is not listed between CO_2 emission savings from efficiency gains. Although the appliance efficiency for cooking products increases in the BAT-scenario, a switch from gas to more energy-efficient electric cooktops and ovens makes only sense under the alternative supply scenario and not the reference supply scenario. CO_2 emission savings from cooking are therefore only included in savings from the decarbonisation of the electricity grid.

Figure 4-8: Contribution of CO_2 emission reduction opportunities between the BAU-scenario and the BAT-scenario



4.2.5 Sensitivities of parameters

Sensitivities for future energy demand and CO_2 emissions were tested regarding variations in economic development, income distribution and dwelling occupancy. Results confirm the importance to consider income distribution for energy demand and CO_2 emission projections in the household sector. While under high GDP per capita growth rates of 3.8% final energy demand in the BAU-scenario only increases by around 1% in 2030, an increase in the Gini coefficient from 0.543 to 0.407 raises energy demand by 4.6% in 2030.[10] The relation between dwelling occupancy and output parameters is linear. For instance, a faster decrease of the dwelling occupancy rate by 2% leads to an increase in final energy demand of 2.2% under the BAU-scenario. Changes in income growth and distribution have a higher impact on final energy demand, as they have on CO_2 emissions under the BAU-scenario. Activity levels of gas end-uses are less income dependent than electric ones and have a more favorable emission factor.

Levels for higher and upper band of the sensitivity analysis were defined in chapter 3.3.6. In Figure 4-9 and Figure 4-10, these ranges are visualized. Under the BAU-scenario, final energy demand has a range from 122 PJ/year to 134 PJ/year in 2030. CO_2 emissions are in a band from 8.5 $MtCO_2$ to 9.3 $MtCO_2$. Furthermore, in the BAT-scenario final energy demand varies between 50 PJ/year to 55 PJ/year and CO_2 emissions between 1.9 $MtCO_2$ to 2.1 $MtCO_2$ in 2030.

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[10] In 2010, countries with a GINI coefficient close to 0.543 were Colombia and Honduras, and close to 0.407 Madagascar, Thailand and the United States (The World Bank, 2015). Even a coefficient of 0.407 still indicates a quite unequal income distribution.

Figure 4-9: Results from the sensitivity analysis for final energy demand

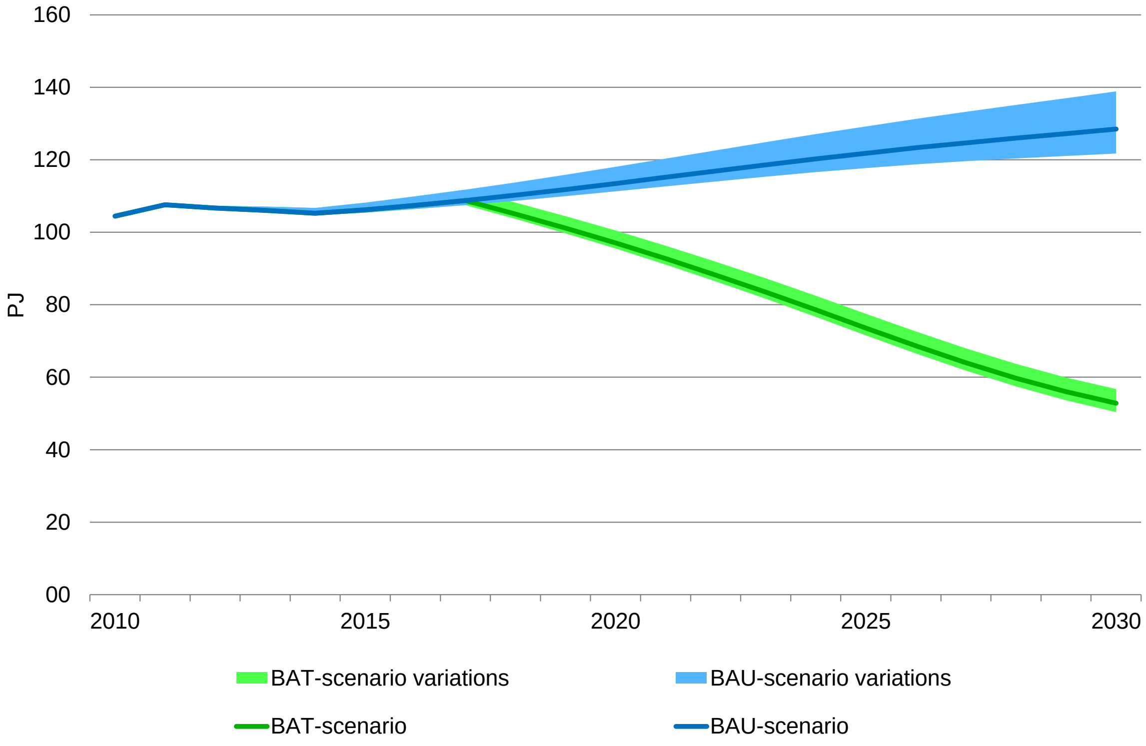
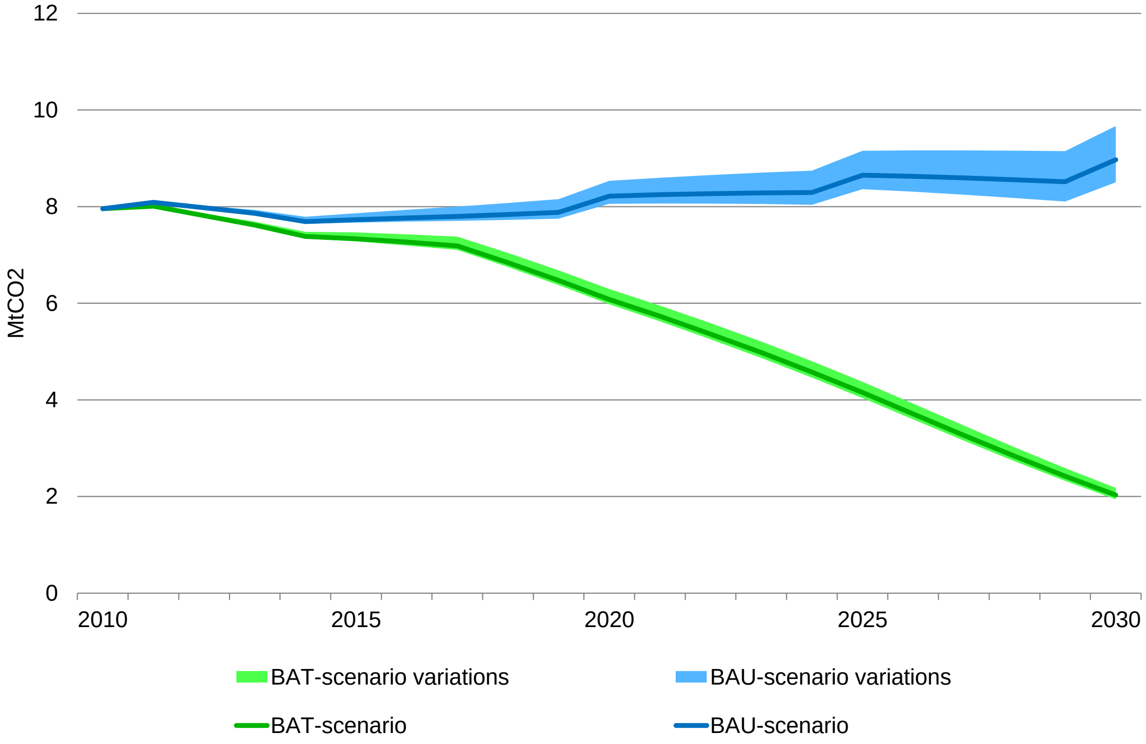


Figure 4-10: Results from the sensitivity analysis for CO_2 emissions



5 Conclusions and recommendations

A slowdown in the increase of population and medium economic growth are giving way to a low-carbon development in Mexico's largest metropolitan area. With concentrating roughly one eighth of national's residential energy demand, the MCMA is a major pillar for energy efficiency policies and measures concerning the sector. Nevertheless, if no action is taken final energy demand is expected to increase by 23% by 2030.

The constructed scenarios in the present thesis demonstrate that the residential sector can play a major role in climate change mitigation. The investigation indicates that a decrease of approximately 49% of the MCMA's final residential energy demand in 2010 is possible by 2030. In theory, accelerating the turnover of appliances, a decrease of even 60% could be achieved. This is attainable through the proliferation of today's most energy efficient building equipment. The saving is achievable without stepping back in comfort or interceding in equipment saturation and usage.

The scenario work also demonstrates that measures in the residential sector require time to show their full impact. Associated to that is a lock-in risk meaning that appliances once purchased with low energy efficiency are normally not exchanged before the end of their lifetime. This shows the importance of ambitious efficiency policies for household appliances and equipment with long lifetimes.

The residential sector is directly interlinked with the power sector. Scenarios demonstrate that both sectors can contribute in almost equal parts to CO_2 emission reductions. Model outcomes suggest that CO_2 emissions in 2010 could be reduced by 3.6 million tons by 2030 through reductions in energy demand. The effect of a decarbonized power sector on CO_2 emissions caused by household activities in the MCMA is estimated to 3.4 million tons in 2030 accounting for the other half of total potential savings. The Greenpeace energy [r]evolution scenario for energy supply in Mexico suggests that electricity could become a cleaner energy source than local gas combustion by 2025. Under this premise, a switch of households from gas to electricity for cooking and water heating end-use services will save CO_2 emissions. This also demonstrates that consistent policy at local and national level, but also between the sectors is required.

A future pathway for the MCMA involving highly energy-efficient residential buildings in combination with the supply of clean energy produced within the metropolitan area or imported can contribute to avoid impacts of climate change in the future. Conducted scenarios show that CO_2 emissions caused from residential activity in the MCMA could be reduced by 75% from eight $MtCO_2$ per year in 2010 to two $MtCO_2$ per year in 2030. In relation to the defined baseline scenario, this means a decrease of 78% in 2030. National planning documents state that Mexico has to reduce 72% (27 $MtCO_2e$) of its GHG emissions in the building sector (residential and commercial sector) in relation to a defined baseline scenario by 2030 to meet the set national climate change goal (INECC, 2010). Although it is not possible to compare results developed here for the MCMA directly with those from national planning documents without having an inside into underlying modeling technique, assumptions and so on, results demonstrate that the MCMA could contribute significantly to achieve national reduction targets. Beside climate change mitigation, energy efficiency initiatives in the residential sector can also have other benefits including improvements in energy security and sovereignty, elimination of city air pollution, water savings, new business opportunities and employment creation.

At the same time, different market barriers hamper the realization of substantial, partly cost-effective measures for energy efficiency opportunities in the residential sector. Many of these barriers could be overcome or mitigated through the implementation of policies and measures.

Although local governments are limited in their possibilities to interfere in residential energy demand (e.g. they cannot implement appliance standards) opportunities for local policy should be perceived, as they allow taking into account present climatic conditions, building types, stakeholder groups, and household characteristics. A broad portfolio of instruments is available and increasingly applied worldwide at national and city level to capture energy savings. Among local policy instruments, green building and energy codes have been particularly effective in achieving large energy reductions.[11] Possibilities for local energy efficiency policy in the MCMA are given under the current institutional framework through local building codes and local climate action programs. An obstacle for regional planning in the MCMA is the complex institutional system. The development of a common and coordinated policy and shared vision for climate change mitigation and adaption in the metropolitan area is crucial for effective action.

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[11] The Green Building City Market Briefs (C40, et al., 2015) provides a comprehensive catalogue of successful policies, programs and projects in the building sector in cities.

Policy in the MCMA for the residential sector should in particular focus on water heating. Scenario results demonstrate that in terms of potential energy and CO_2 emission savings, water heating is expected to provide the largest unused reduction potential. It is estimated that the energy intensity of water heating could be reduced by 67% to current level through the replacement of conventional gas water heaters with solar and heat pump water heaters and the installation of low-flow fixtures. Besides, energy efficiency gains are also possible for lighting, cooking, refrigerators and televisions. To exploit the existing potential local building codes need to integrate energy aspects and mandate the implementation of energy efficient equipment. An extension of existing programs from the Federal District including the certification scheme for sustainable housing and the sustainable housing program to the whole metropolitan area could reduce energy consumption from residential buildings as well.

At a national level, Mexico's standard and labelling program showed to be effective in achieving energy efficiency improvements. To maintain an impact it is crucial that MEPS for appliances are continuously updated. A common barrier for energy efficient products are their high initial costs. Hence, financial support schemes are one major mechanism to promote energy efficient technologies. Policies should also take into account that these high initial costs are especially a barrier for low-income families. Therefore, mandates for energy efficiency alone can put additional pressure on these groups. However, if low-income groups are supported in the acquisition of energy-efficient equipment, these will benefit from lower energy bills and CO_2 emissions are saved at the same time. By contrast, energy subsidies encourage excessive energy use and hamper the purchase of energy-efficient products. Revenues from saved subsidies could be used in a targeted way to offset energy prices, but at the same time provide incentives for energy-efficient and low-carbon technologies. Furthermore, the promotion of consumer awareness of products and behavior could also reduce significant energy use.

Finally, a conducted review on residential energy data at metropolitan and national level revealed that available data in Mexico is quite limited. To facilitate research in the field in particular the collection and public provision of data on the state of energy-efficiency levels of commercialized domestic appliances and equipment in Mexico would need to be extended. In addition, the generation of energy balances and collection of socio-economic data at a metropolitan level could improve the reliability of future energy scenarios at a regional level in Mexico. A good idea could be the amplification of existing household surveys by INEGI, integrating a larger number of questions on energy use in Mexican households.

6 Outlook

The developed model in the thesis is subject to several constraints and simplifications. Improvements could include the integration of future expected changes in user behavior, energy prices and autonomous technological development. In addition, the separate modeling of certain policies and measures may be of interest, for instance MEPS, labels, building codes, and appliance substitution programs. Not covered by the thesis is also the analysis of costs associated with energy efficient measures. However, such an analysis is useful to evaluate the required investment, as well as identify cost-effective measures that should be realized not only from an environmental point of view, but also an economic one.

A possibility that the developed model offers is to combine it with aspects of fuel and energy poverty in cities. Even if access to modern energy carriers is given, low-income groups are often not able to afford the purchase of expensive household equipment. The financial barrier to obtain the equipment is typically higher than to afford sufficient amounts of energy, which are often subsidized. In the REDUCE model appliance ownership is projected by income decile based on defined future developments of household wealth and its distribution within society.

It is important to consider energy demand from households not as a single sector, but as one component of the energy system. To achieve the required energy transition to reach GHG emission reduction goals set out by the international community, countries and local governments, the residential sector of cities should be integrated into intelligent energy systems and urban planning. Local potentials for synergies between sectors need to be identified and used. For instance, high energy densities of cities offer great opportunities for waste-heat recycling and district heating and cooling. Demand side management to balance an increasing share of fluctuating renewable energies in supply is another aspect. Here, a lot of research still has to be done.

Finally, the comparison of presented results with other studies is always required, considering the underlying assumptions as well as system boundary. In principle, the used methodology is transferable to any kind of city, as long as required data is available. Especially BATs are not limited to the use in the MCMA.

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8 Annex: Model inputs

8.1 Boundaries of the MCMA

Table 8-1: Municipalities and delegations composing the MCMA (CONAPO, et al., 2012)

Federal District	State of México			Hidalgo
Álvaro Obregón	Acolman	Ecatzingo	San Martín de las Pirámides	Tizayuca
Azcapotzalco	Amecameca	Huehuetoca	Temamatla	
Benito Juárez	Apaxco	Hueypoxtla	Temascalapa	
Coyoacán	Atenco	Huixquilucan	Tenango del Aire	
Cuajimalpa de Morelos	Atizapán de Zaragoza	Isidro Fabela	Teoloyucán	
Cuauhtémoc	Atlautla	Ixtapaluca	Teotihuacán	
Gustavo A. Madero	Axapusco	Jaltenco	Tepetlaoxtoc	
Iztacalco	Ayapango	Jilotzingo	Tepetlixpa	
Iztapalapa	Chalco	Juchitepec	Tepotzotlán	
La Magdalena Contreras	Chiautla	La Paz	Tequixquiac	
Miguel Hidalgo	Chicoloapan	Melchor Ocampo	Texcoco	
Milpa Alta	Chiconcuac	Naucalpan de Juárez	Tezoyuca	
Tláhuac	Chimalhuacán	Nextlalpan	Tlalmanalco	
Tlalpan	Coacalco de Berriozábal	Nezahualcóyotl	Tlalnepantla de Baz	
Venustiano Carranza	Cocotitlán	Nicolás Romero	Tonanitla	
Xochimilco	Coyotepec	Nopaltepec	Tultepec	
	Cuautitlán	Otumba	Tultitlán	
	Cuautitlán Izcalli	Ozumba	Valle de Chalco Solidaridad	
	Ecatepec de Morelos	Papalotla	Villa del Carbón	
		Tecámac	Zumpango	

8.2 Parameters in the base year 2010

8.2.1 Appliance stocks

Table 8-2: Number of first appliances in households in the MCMA in 2010 (INEGI, 2010a)

Appliance	Saturation [%]	Number of appliances* [millions]
Water heater	71	3.9
Cook stove	98	5.3
Refrigerator	89	4.8
Washing machine	76	4.1
Television	98	5.3
Computer	42	2.3

* Population size of 20.5 million residents (CONAPO, 2013) and average household size of 3.78 (INEGI, 2010a)

Table 8-3: Number of lighting points in households in the MCMA in 2010 (INEGI, 2010b and INEGI, 2010a)

Appliance	Points per room	Number of rooms per household	Number of points* [millions]
Lighting points	2	4	43.6

* Population size of 20.5 million residents (CONAPO, 2013) and average household size of 3.78 (INEGI, 2010a)

Table 8-4: Number of second televisions in households in the MCMA in 2010 (INEGI, 2010b and INEGI, 2010a)

Appliance	Saturation [%]	Number of TVs* [millions]
2nd television	66	3.6

* Population size of 20.5 million residents (CONAPO, 2013) and average household size of 3.78 (INEGI, 2010a)

8.2.2 Age distributions

Table 8-5: Distribution of appliance ages based on survey data from the Mexican Federal District in 2010 (INEGI, 2010b)

Appliance	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cook stove	17%	0%	1%	1%	1%	5%	1%	2%	5%	2%	16%	2%	6%	4%	4%	8%	5%	6%	6%	5%	3%
Refrigerator	11%	0%	1%	1%	1%	5%	1%	2%	4%	2%	16%	2%	6%	4%	6%	11%	5%	7%	6%	6%	4%
Washing machine	6%	0%	1%	0%	0%	3%	1%	1%	3%	2%	13%	2%	7%	6%	7%	12%	8%	9%	8%	7%	5%
Television										14%	13%	2%	6%	4%	6%	13%	6%	10%	10%	11%	6%
Computer											3%	6%	3%	2%	4%	10%	7%	14%	19%	18%	14%

Comment: The percentage for the last year, which is documented in the table, represents appliances of that year or older.

Table 8-6: Distribution of appliance ages for lighting for the MCMA in 2010
Own regional estimation based on national data from (Andrade Salaverría, 2010 and UN DESA, 2014a)

Appliance	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Fluorescent lamp											3%	3%	7%	8%	9%	10%	11%	11%	12%	13%	14%

Table 8-7: Distribution of appliance ages for water heaters based on data from the USA (Lutz, et al., 2011)

Appliance	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Water Heater	10%	2%	2%	2%	2%	3%	3%	3%	3%	4%	5%	5%	6%	6%	6%	7%	7%	7%	7%	7%	7%

Comment: The percentage for the last year, which is documented in the table, represents appliances of that year or older.

8.2.3 Historic unit energy consumptions

Table 8-8: Estimation of historic developments for UECs of gas end-uses (in GJ), 1994-2010

Appliance	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Water Heater	21.8	21.5	21.1	20.8	20.4	20.1	19.7	19.4	19.1	18.7	18.4	18.1	17.7	17.4	17.1	16.8	16.5
Cooking	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9

Table 8-9: Estimated UEC for lighting points in 2010
Own estimation based on (INECC, 2012b) & (Andrade Salaverría, 2010)

Appliance	UEC	Share
IL	43.8 kWh	61%
CFL	11.0 kWh	39%
Total	30.9 kWh	

Table 8-10: Estimated historic developments for UECs of electric appliances (in kWh), 1994-2005
Own estimations based on (Sánchez Ramos, et al., 2006), (McNeil, et al., 2012) & (CONUEE & GIZ, 2009)

Appliance	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
R & R/F	828	564	538	512	495	477	460	442	424	407	389	371	364	358	351	344	337
Washing machine	103	94	85	76	76	75	75	75	75	75	75	74	73	71	70	68	66
1st TV						123	123	123	123	123	123	123	123	123	149	156	161
2nd TV						84	84	84	84	84	84	84	84	84	101	105	109
Computer							151	151	148	145	142	139	136	130	125	120	114
OEA																	344

8.2.4 Water heater efficiencies

Table 8-11: Energy efficiency assumptions for conventional gas water heaters 1994-2010
Own estimation based on (SEGOB, 1995), (SEGOB, 2000), (SEGOB, 2011), (SENER, 2013), (US DOE, 2003) and (EIA, 2015)

Efficiencies	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
RE storage	0.70	0.70	0.70	0.71	0.71	0.72	0.72	0.73	0.74	0.74	0.75	0.76	0.77	0.78	0.78	0.79	0.80
EF storage	0.50	0.50	0.51	0.51	0.52	0.53	0.53	0.54	0.55	0.55	0.56	0.57	0.57	0.58	0.59	0.59	0.60
EF inst.	0.70	0.70	0.71	0.71	0.71	0.71	0.72	0.73	0.74	0.75	0.76	0.77	0.78	0.79	0.80	0.81	0.82

8.2.5 Time of use

Table 8-12: Time of use per day for electric appliances

End-use	Time of use [hours/appliance]	Comment	Source
Lighting	2	depending on source: 2-5 hours	(INECC, 2012b)
Refrigeration	9.6	use factor of 40 %	(Sánchez Ramos, et al., 2006)
Cloth washing	1.68	use factor of 7 %	(Sánchez Ramos, et al., 2006)
TV	1st: 6; 2nd: 4	2nd TV own estimation	(CONUEE & GIZ, 2009)
Computer	3	-	(CONUEE & GIZ, 2009)

Table 8-13: Estimated hot water demand in 2010
Own estimation based on (Quintanilla Martínez, et al., 2000 and INEGI, 2010a)

Income Decile	Hot water consumption (50 °C) [l/(day*pers)]	Saturation of water heaters [%]
1	39	53
2	47	55
3	50	57
4	54	64
5	57	69
6	60	72
7	64	76
8	68	81
9	73	90
10	80	96
Average per person	61	71
Average per household	**231**	

8.3 Projections of parameters for 2010-2030

8.3.1 Socio-economic development

Table 8-14: Projections of population size and households (in millions) 2010-2030 (CONAPO, 2013 and Table 8-15)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Population	20.5	20.7	20.8	21.0	21.2	21.3	21.5	21.7	21.8	21.9	22.1	22.2	22.4	22.5	22.6	22.7	22.8	22.9	23.1	23.2	23.2
HH	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.7	6.8	6.9	7.0	7.1	7.1	7.2

Table 8-15: Projection of dwelling occupancy (in persons per household) 2010-2030
Own estimation based on (CONAPO, 2014a and INEGI, 2010a)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Dwelling occupancy	3.8	3.7	3.7	3.7	3.6	3.6	3.6	3.5	3.5	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.2	3.2

Table 8-16: Projection of GRP per capita growth (in PPP US dollar 2010) 2010-2030 (Manders, et al., 2012)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Growth rate		3.8%	3.8%	3.7%	3.7%	3.7%	3.6%	3.6%	3.5%	3.5%	3.4%	3.4%	3.4%	3.3%	3.3%	3.2%	3.2%	3.2%	3.1%	3.1%	3.1%

8.3.2 Appliance stocks

Table 8-17: Projections of appliances (in millions) under the BAU- and BAT-scenario 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Water Heater	3.84	3.94	4.04	4.14	4.25	4.35	4.45	4.55	4.65	4.75	4.85	4.95	5.05	5.14	5.24	5.33	5.43	5.52	5.61	5.69	5.78
Cooking	5.30	5.40	5.50	5.60	5.69	5.79	5.89	5.98	6.07	6.16	6.25	6.34	6.43	6.51	6.59	6.67	6.75	6.83	6.91	6.98	7.05
Lighting	43.6	44.6	45.6	46.6	47.6	48.5	49.5	50.5	51.5	52.4	53.3	54.3	55.2	56.1	57.0	57.9	58.7	59.6	60.4	61.2	62.0
R & R/F	4.81	4.92	5.02	5.12	5.22	5.32	5.41	5.51	5.61	5.70	5.79	5.89	5.98	6.07	6.15	6.24	6.32	6.40	6.48	6.56	6.64
Washing machine	4.15	4.25	4.35	4.46	4.56	4.67	4.77	4.87	4.97	5.07	5.17	5.27	5.36	5.45	5.54	5.63	5.72	5.80	5.89	5.97	6.12
1st TV	5.33	5.43	5.53	5.63	5.73	5.83	5.92	6.02	6.11	6.20	6.29	6.38	6.47	6.55	6.63	6.72	6.79	6.87	6.95	7.02	7.09
2nd TV	3.53	3.64	3.75	3.86	3.98	4.09	4.21	4.32	4.43	4.54	4.66	4.77	4.88	4.99	5.10	5.20	5.31	5.41	5.52	5.62	5.72
Computer	2.71	2.85	3.00	3.15	3.30	3.46	3.62	3.79	3.96	4.13	4.30	4.41	4.52	4.63	4.74	4.84	4.95	5.05	5.15	5.25	5.35

Table 8-18: Projections of appliances (in millions) under the income distribution scenario (Gini coefficient of 0.407 by 2030), 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Water Heater	3.84	3.96	4.08	4.20	4.32	4.44	4.56	4.68	4.79	4.91	5.03	5.15	5.26	5.37	5.49	5.60	5.71	5.82	5.92	6.03	6.13
Cooking	5.30	5.40	5.50	5.60	5.69	5.79	5.89	5.98	6.07	6.16	6.25	6.34	6.43	6.51	6.59	6.67	6.75	6.83	6.91	6.98	7.05
Lighting	43.6	44.7	45.8	46.9	47.9	49.0	50.1	51.2	52.2	53.2	54.3	55.3	56.3	57.3	58.3	59.3	60.2	61.2	62.1	63.0	63.9
R & R/F	4.81	4.92	5.03	5.14	5.24	5.35	5.45	5.56	5.66	5.76	5.86	5.96	6.05	6.15	6.24	6.33	6.42	6.51	6.59	6.68	6.76
Washing machine	4.15	4.26	4.38	4.49	4.60	4.72	4.83	4.94	5.06	5.17	5.28	5.38	5.48	5.58	5.68	5.78	5.87	5.97	6.06	6.15	6.30
1st TV	5.33	5.43	5.53	5.63	5.73	5.83	5.92	6.02	6.11	6.20	6.29	6.38	6.47	6.55	6.63	6.72	6.79	6.87	6.95	7.02	7.09
2nd TV	3.53	3.66	3.80	3.94	4.08	4.22	4.37	4.51	4.65	4.79	4.93	5.08	5.22	5.35	5.49	5.63	5.76	5.90	6.02	6.15	6.28
Computer	2.71	2.87	3.04	3.22	3.40	3.59	3.78	3.97	4.17	4.38	4.59	4.73	4.87	5.01	5.15	5.29	5.42	5.56	5.69	5.82	5.95

8.3.3 Unit energy consumptions

Table 8-19: Projections of UECs (in GJ) of new appliances under the BAU-scenario 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Water Heating	16.6	16.3	15.9	15.8	15.8	15.7	15.7	15.6	15.6	15.6	15.5	15.5	15.5	15.4	15.4	15.4	15.4	15.3	15.3	15.3	15.3
Cooking	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Lighting	0.11	0.11	0.09	0.07	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
R & R/F	1.21	1.19	1.16	1.14	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
Washing machine	0.24	0.23	0.23	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
1st TV	0.58	0.60	0.60	0.60	0.61	0.62	0.61	0.61	0.60	0.60	0.59	0.57	0.55	0.50	0.44	0.36	0.39	0.39	0.39	0.39	0.39
2nd TV	0.39	0.40	0.40	0.40	0.41	0.42	0.41	0.41	0.41	0.40	0.40	0.39	0.37	0.34	0.30	0.24	0.27	0.27	0.27	0.27	0.27
Computer	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
OEA	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24

Table 8-20: Projections of UECs (in GJ) of new appliances under the BAT-scenario 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Water Heating	16.6	16.3	15.9	15.8	15.8	15.7	15.7	15.6	2.46	2.45	2.45	2.45	2.44	2.44	2.44	2.43	2.43	2.43	2.43	2.42	2.42
Cooking	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Lighting	0.11	0.11	0.09	0.07	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
R & R/F	1.21	1.19	1.16	1.14	1.11	1.11	1.11	1.11	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Washing machine	0.24	0.23	0.23	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
1st TV	0.58	0.60	0.60	0.60	0.61	0.62	0.61	0.61	0.36	0.36	0.35	0.34	0.33	0.32	0.31	0.31	0.36	0.36	0.36	0.36	0.36
2nd TV	0.39	0.40	0.40	0.40	0.41	0.42	0.41	0.41	0.24	0.24	0.24	0.23	0.23	0.22	0.21	0.21	0.24	0.24	0.24	0.24	0.24
Computer	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
OEA	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24

8.3.4 Hot water demands

Table 8-21: Projections of hot water demand (in liters per day and household) 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
BAU	232	231	230	229	228	228	227	226	226	225	225	224	223	223	222	222	221	221	221	220	220
BAU-ID	232	231	231	231	231	230	230	230	230	230	230	230	230	230	230	229	229	229	229	229	229

Comment: In the BAT-scenario hot water demand is reduced by 25% from 2018 on for new appliances. BAU-ID stands for a sub-scenario where the Gini coefficient decreases to 0.407 in the MCMA by 2030.

8.3.5 Technology shares

Table 8-22: Assumptions on technology shares (in %) for new water heaters under the BAU-scenario 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage	36	35	35	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34	34
Inst.	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64
Solar	0.5	1.0	1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Table 8-23: Assumptions on technology shares (in %) for new water heaters under the BAT-scenario 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Storage	36	35	35	34	34	34	34	34	0	0	0	0	0	0	0	0	0	0	0	0	0
Inst.	64	64	64	64	64	64	64	64	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar (g)	1	1	2	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0
HP	0	0	0	0	0	0	0	0	30	30	30	30	30	30	30	30	30	30	30	30	30
Solar (e)	0	0	0	0	0	0	0	0	70	70	70	70	70	70	70	70	70	70	70	70	70

Table 8-24: Assumptions on technology shares (in %) for lighting under the BAU-scenario 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
IL	61	57	44	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FL	39	43	56	73	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 8-25: Assumptions on technology shares (in %) for lighting under the BAT-scenario 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
IL	61	57	44	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FL	39	43	56	73	100	100	100	100	80	60	40	20	0	0	0	0	0	0	0	0	0
LED	0	0	0	0	0	0	0	0	20	40	60	80	100	100	100	100	100	100	100	100	100

Table 8-26: Assumptions on technology shares (in %) for new televisions under the BAU- and BAT-scenario 2010-2030

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
LED-LCD	7	43	54	66	77	98	100	99	98	97	95	91	84	71	49	11	0	0	0	0	0
OLED	0	0	0	0	0	0	1	1	2	3	5	9	16	29	51	89	100	100	100	100	100
PDP	12	10	8	6	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CCFL-LCD	56	47	38	28	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CRT	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LED-LCD	7	43	54	66	77	98	100	99	98	97	95	91	84	71	49	11	0	0	0	0	0

8.3.6 Energy efficiencies of water heaters

Table 8-27: Projections of energy efficiencies for water heaters under the BAU- and BAT-scenario 2010-2030

Eff.	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
RE storage	0.80	0.80	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
EF storage	0.60	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
EF inst.	0.82	0.83	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
EF HP									2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

8.4 Functions

8.4.1 Appliance saturation

Table 8-28: Parameters for logit model of appliance ownership

	Constant value	Logit function		
		a	b	S_{max}/A_{max}
Water heaters		17.3738	0.3124	96%
Cook stoves	98%			
Rooms		6.8850	0.1270	5.0
Refrigerators		17.0818	0.0858	97%
Washing machines		24.6293	0.1652	87%
1st Televisions	98%			
2nd Televisions		26.2417	0.6371	1.0
Computers		18.1860	0.7494	82%

Note: Income in 10 thousands of monthly income in PPP US dollar in 2010

8.4.2 Hot water demand

Table 8-29: Parameters for logit model of hot water demand

Logit function		
a	b	$HWDP_{max}$
17.374	0.312	80

8.5 Modeling of water heaters

8.5.1 Equations

Equation 8-1: WHAM equation for daily energy consumption of a storage water heater (US DOE, 2003)

$$Q_{in}\left[\frac{kJ}{day}\right] = \frac{vol * den * c_p * (T_{tank} - T_{in})}{RE} * \left(1 - \frac{UA * (T_{tank} - T_{amb})}{P_{on}}\right) + 24\,\frac{h}{day} * UA * (T_{tank} - T_{amb}) * 3600\,\frac{J}{Wh}$$

Equation 8-2: Standby heat loss coefficient (WHAM equation) (US DOE, 2003)

$$UA\left[\frac{kW}{K}\right] = \frac{\frac{1}{EF} - \frac{1}{RE}}{(T_{tank} - T_{amb}) * \left(\frac{1.99278}{kW} - \frac{1}{RE * P_{on}}\right)}$$

Equation 8-3: Energy consumption of an instantaneous water heater

$$Q_{in}\left[\frac{kJ}{day}\right] = \frac{vol * den * c_p * (T_{tank} - T_{in})}{EF}$$

8.5.2 Input parameters

Table 8-30: Input parameters for conventional water heaters

Symbol	Meaning	Value	Unit	Comment
Q_{in}	total water heater energy consumption		[kJ/day]	
vol	daily draw volume	Table 8-13 Table 8-21	[l/day]	
den	density of water (45°C)	0.99	[kg/l]	
c_p	specific heat of water (45°C)	4.18	[kJ/(kg*K)]	
T_{tank}	tank thermostat set point temperature	50	[°C]	
T_{in}	inlet water temperature	17	[°C]	Equal T_{amb}
RE	recovery efficiency	Table 8-11 Table 8-27		
EF	Energy factor	Table 8-11 Table 8-27		
UA	standby heat loss coefficient	calculated	[kW/K]	
P_{on}	rated input power	3.2	[kW]	Estimated based on water demand
T_{amb}	temperature of ambient air surrounding water heater	17	[°C]	RET Screen: av. ambient air temperature Mexico City

Table 8-31: Input parameters for the reference solar water heater system (NRCAN, 2012 and Mauthner, et al., 2015)

Parameter	Unit	Value
Site conditions		Table 8-32
Daily hot water use	l/day	Table 8-13 Table 8-21
Hot Water Temperature	°C	50
Inlet water temperature	°C	15.8-17.7
Tracking		Fixed
Slope	°	19.4
Azimuth	°	0
Collector type		Glazed
Fr (tau alpha)		0.8
Fr UL coefficient	W/(m²*°C)	3.69
Temperature coefficient for Fr UL	W/(m²*°C)	0.007
Miscellaneous losses solar water heater	%	1
Storage capacity per solar collector area	l/m²	75
Heat exchanger efficiency	%	80
Miscellaneous losses system	%	1
Solar fraction	%	70

Comment: Site reference conditions: Mexico City/Juarez

Table 8-32: Reference site conditions from the ground monitoring station in Mexico City/Juarez (NRCAN, 2015)

Month	Air temperature	Daily solar radiation - horizontal	Wind speed at 10 m
	[°C]	[kWh/m²/day]	[m/s]
January	13.9	4.56	2.5
February	15.4	5.31	2.6
March	17.5	6.00	2.6
April	18.7	5.86	3.0
May	19.2	5.61	3.0
June	18.6	5.47	3.1
July	17.5	5.06	2.6
August	17.7	5.00	2.4
September	17.4	4.53	2.6
October	16.4	4.61	2.4
November	15.4	4.47	2.1
December	14.2	4.22	2.0
Annual	16.8	5.06	2.6