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UNIVERSIDADE Đ COIMBRA

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Assessing the Colombian Energy Transition Plan and the Energy Efficiency Potential to Decarbonize the Economy

Dissertation under the Master of Science Degree in Energy for Sustainability supervised by Professor Pedro Manuel Soares Moura and presented to the Department of Mechanical Engineering, Faculty of Science and Technology, University of Coimbra.

August 2022

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ASSESSING THE COLOMBIAN ENERGY TRANSITION PLAN AND THE ENERGY EFFICIENCY POTENTIAL TO DECARBONIZE THE ECONOMY

Master Dissertation

Under the supervision of Professor Pedro Moura
Mechanical Engineer Department
Science and Technology Faculty

University of Coimbra | August 2022

Abstract

Electrical systems have changed considerably in the last decades incorporating several new variables. The challenge for the next 30 years is to meet growing energy demand with fewer fossil fuels to increasingly reduce greenhouse gas emissions and achieve carbon neutrality. Particularly in Colombia, several actions need to be carried out to decarbonize through diversification with non-conventional renewables, and disruptive measures that enable efficient energy use. The country has designed a rigorous roadmap to meet the energy needs of the coming decades dealing with all uncertainties, derived from a huge set of nonlinear variables present in the energy sector. Therefore, it is imperative to use the proper tools that allow decision-makers to evaluate and compare alternatives to make smarter decisions.

This study analyzed the Colombian outlook, considering the underway roadmap to achieve energy diversification and maximize the energy efficiency potential; not from the perspective of prediction, but from a pragmatic discussion. The study intends to answer the following research questions: Is Colombia adopting the right strategies to potentialize efficient use of its energy resources? To what extent is the National Energy Plan 2020-2050 a driver of the country's energy transition and what are the initiatives proposed in it based on? Which are the limitations and weaknesses present in the National Energy Transition Plan 2020-2050 regarding the energy efficiency prospection? Which strategies should be incorporated into the Colombian framework to promote the efficient use of energy in all economic sectors? To answer it, it was necessary to examine how the sector has changed in the recent past; the main ongoing initiatives set to achieve the national commitments for mid-century; and the determinant variables.

It was noted that there are numerous initiatives, some of which are quite ambitious to be achieved in the near future. Additionally, some sectors require greater efforts because they are the ones that mobilize carbon neutrality and some specific variables influence directly the demand side performance. For the comparative analysis, a new scenario was modeled to the National Energy Transition Plan 2020-2050 and assessed with the LEAP software tool.

Keywords: Energy Efficiency, LEAP, energy planning, Colombia, Decarbonization, Net-Zero scenario.

Resumo

Os sistemas elétricos mudaram consideravelmente nas últimas décadas incorporando várias novas variáveis. O desafio para os próximos 30 anos é dar resposta à crescente procura de energia com menos combustíveis fósseis, para reduzir cada vez mais as emissões de gases de efeito estufa para quase zero. Particularmente na Colômbia, têm que ser implementadas várias ações para assegurar a descarbonizar por meio da diversificação com energias renováveis e medidas que possibilitem o uso eficiente da energia. Para tal, o país desenhou um roteiro rigoroso para atender as necessidades energéticas das próximas décadas lidando com todas as incertezas, derivadas de um enorme conjunto de variáveis não lineares presentes no setor energético. Portanto, é imperativo o uso de ferramentas adequadas que permitam aos tomadores de decisão avaliar e comparar alternativas.

Este estudo analisou as perspetivas colombianas, considerando o roteiro para alcançar a diversificação energética e maximizar o potencial de eficiência energética; não do ponto de vista da previsão, mas de uma discussão pragmática. O estudo pretende responder às seguintes questões de investigação: A Colômbia está a adotar as estratégias corretas para potencializar o uso eficiente de seus recursos energéticos? Em que medida o Plano Nacional de Energia 2020-2050 é um impulsionador da transição energética do país e em que se baseiam as iniciativas nele propostas? Quais são as limitações e fragilidades presentes no Plano no que diz respeito à prospeção da eficiência energética? Que estratégias devem ser incorporadas para promover o uso eficiente da energia em todos os setores económicos? Para responder a estas perguntas foi necessário examinar como o setor mudou no passado recente; as principais iniciativas em curso para cumprir os compromissos nacionais para meados do século; e as variáveis determinantes.

Constatou-se que existem inúmeras iniciativas, algumas das quais bastante ambiciosas para serem alcançadas no futuro próximo. Adicionalmente, há setores que requerem maiores esforços porque são eles que mobilizam a neutralidade carbônica e existem algumas variáveis específicas que influenciam diretamente o desempenho do lado da procura. Para a análise comparativa, foi modelado um novo cenário para o Plano Nacional de Transição Energética 2020-2050 avaliado com o a ferramenta de software LEAP.

Palavras-chave: Eficiência Energética, LEAP, planejamento energético, Colômbia, Descarbonização, Cenário Net-Zero.

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List of Acronyms

Acronym	Explanation
BAU	Business as usual
BAT	Best available technology
BAT COL	Best available technology - Colombia
BAT Int	Best available technology - International
BEU	Useful Energy Balance
CEPAL	Economic Commission for Latin America and the Caribbean (Unite Nations)
CONPES	National Council for Economic and Social Policy
DSM	Demand-side management
EE	Energy efficiency
ENME	National Electric Mobility Strategy
FNCER	Non-conventional sources of renewable energy
GDP	Gross Domestic Product
GHG	Greenhouse gases
IPCC	Intergovernmental Panel on Climate Change (Unite Nations body)
IEA	International Energy Agency
LEAP	Long-range Energy Alternatives Planning System
LPG	Liquefied Petroleum Gas (Also GLP)
MEPS	Minimum energy performance standard
MMCOP	Millions of Colombian Pesos
NEBs	Non-energy benefits
NDC	National Determined Contribution
NIS	National Interconnected System
OECD	Organization for Economic Co-operation and Development
OLADE	Latin American Energy Organization
PEN	National Energy Plan
PROURE	Rational and Efficient Use of Energy Program
SDG	Sustainable Development Goals
UPME	Mining and Energy Planning Unit (Government Agency)
URE	Rational and Efficient Use of Energy
ZNI	Non-interconnected zones

Chapter 1
Introduction

1.1 Motivation

Electrical systems around the globe have changed considerably in the last decades. From coal, natural gas, nuclear power and oil, to renewable energy sources such as hydropower, solar and wind power in the current century, always seeking the most efficient alternative to meet the energy needs of the growing population. The changes have been driven by diverse variables such as technological advances, energy resource discoveries, energy prices, social pressures, political interests, economic and industrial growth, decision-makers and other factors. The main constant is that global energy consumption has steadily increased over time. The threat of climate change is motivating governments now more than ever to support renewable energy projects with grants, tax relief, among other incentives. This makes the future of renewable energy very promising, especially in underdeveloped countries, where this new scenario could represent a new ocean of opportunities to strengthen their economies. From a global scenario perspective, the challenge for the next 30 years is to meet growing energy demand with fewer fossil fuels while reducing greenhouse gas emissions to zero. Although liquid fuels will continue to have a share of the matrix, countries such as Colombia, are implementing decarbonization plans through diversification with non-conventional renewables, with disruptive resources such as green hydrogen and through a set of policies that promote efficient energy use in the industry.

The strategies to achieve the targets set by the Colombian government for 2050 as the inflection point in the global warming panorama are part of a rigorous plan carefully crafted to meet the energy needs of the coming decades. However, this is not an easy task, considering that we live in a time full of uncertainties, influenced by several variables. It is known that the population and industry are expected to grow, which requires strategic energy management, and flexible enough to be restructured over time according to the new needs. Therefore, it is imperative to model energy systems with proper tools that grant decision-makers the adequate examination of different possible scenarios estimated under the assumption of different criteria. It brings, as a result, a range of alternatives allowing comparison, assessing trade-offs, also ranking the relevance of each criterion. The analysis supported by technology allows the regulators to make smarter decisions among a set of scenarios varying depending on the resources available in the territory, the regulation in the country, and the stakeholders involved (communities, regulators, grid operators, utilities, investors, and energy consumers). This study seeks to correlate different elements from the Colombia Energy Plan 2020-2050 that would allow identifying the possible trade-offs. The long-term effects of the pandemic triggered by the virus COVID -19 and the war between Russia and Ukraine cannot yet be estimated and are therefore not considered in this study.

1.2 Objectives

It has been shown that in general terms *The National Energy Plan 2020-2050* (and other government-related documents) contemplates the promotion of technology as the main driver of Energy Efficiency. However, one cannot lose sight of the fact that achieving a cultural change that allows more active and successful participation from the demand side requires other regulatory instruments such as certification mechanisms, control mechanisms, tax and tariffs incentives, and sanctions. Those are drivers that were not deeply considered in the scenarios of the National Plan, especially regarding Energy Efficiency. Therefore, this study intends to correlate the PEN 2020-2050 with regulatory instruments develop before and after the plan.

In such context, this study intends to answer the following research questions:

- *Is Colombia adopting the right strategies to potentialize efficient use of its energy resources?* Studying and figuring out which are the instruments that police-makers have considered to bring into action what was written as a roadmap.
- *To what extent is the National Energy Plan 2020-2050 a driver of the country's energy transition and what are the initiatives proposed in it based on? E*xamining how the national roadmap was created to guide the country's energy transition and the goals to be achieved in the short, medium, and long term.
- *Which are the limitations and weaknesses present in the National Energy Plan 2020-2050 regarding the energy efficiency prospection?* Analyzing the possible barriers and boundaries that the plan would be to face at first to achieve its full deployment.
- *Which strategies and actions should be incorporated into the Colombian framework to promote the efficient use of energy in all economic sectors?* Identifying possible additional measures that can be implemented by regulators to accelerate the involvement of all sectors

of the economy especially energy, building, and transport as the main emitters of the greenhouse gasses in the country.

The objective of this dissertation work is to assess *The National Energy Plan 2020-2050,* which is a document structured by Colombian energy regulators with the purpose to plan a sustainable and responsible energy transition in coherence with Global commitments to decarbonize the economies by mid-century and achieve the net-zero target. Besides all the government documents and programs that have been established to support its deployment. The analysis will have special attention to the possible scenarios in terms of Energy Efficiency (EE) pathways as the first-principle more reliable energy transition. Using the same energy modeling system tool used by regulators to design this roadmap, this study will carry on new variations as a new scenario in order to identify the sensitiveness to other factors. In the end, it is expected to have the arguments to answer the proposed research questions.

1.3 Thesis Structure

The thesis is divided into five chapters to facilitate the unfolding of information found through the research. **Chapter 2** provides a general overview of the energy transition and the role of energy efficiency in achieving greater impacts in the global decarbonization process. This chapter also includes a study of the energy transition policies that have enabled Colombia to lead the way in Latin America. **Chapter 3** deals with the review of PEN 2020-2050, describing the philosophy of the plan and presenting details of the roadmap vision, the structure of the entire plan, the goals, milestones, barriers, proposed initiatives and technologies. This review will focus on the sections of the plan that address energy efficiency from a demand-side perspective as a central issue. **Chapter 4** presents new considerations for proposing a new scenario in LEAP to verify the sensitivity of the model to certain assumptions and initiatives, and includes some conclusions and discussion. Finally, **Chapter 5** presents the main conclusions and the options of future work.

Chapter 2
Energy Transition and Energy Efficiency Framework

2.1 General Overview

The energy sector in Colombia is one of the main pillars of the country's development due to its contribution to economic growth, increased private investment and employment generation. It has performed a leading role in the sustained growth of the Colombian economy. The energy sector also contributes to the financing of a significant portion of the national budget, which is dedicated to social development through the collection of royalties, taxes and dividends. The importance of the mining and energy sector as one of the engines of development in the country becomes clear when considering that its share in GDP increased from 9.7% in 2006-2009 to 11.2% in 2021 (Zárate Nieves & Vidal Hernández, 2016).

Simultaneously, there is a growing awareness of the importance of EE on a global scale. Evidence shows that EE is indeed capable of effectively influencing global energy demand, and even more so as the world economy is being restructured and many emerging economies are greatly increasing their energy needs. For this reason, EE is playing an increasingly important role in countries' energy transition policies (Guerra & Guillén, 2021).

By enabling significant savings in energy consumption and, consequently, greenhouse gas emissions, EE has a direct impact on climate change mitigation. It also reduces dependence on fossil fuels, promotes energy conservation, improves the competitiveness of productive sectors, enables better resource allocation, increases energy security, and improves energy access. Taking all of these benefits together, there is a clear case for promoting the development of EE measures in a country. However, to achieve its maximum potential, it is necessary to remove economic, regulatory, political, institutional, cultural, technological, informational, and financial barriers that ultimately block the development of a market for goods and services in this area (Guerra & Guillén, 2021). In the end, it will attract new economic development opportunities and improve the living conditions of Colombians (Zárate Nieves & Vidal Hernández, 2016).

For many years, efforts in Colombia have been mainly focused on expanding the generation matrix in a responsible and careful way and optimizing resources on the supply side. This work aims to assess how the PEN 2020-2050 addresses the incorporation of policies and programs to increase

EE in the country, approaching the end-user and understanding that the demand side has equal importance (Guerra & Guillén, 2021).

2.2 Energy Efficiency in the Energy Transition Scenarios

We have always depended on energy to survive. Fire was the first source of energy used by humans. It continued to be so until the eighteenth century when the first steam engine was invented, although it also used fire as an energy source, it used steam to drive mechanisms, completely transforming society, industry, and cities in general. The locomotive was one of those inventions that emerged with the steam engine, making use of wood and coal for its operation. A century later, these energy sources were replaced by oil and gas, leading to the appearance of the first public lighting networks in the 19^{th} century. The invention of the electric light bulb and electric motors added up to the establishment of a reliable system of electricity generation, and accelerated the electrification of first-world countries in the 20^{th} century (Forrester, 2016). With electricity, production chains were made more dynamic, making economies grow substantially. Nevertheless, the consumption of fossil fuels is not sustainable in the long term, besides these energy sources cause severe damage to the environment, causing an increase in the earth's temperature due to the emission of greenhouse gases (GHG), which is now known as global warming, becoming an environmental emergency that transcends borders and whose effects could be devastating for the entire world population (Enric Ventura, 2018). To counteract its effects, for some years several countries have begun to incorporate renewable energy sources into their energy matrix to replace fossil fuels, which today are very competitive in terms of prices while their environmental impact is significantly lower.

The world economy is usually strongly correlated with electricity use. The development of the countries is highly linked to the composition of their energy matrixes and for three centuries, the different forms of energy have enabled industrial, technological and social development with a high impact on people's quality of life. Nations with sufficient and accessible energy sources at low costs have achieved their energy independence, thus reaching a competitive advantage in a globalized world. As it is mentioned by Masson and Delmotte (2019) (Masson-Delmotte et al., 2019), it is essential for a transformative systemic change farreaching to limit the warming to 1.5°C above pre-industrial levels, that upscales and accelerates multilevel and cross-sectoral climate mitigation measures. Though, recent developments have shown a consistent increase in electricity generation year on year since 1985 (*Figure 1*), with an average annual growth globally of 3.5%, mainly covered by fossil fuels (*Figure 2*) (Our World in data, 2022b). Secure energy transitions involve an understanding of the multi-directional flows of energy across this complex system, guaranteeing that change in one area is complemented by change elsewhere (IEA, 2021).

For decades, the growth of energy consumption has been mainly driven by the population and economic growth of the nations, with improvements in access to electricity, and higher use of electrical appliances and space cooling resulting from increasing living standards. According to IPCC (Masson-Delmotte et al., 2019), it is expected that these trends will continue in the future, with an increase in the energy consumption of 50% by 2050 - compared with 2010 - energy consumption if rigorous measures are not taken to make significant improvements in EE that reverse the trend. To strengthen the global response, all countries must significantly raise their level of ambition. The ongoing transition of the electricity sector is closely linked to the fourth industrial revolution, in which there is a commitment to the use of new technologies, and digitization. This brings benefits such as economic growth, improved industrial practices, and a reduction in GHG emissions (National Energy Department et al., 2022b).

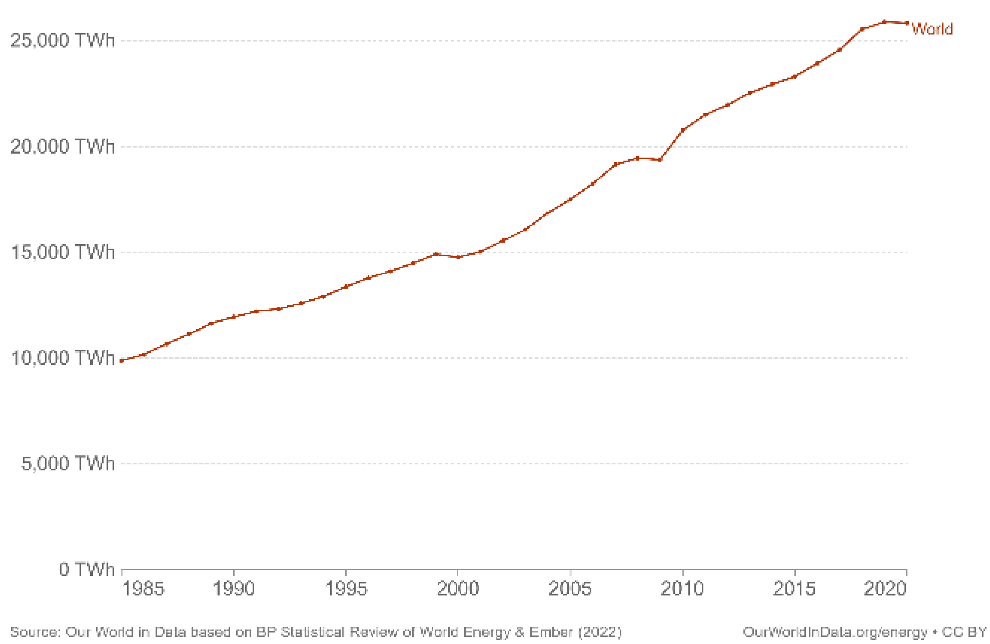


Figure 1 World Electricity Generation from 1985 to 2020, (Our World in data, 2022b)

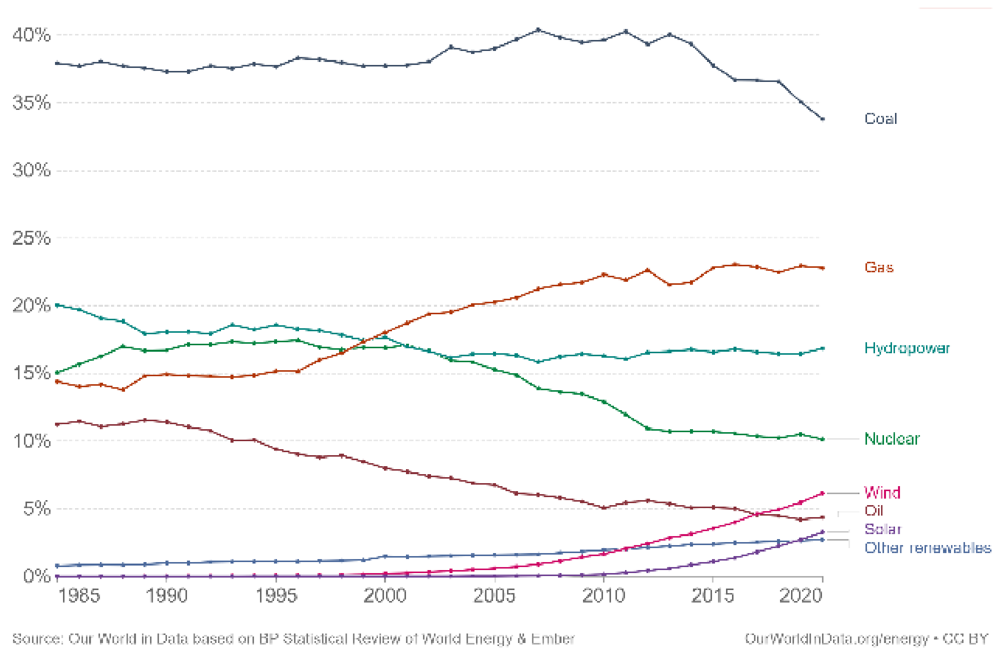


Figure 2 Share of world electricity Production by source, (Our World in data, 2022b)

According to the International Energy Agency (IEA) (IEA, 2021b), the energy sector is now responsible for about three-quarters of GHG emissions and holds the key to averting the worst effects of climate change, perhaps the greatest challenge facing humanity. This requires nothing less than a complete transformation of the way we generate, transport, and consume energy. Much work remains to be done to turn today's impressive ambitions into reality, especially given the different situations in each country and their varying abilities to make the necessary changes. It is important to highlight the priority actions needed today to ensure that the opportunity to achieve net-zero energy by 2050 - which, while small, is achievable - is not lost. In the same document, the IEA (IEA, 2021b) suggests that this should be the decade of massive clean energy expansion bringing up the now-available clean and efficient energy technologies to achieve the deep cuts in global emissions by 2030, supported by policies that drive their deployment (*Figure 3*).

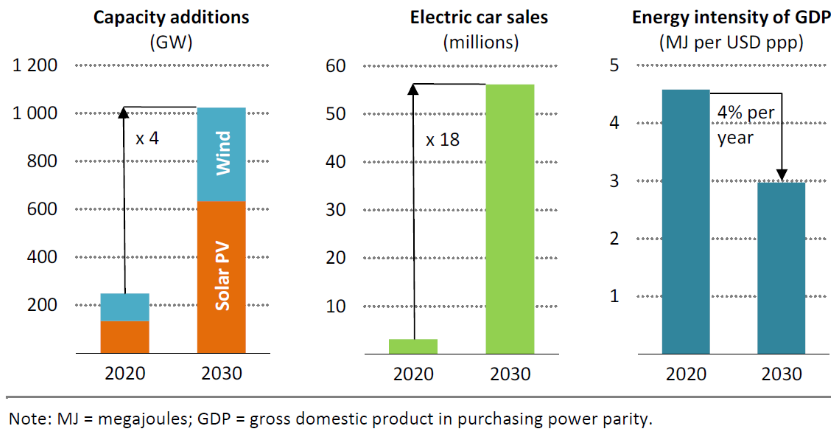


Figure 3 Key clean technologies ramp up by 2030 in the net zero pathway, (IEA, 2021b)

Regulators' efforts, technology innovation, and the increasing urgency of decelerating global warming are ushering forward a new energy economy. There is no guarantee that the energy economy emerging will be smooth, but it is already clear that it promises to be quite different from the one we have today (IEA, 2021). For IPCC (Masson-Delmotte et al., 2019), reaping EE potentials hinges critically on advanced energy management systems, as well as targeted policies to fast-track the adoption of the best available technology (BAT). Recovering and reusing the waste heat under economically and technically viable conditions benefits the electrical system overall. Moreover, demand-side management (DSM) strategies could modulate the level of industrial activity in line with the availability of resources in the power system. Besides, DSM has been identified as necessary to improve efficiency in electricity consumption enabling more transparent consumer choice and, in the end, leading to a shift in the peak demand (Foley et al., 2010). Such a radical transformation also calls for new approaches to how power systems are designed, planned, and operated (Kira Taylor, 2021).

The efficient use of energy remains a cornerstone of any approach to energy security. End-user EE acts as a brake on peak demand and therefore mitigates the need for additional infrastructure upstream. A clean energy transition also requires that waste heat, bioenergy, or other potential losses or by-products of economic activity be put to productive use. Measures in this area can further dampen demand, but are likely to create integration challenges as supply chains become closely interconnected. In the meantime, more robust instruments are needed to manage electricity flows into and out of multiple sectors as their share of consumption increases (IEA, 2021).

A decade ago, Bigano (2010) argued already that improving EE could perform a pivotal role in managing energy security, allowing many countries to reduce their dependence on external sources or their exposure to energy price volatility. Bigano (2010) suggested at that time, that energy savings should be considered a policy priority when concerns for energy security are particularly strong. Four years later of this publication, the IEA in an effort to activate the huge untapped potential of energy-efficiency, issued a report on the *Multiple Benefits of Energy Efficiency* (Campbell, 2015) which emphasizes that if current trends continue in the years to come, two-thirds of the economic potential to improve EE will remain untapped until 2035. It is crucial to bring efforts together to apply the EE first principle, ensuring better use of the limited resources that humanity has today.

In its last *Energy Efficiency Report*, IEA (2021a) states that about 80% of the additional EE gains over the next decade will result in net cost savings for consumers, taking into account both the initial cost of the measures and the lower operating costs. This guarantees lower energy bills and cushions the impact of price volatility. This is one of the reasons why EE plays an important role in the policy mix in the net-zero emissions by 2050 scenario. IEA in its document *NET Zero by 2050 – A roadmap for the Global Energy Sector* (IEA, 2021b) also illustrates (*Figure 4*) that not all projected reductions in the energy demand in the 2030 and 2050 scenarios will come from EE, also electrification and end-user behavior could have a significant impact in industry, transport and buildings sectors.

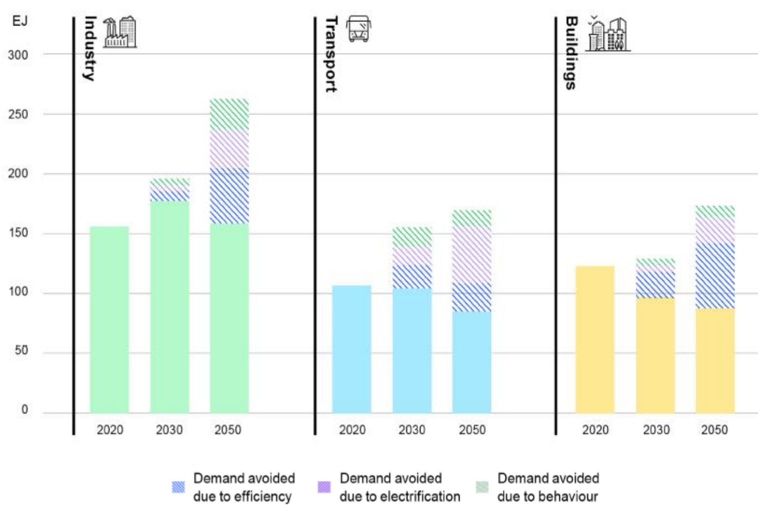


Figure 4 Energy efficiency milestones in the Net Zero Emissions by 2050 scenario, (IEA, 2021b)

The energy savings that result from this change in perspective can be expressed in monetary terms. However, it cannot be limited to the economic or environmental perspective, because that would be to ignore its true value. The implementation of BAT often brings non-energy benefits (NEBs) that are not energy benefits in and of themselves (Cooremans, 2012). The IEA (Campbell, 2015), explains the multiple benefits that EE brings and makes clear that it affects not only the electricity sector, but also many other sectors of the economy (*Figure 5*). Besides, IEA (Campbell, 2015) adds a classification of benefits into five broad categories *(Table 1)*, which provides a better understanding of all the dimensions generally covered specifically for the industrial sector.

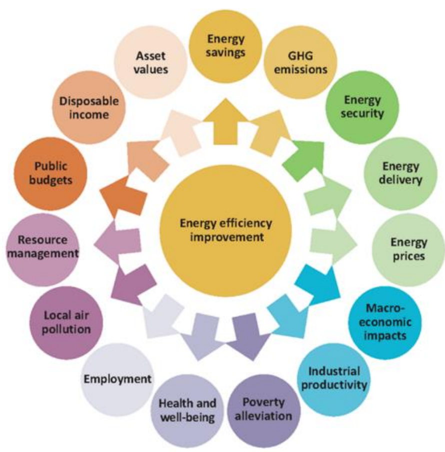


Figure 5 Multiple benefits of EE, (Campbell, 2015)

Table 1 Benefits classified by categories, (Campbell, 2015)

Competitiveness	Ability to enter new markets; reduced production costs, etc.
Production	Capacity utilization, improved product quality, etc.
Operation and maintenance	Improved operation; reduced need for maintenance, etc.
Working environment	Site environment quality; worker health and safety; etc.
Environment	Air pollution; solid waste; wastewater; reduced input materials, etc.

2.3 Tools to Facilitate Restructuring the Energy Systems

The requirements for energy system models have been changing in recent decades. With the increasing introduction of a high share of renewable energy generation, new challenges have arisen. In addition to the climate targets of the Paris Agreement, the national GHG strategies of industrialized countries include a complete restructuring of their energy systems (Lopion et al., 2018). The current transition to a low-carbon energy system is shaping an increasingly complex energy system framework. This pushes the boundaries of energy modeling towards the development of modeling frameworks capable of representing the interdependencies among policy, energy infrastructure development, market behavior, environmental impacts, and security of supply (Crespo del Granado et al., 2018). In order to approach all dimensions arising from the upheaval in the power sector, it is essential to conduct an assessment based on a quantitative analysis that is able to capture uncertainties in order to provide transparency to decision-makers regarding assumptions and methodological issues (Oberle & Elsland, 2019).

Electricity systems models are software tools used for power demand and power system management, electricity trading, and power generation expansion planning. Different portfolios and scenarios are modeled to compare the impacts of policy decisions and business development plans in electricity systems to best advise governments and industry on the most cost-effective economic and environmentally friendly approach to the electricity supply while maintaining a secure supply of sufficient high-quality electricity (Foley et al., 2010). The models map key techno-economic parameters that influence decisions on the expansion of electricity grids, taking into account projected demand, the resources available to meet it, and the portfolio of energy technologies to be developed and included in the matrix. Since the first oil crisis in 1973, power system modeling in conjunction with an energy scenario has been used very frequently to provide answers to the needs of policymakers and government agencies in many countries (Oberle & Elsland, 2019).

In general, models can be divided into two categories: Top-down energy models attempt to represent the economy as a whole at the national or regional level and assess the aggregate impact of energy and/or climate policies in monetary units. Unlike bottom-up modeling, these equation-based models take an aggregate view of energy sectors and the economy when simulating economic development, associated energy demand and supply, and employment (Herbst et al., 2012). Models tend to focus on specific features or parts of the energy system. It is possible to find instruments of modeling that combine both analysis categories allowing the user to choose according to the available data for each variable. Therefore, the selection of the tool for the analysis of national energy policies should be done carefully.

Energy system models differ in terms of data requirements, technology specification, skill requirements, and computational complexity. Some models are technologically explicit and require a huge database, which is usually not readily available in developing countries (Connolly et al., 2010). No energy tool addresses all the issues associated with energy system transformation. Instead, the "ideal" energy tool depends heavily on the specific goals that must be met (Connolly et al., 2010).

Climate change-induced policies have far-reaching impacts on the entire energy system and affect various sectors of the economy (Crespo del Granado et al., 2018). To analyze different decarbonization pathways for the energy system, existing models have been traditionally focused on specific energy sectors, taken specific research perspectives, evaluated only certain technologies, or examined isolated components and factors of the energy system. However, few efforts have been made to successfully model a broader picture of the energy system.

LEAP is not a model of a particular energy system, but a tool to create models of different energy systems, each requiring its own unique data structures. LEAP supports a wide range of different modeling methods: On the demand side, these range from bottom-up, end-user accounting techniques to top-down macro-modeling. The tool has been adopted by hundreds of organizations in more than 150 countries worldwide. Users include government agencies, academics, non-governmental organizations, consulting firms, and utilities, and it has been used at scales ranging from cities and states to national, regional, and global applications (Stockholmen Environment Institute, 2011). This study proposes to review the energy transition roadmap recently prepared by the Colombian government with a multi-criteria decision approach for sorting energy-efficiency initiatives using LEAP as a tool to model and evaluate the different dimensions of the energy transition. The objective is to assess all the major effects of the initiative, both positive and negative, including the often-forgotten side effects (Neves et al., 2008).

LEAP is developed based on the concept of long-term scenario analysis. Scenarios are internally consistent narratives about how an energy system might evolve over time. Using LEAP, policy analysts can create and then evaluate alternative scenarios by comparing their energy requirements, their social costs and benefits, and their environmental impacts. Scenarios are based on a comprehensive accounting of energy consumption, conversion, and production in a given region or economy under a set of alternative assumptions about population, economic development, technology, prices, etc. Thanks to LEAP's flexible data structures, the analysis can be as detailed as the user desires in terms of technical specifications and end-use. With LEAP, users can go beyond simple accounting and create sophisticated simulations and data structures. Unlike macroeconomic models, LEAP does not attempt to estimate the impact of energy policy on employment or GDP, although such models can be run in conjunction with LEAP. Similarly, LEAP does not automatically generate optimal or market equilibrium scenarios, although it can be used to identify least-cost scenarios. Important advantages of LEAP are its flexibility and ease of use, which allow decision-makers to move quickly from policy ideas to policy analysis without having to resort to more complex models (Stockholm Environment Institute, 2011).

LEAP was considered the most appropriate tool for the analysis of this work for the following reasons:

- It was the tool used for structuring the Colombian Roadmap for Energy Transition, and its use for this work will facilitate the variation and evaluation of some parameters and allow comparisons with the official document.
- It demands a low quantity of initial data.
- The license for students is free.
- It is flexible and easy to use.

2.4 Colombian Framework

Between 1975 and 2019, the Colombian population has doubled, from 24 to 49 million inhabitants (approximate figures). Similarly, the GDP has grown 4.8-fold, from 183,809 MMCOP to 881,429 MMCOP (DANE, 2020) which is equivalent to 43.6 M€ and 209 M€, respectively. This population and productivity growth have resulted in a significant increase in energy consumption and a change in the composition of the energy supply. During the same period, the final energy consumption in Colombia increased from 728 PJ to 1,346 PJ, due to the country's productive and economic transformation. These figures show the transformation from a poorly connected and industrialized country to a more urbanized and modern country. In contrast, there is also evidence of a decrease in household energy consumption, which was the most intense sector in 1975. This fact is explained by the substitution of firewood for more efficient sources such as natural gas (as the primary energy source) and electricity (as energy carrier) (Ministry of Mines and Energy et al., 2020).

Energy transformation implies a structural change of the whole system, including how and where the energy is generated, how the energy is distributed and transported, but also how the energy is consumed (Ministry of Mines and Energy et al., 2020). For responsible planning of the national power system, it is first essential to understand the framework of the country, how the matrix has been structured over the past 50 years, besides what its strengths and weaknesses are.

Colombia is considered one of the main emerging economies of South America, with a giant potential for economic growth and ever-growing energy demand. *Figure 6* displays the Country's growth in terms of energy generation during the last two decades (Our World in data, 2022a). According to the UPME (Mining and Energy Planning Unit), Colombian energy consumption has increased more than 500% in the past 55 years.

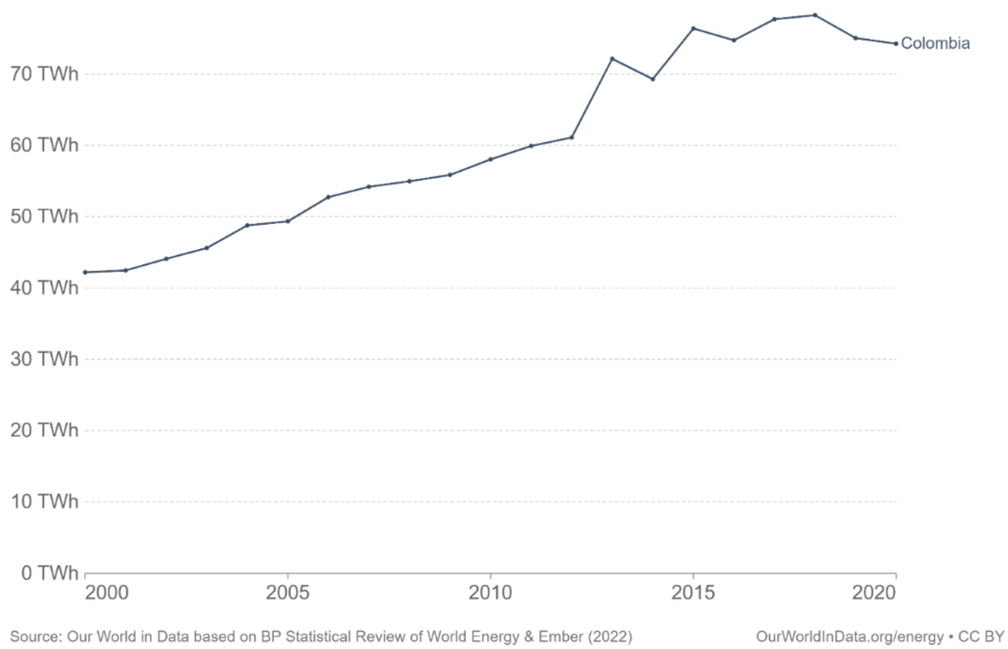


Figure 6 Colombia Electricity Generation 2000 – 2020, (Our World in data, 2022a)

The country has one of the cleanest electricity generation matrices in the world (World Economic Forum, 2017); despite being one of the main coal producers in the region (Climate Transparency, 2021), the electrical matrix is supplied almost completely based on Hydropower; non-renewable sources still represent around 30%; and there is a minimum share of other renewable energy sources (less than 2% by the end of 2020) (Our World in data, 2022a). The dynamic of the energy matrix of the country is illustrated in *Figure 7*. It has some drawbacks in terms of vulnerability under weather phenomena as a result of the lack of complementary resources.

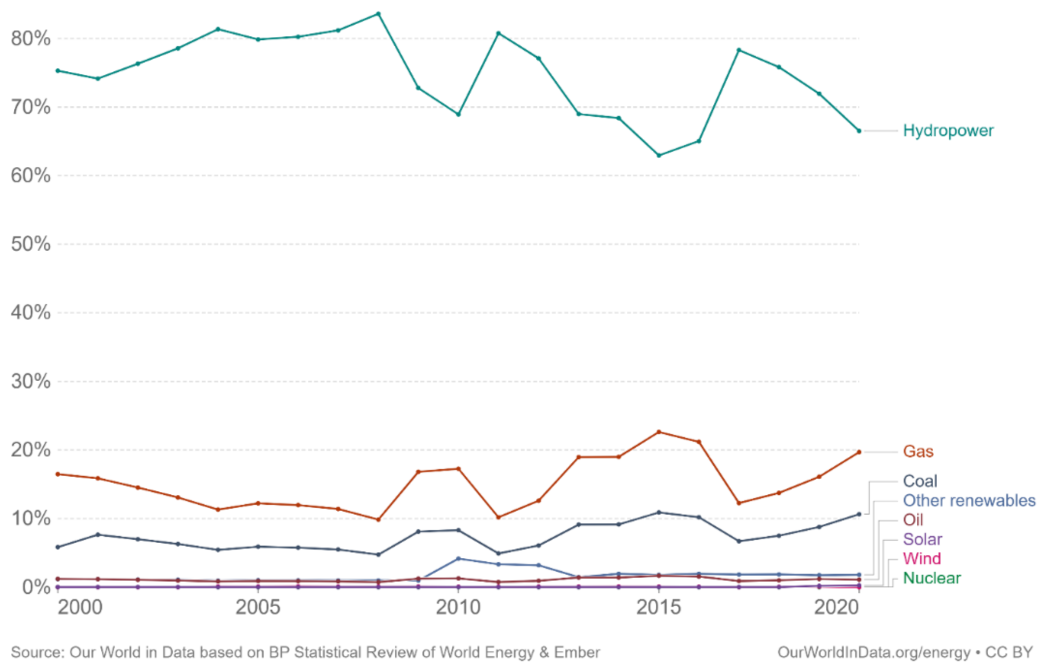


Figure 7 Share of electricity by source 2000 – 2020, (Our World in data, 2022a)

The country has a large proportion of the surface not covered by the national electricity grid. Those areas are named the non-interconnected zones (ZNI by its initials in Spanish) and they are mostly provided by diesel engines. *Figure 8* illustrates the National Interconnected System (SIN) that empowers only 48% of the national territory, but where 96% of the population is covered. Additionally, it shows the ZNI that accounts for 52% of the country's area and 625,000 people. However, the ZNI are relevant to the country because of their solar and wind energy potential, which have not been developed until 2019 for being located at remote sites, often with difficult access and with great ecological and ethnic interest (Gómez-Navarro & Ribó-Pérez, 2018).

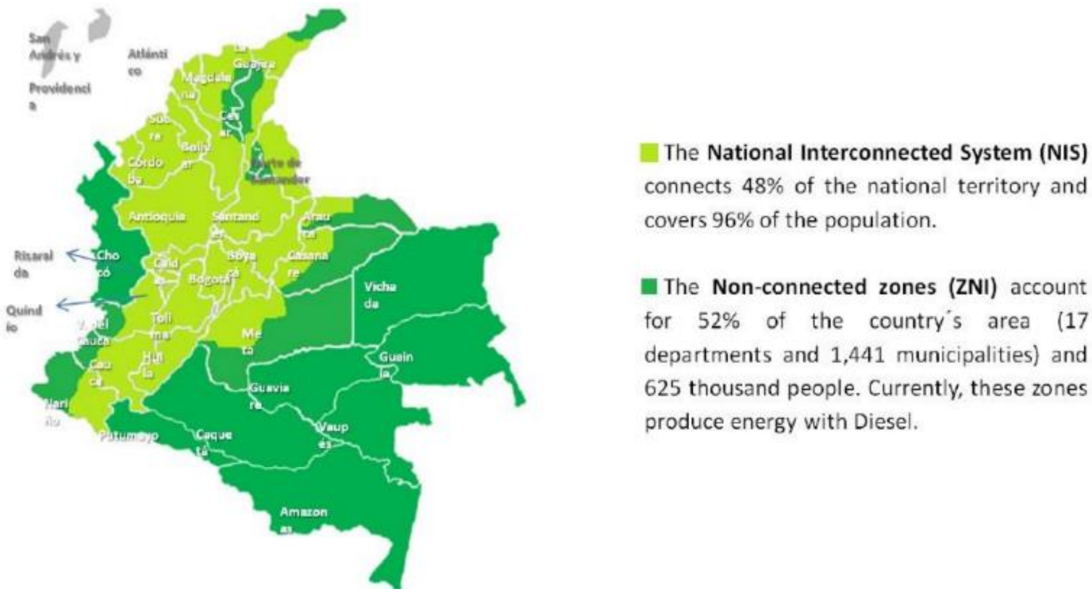


Figure 8 Connected and Non-connected Zones in Colombia, (Gómez-Navarro & Ribó-Pérez, 2018)

Thanks to the development and implementation of various regulatory instruments, policies to promote the incorporation of non-conventional renewable energy sources (solar, wind, and biomass energy), renewable energy auctions, and official energy transition plans, Colombia has emerged in recent years as one of the leaders in the Latin American region in the energy transition. The country has made significant progress in diversifying its electric matrix (National Energy Department et al., 2022b).

Regarding the energy intensity in Colombia (*Figure 9a*), it reached 2.26 MJ/USD in 2015 compared with the world average which is almost double, with 5.44 MJ/USD. In comparison with other countries in Latin America this figure is very close in Peru, with 2.76 MJ/USD, and in Panama is 2.17 MJ/USD. Meanwhile, it is lower than other countries where the levels of industrialization are higher, such as Argentina with 4.34 MJ/USD, Chile with 3.78 MJ/USD and Mexico with 3.74 MJ/USD (Ministry of Mines and Energy et al., 2020). On the other hand, the per-capita consumption of electricity on a global scale is 3,132 kWh/year, while in Colombia it was 1,312 kWh/year in 2019. *In Figure 9b* is possible to compare the Colombian indicator with similar economies, such as Ecuador with 1,376 kWh/year; Chile with 3,879 kWh/year, Argentina with 3,074 kWh/year and Brasil with 2,619 kWh/year (Ministry of Mines and Energy et al., 2020).

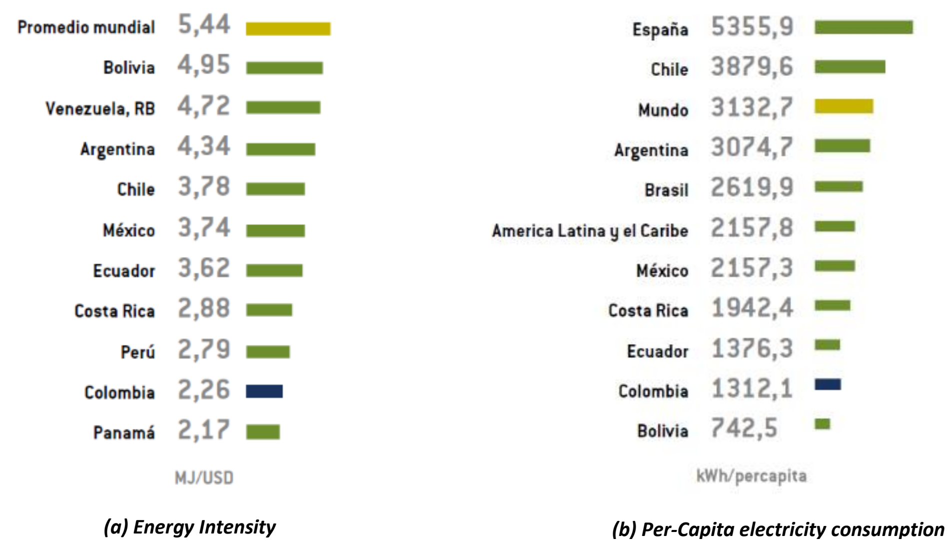


Figure 9 Energy Intensity Vs Per-Capita electricity consumption, (Ministry of Mines and Energy et al., 2020)

2.5 Energy Transition Policy Background

The energy transition is a global trend, and Colombia is not alone on that road. Around the world, numerous public and private resources are being mobilized toward the production of energy and end-use equipment that will enable a reduction in the use of fossil fuels. The country needs a long-term planning process in the form of a roadmap that provides continuity to meet the ambitious goals to be achieved by 2050. This does not mean that the roadmap should be rigid and contain a series of steps that must be followed rigorously. On the contrary, it must be the basis for designing and implementing new policies according to the economic, climatic and geopolitical changes that affect the national panorama, without losing sight of the goal; as explained by The Ministry of Mines and Energy (2020). The planning document should be State policy, without its development being subject to the will, vision, or ideology of the administration serving it. It has the potential to create direct benefits for consumers, protect and allocate available resources, and monitor the environment (Guerra & Guillén, 2021).

As an important vector in decarbonization, an EE law is not an end in itself and will not be successful if it is developed in isolation from and in anticipation of the demands of the political system, businesses, and consumers. An EE law must work to lay the groundwork for a social compact in which there is consensus on the role of EE as a public policy and which promotes cultural change (Guerra & Guillén, 2021).

To combat climate change, the pledges made by Colombia in the Paris Agreement were approved by the issuance of Law 1844 of 2017, which establishes the country's commitment to reduce greenhouse gas emissions by at least 20% by 2030. In the update report published in 2020, Colombia's determined contribution (NDC) (Colombian Government, 2020), the country raised the challenge and committed to (i) emit a maximum of 169.44 Mt $CO_{2\ eq}$ in 2030 (representing a 51% reduction in emissions compared to the projection of emissions in 2030 in the BAU scenario), initiating a decline in emissions between 2027 and 2030 leading to carbon neutrality at mid-century. (ii) Establish carbon budgets for 2020-2030 no later than 2023. (iii) Reduce black carbon emissions by 40% from 2014 levels. However, the country had already signed the Organization for Economic Cooperation and Development's Declaration on Green Growth in 2009, in which 34 countries pledged to strengthen their green growth efforts and develop tools and policies so that economic growth reaches a balance that reduces its impact on the climate crisis (Ministry of environment and sustainable development et al., 2019).

2.6 National Efforts to Strengthen Energy Efficiency Policies

The commitment to EE is consistent with the challenges of national energy policy. On the one hand, it helps address the ongoing challenge of meeting growing demand at a reasonable price, and on the other, it contributes to mitigating climate change (Ministry of mines and energy & Mining-Energy Planning Unit, 2021). For this reason, the IEA has called it "the fuel for a sustainable global energy system" (IEA, 2021a). In the particular case of Colombia, EE has a high potential for economic and consumption savings. According to the Useful Energy Balance carried out by UPME (2019), EE can represent a cost reduction of between USD 6,600 and 11,000 million per year, which contributes to improving the competitiveness of national production and the affordability of energy for the country's inhabitants.

However, barriers have been identified in the national market that does not allow the full deployment of EE in all sectors of the economy. Namely, there is a lack of codes and standards, which makes it difficult to introduce new technologies. There is also evidence of the presence of "economic myopia," in which decision-makers do not consider the flows associated with future consumption at the time of an investment in this area. Even more, especially in the household sector, the main obstacle is that the householder who has to make the investment in the technology is not necessarily the one who will enjoy the economic benefits it will bring. Given these identified barriers, the promotion of EE requires the regulation and setting of standards, fiscal incentives, the dissemination of information and mechanisms that allow the evaluation of externalities (Ministry of mines and energy & Mining-Energy Planning Unit, 2021).

2.6.1 CONPES 3934 of 2018 – Green Growth Policy

Colombia has made commitments to improve productivity, economic growth, climate change and the efficient use of the country's natural resources. In 2018, The National Council for Economic and Social Policy (CONPES) published the Green Growth Policy, proposing to promote the increase of the country's productivity and economic competitiveness by 2030, ensuring the sustainable use of natural capital and social inclusion, in a way that is compatible with the climate. Specifically for the energy sector, measures were identified to promote and strengthen (i) energy efficiency, (ii) vehicle and equipment labeling, (iii) the development of water monitoring tools in mining areas, (iv) the revitalization of the regulatory agenda to include non-conventional sources of renewable energy (FNCER), (v) the evaluation of the establishment of an energy observatory, (vi) the preparation of technical guidelines for the inclusion of energy storage systems, and (vii) the development of a roadmap to ensure the deployment of advanced metering infrastructure. Although the measures contained in such policy have already been implemented and have contributed to solving specific problems related to the energy transition, this progress is not final or conclusive, and it is necessary to establish new guidelines and measures to consolidate the transition process (National Planning Department et al., 2018).

2.6.2 VI Pact for Transport and Logistics at the Service of Competitiveness and Regional Integration PND-2018-2022

The VI Pact for Transport and Logistics at the Service of Competitiveness and Regional Integration PND-2018-2022 proposes measures to create a competitive and high-quality passenger transport system. In this pact, the financial components that enable technological progress toward zero and low-emission standards are reviewed, mainly by promoting the renewal of the automobile fleet in the systems co-financed by the nation. Likewise, it is planned to increase the transport of goods on the river from 5 to 8 Mt and 328 registered vessels, which means a 35% increase in the transport of goods, and to achieve an extension of railway lines with a commercial operation of 1,077 km, an increase of 61%. It also points out the need to promote energy efficiency in the transport sector and establishes technical and financial support measures for the implementation of public land systems (Pact for Colombia - VI Pact for Transport and Logistics for the competitiveness and Regional Integration 2018-2022., 2018). The document identifies the efforts that should be made to maximize the efficient use of resources available in the country and promote the competitiveness of the transport sector, divided mainly into three basic areas on which the country should focus, listed in *Figure 10*. Additionally, it also mentions the real potential to make improvements in those areas in this decade, which data is represented in *Figure 11*.

Figure 10 Key areas to increase the efficiency in Transport Sector, data source National Planning Department

Figure 11 Targets for the key areas in transport sector, data source National Planning Department

2.6.3 CONPES 3963 of 2019 - Policy for the modernization of the freight automotive transport sector

This policy is in line with a road freight modernization program that aims to reduce the average age of the vehicle fleet with a gross weight greater than 10.5 t from 18 to 15 years by 2022. This is intended to reduce pollutant, environmental, and particulate matter emissions through technological advances that allow for greater efficiency in terms of costs, times, quality, reliability, traceability, and synchronization in freight movements that are part of the national transportation and logistics chain. However, this policy focused exclusively on technological advancement measures in the heavy freight sector, without implementing measures to reduce GHG emissions in urban areas, where the transport of goods weighing less than 10.5 t, plays an important role (National Planning Department et al., 2019).

2.6.4 Law 1955 of 2019, Article 292 - Buildings of Public Administrations

With regard to EE, the aforementioned law requires the national government and all public administrations to conduct an energy audit of their facilities in order to set targets for reducing energy consumption, based on which EE measures will be defined to achieve minimum energy savings targets (Law 1955 of 2019 - National Development Plan 2018-2022, 2019).

Colombia must take great steps to include not only public administrations, but also the tertiary sector in general, and undoubtedly all the industry, in these commitments. The implementation of energy management systems helps companies identify opportunities for adopting energy-efficient technologies. They have been successfully introduced in a number of countries. However, there are only a small number of mandatory EE measures for the industrial sector beyond such management systems, mandatory energy audits, and minimum EE standards for industrial motors (I. E. A. IEA, 2021a). Examples of mandatory audit requirements can be found in emerging economies such as Tunisia and Morocco, as well as in advanced economies such as the European Union. While such measures are necessary, they are only the first steps on the road to a clearer, better-defined path to improving EE in the industrial sector. To enable the next steps, it is important to develop sub-sectoral targets and create an environment that fosters EE through a policy package of regulation, information measures, and incentives (I. E. A. IEA, 2021a).

2.6.5 CONPES 3982 of 2020 – National logistics policy

The policy to promote intermodality is based on three mechanisms to modernize infrastructure for freight transport by road, rail, national rivers, air and sea. First and foremost, it promotes the development of efficient connections between the various modes of transport. Second, strategies for optimizing infrastructure supply to trade terminals are proposed. Finally, transversal strategies are proposed to improve institutional supply in transport and trade (National Planning Department, 2020).

According to CONPES 3982, the majority of the river navigation fleet, with the exception of the one that navigates the Magdalena River, has been in operation for more than 50 years and operates with technologies that produce high GHG emissions. Though inland navigation offers greater EE and a significant reduction in GHG emissions, and although it has the greatest transport capacity per unit of force and therefore lower transportation costs compared to air, road and rail modes, no progress has been made in promoting this mode of transport. On the contrary, it is characterized by its technological obsolescence and the low level of retrofitting of the inland fleet. This means that the currently available vessels are inefficient in the sense described (National Energy Department et al., 2022a). It is also important to note that air transport in Colombia represents 10% of total energy consumption and 6% of CO_2 emissions from the transport sector, but is only 0.07% of the country's freight transport (National Energy Department et al., 2022a).

2.6.6 Useful Energy Balance Study and Rational and Efficient Use of Energy Program 2021

Law 697 of 2001 issued in 2003 promoted the rational and efficient use of energy (URE) and declared it a matter of social, public and national interest, essential for ensuring a complete and timely energy supply, the competitiveness of the Colombian economy, consumer protection and the promotion of the use of non-conventional energies (Law 697 of 2001 - Rational and Efficient Use of Energy, 2003). Since then, this law has been the basis for the elaboration of the Indicative Action Plan of the Rational and Efficient Use of Energy Program (PROURE), introduced in its third version as a prospecting document for the period 2021-2030, which establishes the indicative targets for the country's energy efficiency, understood as a valuable resource within the framework of energy transformation (Ministry of environment and sustainable development et al., 2019). This document identifies the aligned cost-effective measures that allow access to the tax benefits granted by law. This approach aims at an efficient intervention of the State in the promotion of EE measures, whether they are related to technological substitution, adoption of best practices, fuel substitution, or digitalization (Ministry of mines and energy & Mining-Energy Planning Unit, 2021).

PROURE identified a potential energy consumption reduction of 9.34% (equivalent to 1,726 PJ, cumulative value for the 2021-2030 period) due to EE measures alone (as opposed to a BAU scenario) during the 2021-2030 period studied, as shown in *Figure 12*. Of this percentage, the transport sector accounts for 3.71%, followed by residential buildings with 2.89% and finally the industrial sector with 1.41%. In terms of CO2 emissions, PROURE estimates that emissions in the end-use sectors can be reduced by 15.2% by 2030, equivalent to avoiding 87.22 Mt of CO2 (Ministry of mines and energy & Mining-Energy Planning Unit, 2021). This reflects that the potential of the country in terms of energy efficiency is noteworthy.

Own construction

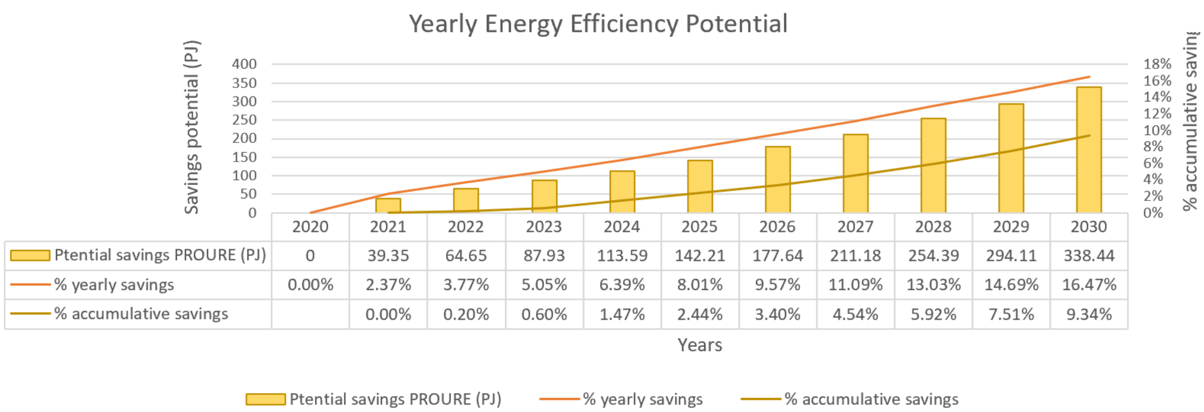


Figure 12 Yearly Energy Efficiency Potential, (Ministry of mines and energy & Mining-Energy Planning Unit, 2021)

The inefficiency in the use of energy resources in Colombia reaches relevant figures. Before analyzing them, it is first important to note, as illustrated in *Figure 13*, that 92.8% of the final energy consumed in the country is mainly in three sectors: Transportation (42.8%), Industry (23.4%) and Household (26.6%) (National Energy Department et al., 2022a).

The study conducted for the construction of the Useful Energy Balance (BEU) in 2018 quantifies the energy losses associated with the inefficiency of end-use equipment. The BEU compares the amount of energy consumed by the technologies currently used in the country with what would be consumed if the best available technologies were used at the national and international levels, the so-called best available technologies (BAT) (Ministry of mines and energy & Mining-Energy Planning Unit, 2021). The results of the BEU study show that in Colombia, useful energy represents only 31% of final energy, an inefficiency of about 69% that costs the country between

USD 1.5 and USD 2.6 million annually. The introduction of BAT would reduce energy consumption/costs by 38% to 62%, while maintaining the same level of production and comfort.

Figure 13 is the scheme presented in the PROURE document, based on (UPME, 2019), to illustrate the general overview of useful energy and inefficiency in the four main sectors of the Colombian economy. The graph also represents the main energy sources for each of the sectors. It can be observed that transport is not only the sector with the highest consumption (43%), but also the one with the highest inefficiency (69%), with useful energy representing merely about 24% of the energy consumed (and paid for). On the other hand, the household sector is the third largest energy consumer in the country, but the second with the greatest potential for energy efficiency (due to the use of firewood for cooking in rural areas) (Ministry of mines and energy & Mining-Energy Planning Unit, 2021).

Figure 14 gives an overview of the foremost mobilizers of energy consumption in the main four sectors of the economy in Colombia. It could be analyzed the primary uses as the proportion of useful energy in comparison with the energy that is lost because of inefficiency and the energy that is not recoverable. It can be clearly seen that the sector with by far the highest inefficiency is transportation with only 25% of the useful energy. It is also the sector with the highest consumption of fossil fuels (causing significant levels of pollution), so it is a global concern to decarbonize this sector and increase the efficiency points.

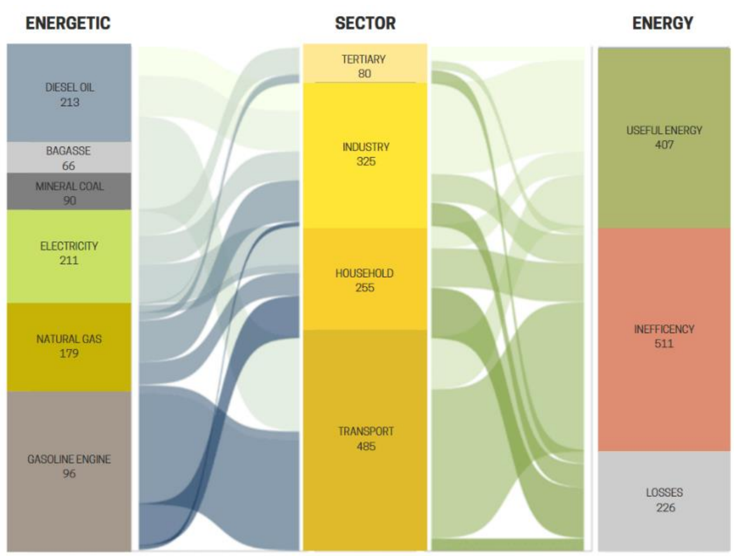


Figure 13 Annual Energy Efficiency potential. Source PROURE 2020-2030.

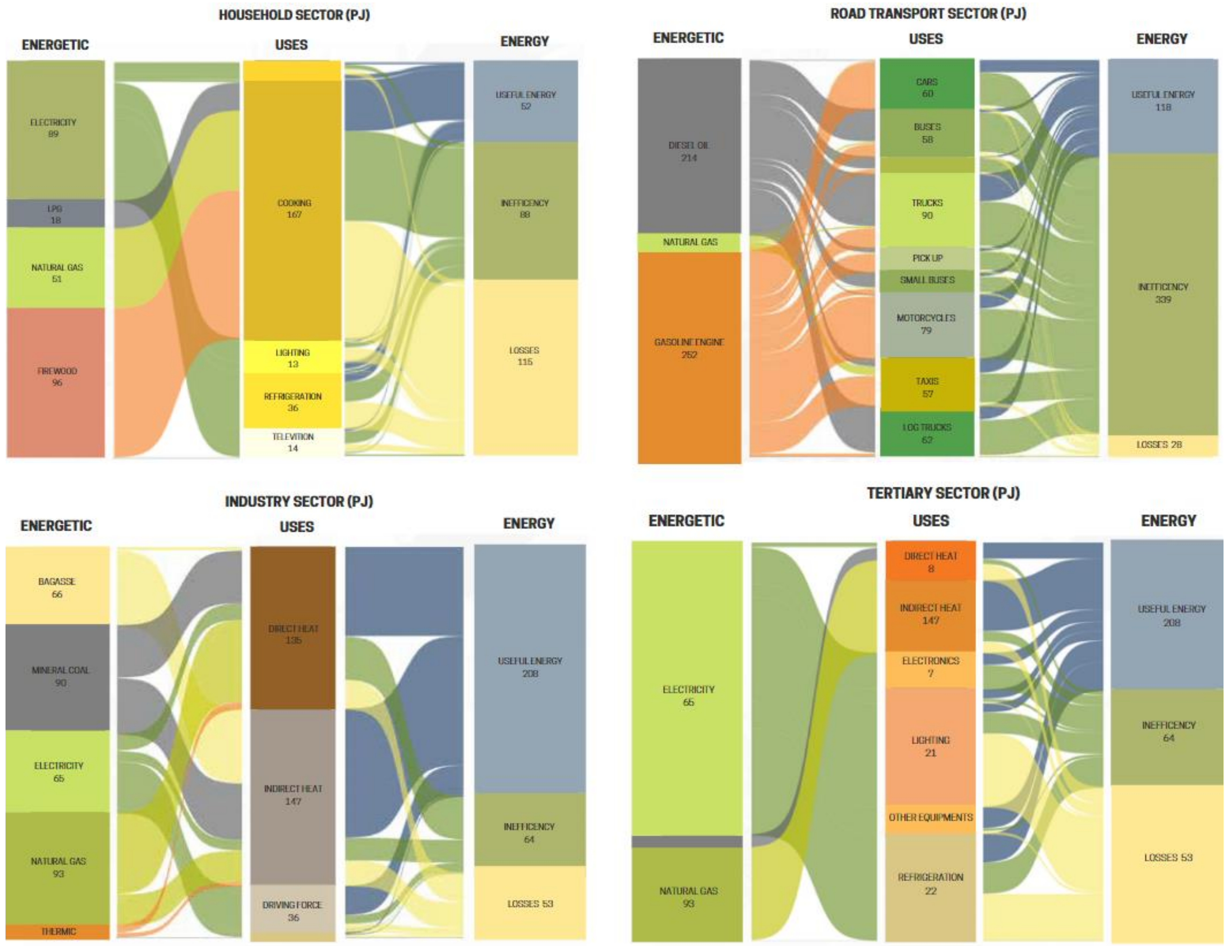


Figure 14 Mobilizers of energy consumption per economic sector, Source PROURE 2020-2030

PROURE introduces the actions and goals in energy efficiency for those sectors. Even though, they are indicative in nature and do not establish mandatory strategies or actions to advance energy efficiency. The measures proposed in the program can be developed in the short and medium term. It also identifies those measures that are desirable from a collective perspective, but where there are barriers and market failures that could be addressed through fiscal incentives. Cost-effectiveness analysis from the standpoint of return on investment for the private sector and the need to provide tax incentives or not was also examined in PROURE report, it is not part of this thesis work tough, serving as a basis for future studies. Some of the actions per sector recommended by PROURE are summarized in *Table 2.*

Table 2 Actions per sector Recommended by PROURE

Own construction

TRANSPORTATION	INDUSTRY
• Tax incentives and government support for the development of statewide rail service that brings network benefits and other positive externalities • Acquisition of electric vehicles to replace liquid fuel vehicles • Acquisition of new natural gas-fueled vehicles to transport freight and passengers • Acquisition of hybrid vehicles throughout the national territory.	• Reduce inefficiencies of energy end-use equipment through technological change in motive power, direct and indirect heat, and cooling. • Promote operating practices to reduce energy consumption at minimal cost. • Creating a culture of EE based on the concept of comprehensive energy management in accordance with NTC ISO 50001, operational control, and advanced sub'metering systems. • Installation of AMI smart metering
HOUSEHOLD	**TERTIARY**
• Replacement of refrigerators with a label equal to A. • Replacement of firewood for cooking in the rural sector • Replacement of inefficient stoves in the urban sector • Installation of LED lights • Installation of smart AMI meters	• Replacement of refrigerators and lighting fixtures (to LED light fixtures) • Replacement of appliances associated with indirect heat • Introduction of smart metering and sub'metering • Introduction of automation technologies • Installation of AMI smart metering • Empowerment of air conditioning, motive power and direct heat with electrical energy

The proposed measures aim to increase the percentage of useful energy in total final energy consumption from 31% in 2019 to 41.1% in 2030 and reduce the country's energy intensity from 2.23 Terajoules per billion Colombian pesos (TJ/billion) in 2019 to 1.59 TJ/billion in 2030 (Ministry of mines and energy & Mining-Energy Planning Unit, 2021). *Figure 15* and *Figure 16* represent the goals comparing the tendentious scenario with PROURE's ambitions in terms of energy intensity and CO_2 emissions intensity.

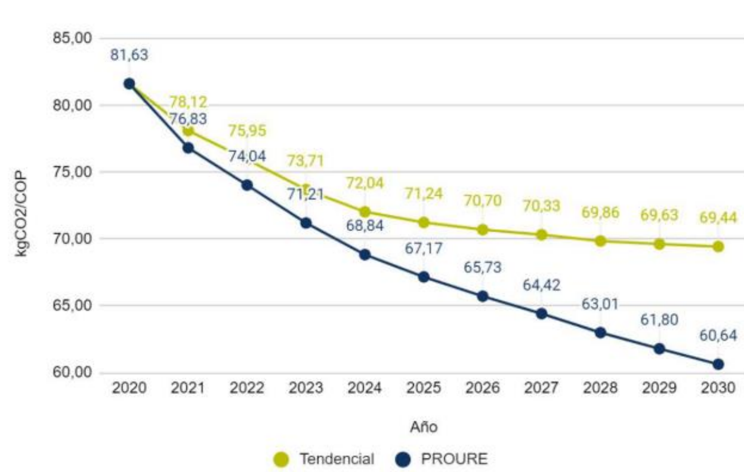


Figure 15 Emission Intensity Index (kgCO₂/COP), (PROURE 2020-2030)

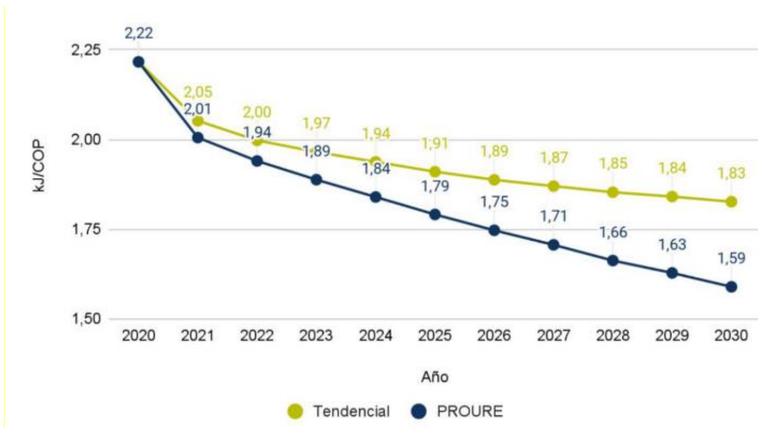


Figure 16 Energy Intensity Index (kJ/COP), (PROURE 2020-2030)

2.6.7 CONPES 4075 of 2022 - Energy Transition Policy

It is not for nothing that the country has been recognized as a regional pioneer in the energy transition, electromobility and closing gaps in the electricity sector. This protagonism is the result of the efforts of the last four years, which include: (i) auctions that allowed the award of long-term contracts integrating renewable generation projects, making a diversified electricity matrix feasible by 2023; (ii) the development of a regulatory and fiscal framework attractive to investors and conducive to new energy generation projects; (iii) the inclusion of new energy sources and technologies in the generation matrix; (iv) the formulation and application of guidelines to strengthen institutions related to the mining and energy sector; (v) launch of the Hydrogen Roadmap that will help reduce the country's pollutant emissions; (vi) launch of the Roadmap for the incorporation of Offshore Wind Energy, whose objective is to take advantage of the winds in the Caribbean region, which are around 13 m/s, above the world average; (vii) National Strategy for Electric Mobility (ENME), which aims to accelerate the diffusion of electric vehicles to proactively reduce emissions in the transport sector and use energy efficiently and rationally (Ministry of environment and sustainable development et al., 2019); and (viii) National Energy Plan 2020 2050 (PEN), which corresponds to an energy prospective document that proposes indicative long-term scenarios for achieving public policy goals (National Energy Department et al., 2022a).

Despite the country's best efforts, these advances have only partially laid the groundwork for the energy transition process, due to the weak linkages between the country's economic sectors and the short- and medium-term nature of the process. The Energy Transition Policy CONPES 4075 in 2022 was created to fill precisely this gap and consolidate the energy transformation process through the formulation and implementation of cross-sector policies and strategies that promote the country's economic, energy, technological, environmental and social growth (National Energy Department et al., 2022a). CONSPES 4075 establishes lines of action aimed at (i) increasing EE, (ii) making progress in closing human capital gaps and designing skills for transition implementation, (iii) structuring the application of new technologies in the mining and energy sector; (iv) developing initiatives to increase the coverage of electricity service, (v) implementing measures for digitalization, monitoring, and information management in the mining and energy sector; and (vi) defining guidelines for technological progress in various modes of transport. The implementation horizon is the period between 2022 and 2028, in which nineteen national entities will carry out ninety-seven actions with a total investment of USD 70 million (National Energy Department et al., 2022a).

2.7 Colombian EE Policies in the Latin America Context

The elaboration and approval of an EE law adapted to the specific context of the country is a milestone for the development of the energy sector; and although it does not guarantee the success of the goals set, it provides a solid foundation that will support the development of EE in the country (Guerra & Guillén, 2021). As shown in *Figure 17*, twelve countries in the region already have EE or rational and efficient energy use laws in place, and another five have EE legislation that is under discussion (Guerra & Guillén, 2021).

Figure 17 Energy Efficiency laws in place in Latin American countries, (Guerra & Guillén, 2021)

EE planning is an important tool for the development of long-term public policy and is established within an appropriate legal framework. It is a process that includes establishing a baseline diagnosis, identifying and characterizing opportunities and barriers, setting goals and measures, and finally establishing quantitative targets and indicators for a specific period of time; all of which must be taken into account and consolidated when creating a national energy efficiency plan. The EE Law may provide for the elaboration and characteristics of the EE Plan; however, the laws, bills and regulations analyzed differ in terms of provisions on this subject. In the case of Colombia, PROURE was created, whose objective is to progressively apply for programs so that the energy sectors meet the minimum EE requirements. (Guerra & Guillén, 2021).

Chapter 3
National Energy Plan and Energy Efficiency Options

3.1 National Energy Plan 2020-2050 (PEN 2020-2050)

The National Energy Plan 2020-2050 (PEN 2020-2050) is an indicative energy prospective document supported and promoted by the Ministry of Mines and Energy and other Colombian government agencies. Its objective is to develop a long-term vision for the Colombian energy sector and identify possible pathways to achieve it. The document proposes different scenarios depending on the policies to be adopted in the coming years to achieve the energy transition that will enable Colombia's sustainable development. The different impacts of each scenario are analyzed, in terms of energy supply, contribution to climate change, technological risks, and costs to the sector. As a starting point, the strategies and objectives already established in the energy sector, the impact of more ambitious policies, and the challenges related to the adoption of technologies that are already commercial and others that are still under development are analyzed (Ministry of Mines and Energy et al., 2020).

Nowadays, Colombia is able to supply its energy demand mainly with internal resources. However, on the long-term horizon, the forecasting of supply and demand indicates that energy self-sufficiency could end if the right measures are not displayed in the coming years. Therefore, the first challenge of the energy sector continues to be the supply of local demand in a reliable, sustainable, and affordable way; making the most of the privileged resources by the country and optimizing the energy supply chain (Ministry of Mines and Energy et al., 2020).

In 2018, the Planning Unit for Mines and Energy (UPME, government entity) prepared the Useful Energy Balance (BEU) for Colombia, a study that quantifies energy losses in the end uses. It was concluded that EE offers one of the greatest potentials (*Figure 18*) for reducing production costs in the country, increasing the competitiveness of the industrial sector and meeting environmental indicators (UPME, 2019). Based on this study, the PEN 2020-2050 concludes that the second challenge is to close the technological gap to improve EE (Ministry of Mines and Energy et al., 2020).

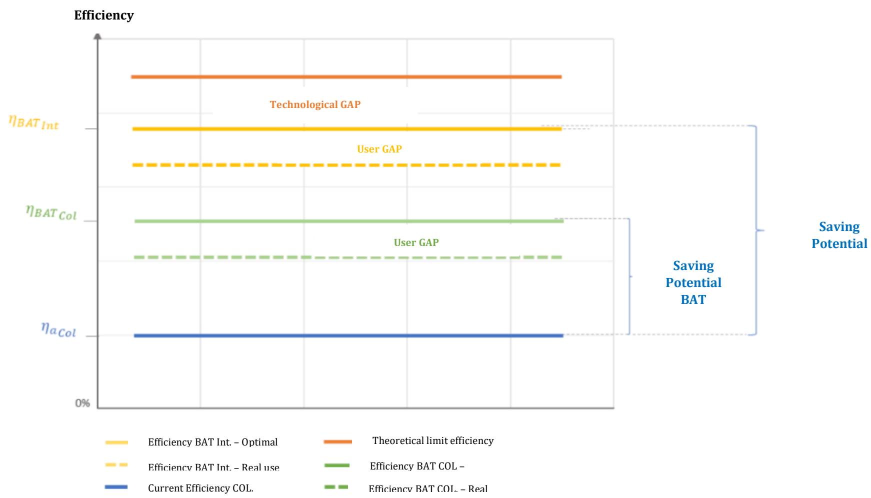


Figure 18 Energy Saving potential in Colombia, source (UPME, 2019)

In the BEU (UPME, 2019), the energy consumed with the BAU technologies used in the country is compared with the energy that would be consumed if national or international BAT were implemented, and an efficiency potential to be achieved for each sector is also calculated (*Figure 19*); it could be observed that for transport sector the useful energy just represents 24% from the final energy, for household sector is 18%, for industry sector is 55%, and for the tertiary sector is 34%. The main result of the BEU is that in Colombia the useful energy barely represents 31% of the final energy and the inefficiency in consumption is about 69%, a situation that costs the country between 6,600 and 11,000 million USD annually (Ministry of Mines and Energy et al., 2020).

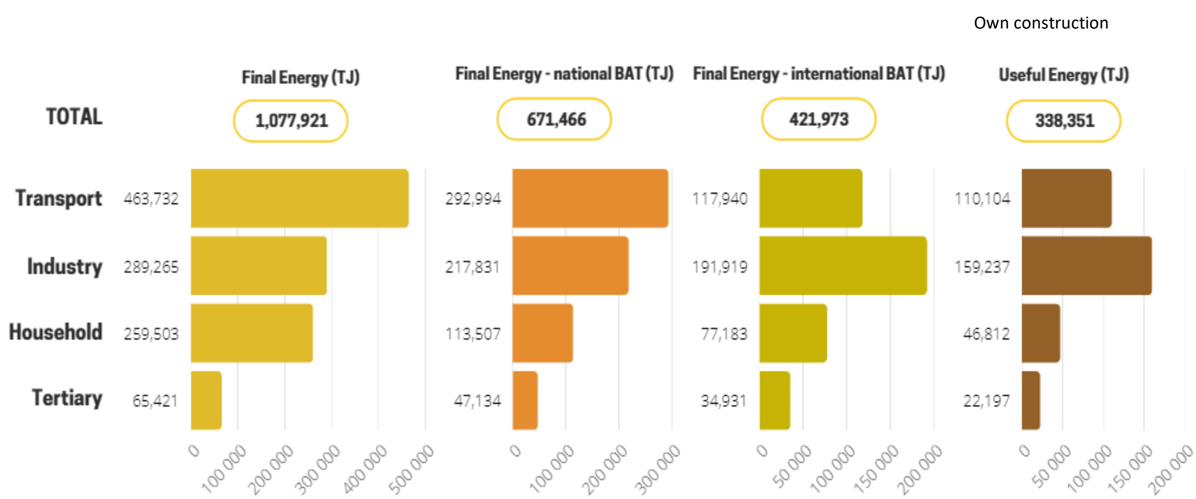


Figure 19 Final energy with the national and international BAT, data source (UPME, 2019)

Table 3 summarizes the results found on PROURE in terms of EE potential, whether national or international BAT was introduced in each of the main energy consumption sectors, and compares them with the BAU figures. In terms of overall figures, EE has the potential to increase from 31% to 80%, with the transport sector achieving a 69% improvement and the household sector 43% (Ministry of mines and energy & Mining-Energy Planning Unit, 2021). In the case of households, the measures could be achievable, but implementation also requires a change in mentality among the population (National Energy Department et al., 2022a).

Table 3 EE Potential in the main consumer sectors, data PROURE

Own construction

	Current EE	Possible EE national BAT	Possible EE international BAT
Total	31%	50%	80%
Transport	24%	38%	93%
Industry	55%	73%	83%
Household	18%	41%	61%
Tertiary	34%	47%	64%

(useful energy/final energy)

Ministry of Mines and Energy (2020) affirms that energy planning in Colombia has two breakdown barriers in three different areas to bring EE to its maximum level for the competitiveness and sustainability of the country. (i) *Diffusing the proper information among the end-user*: better-informed consumers make better decisions. Provide them with the range of alternatives available on the market in terms of energy and technology, but also with the information on how their energy consumption behavior impacts the national power system, the environment and their finances. In this way, the energy prices of the different sources with the different alternatives, for instance, for industries, are relevant to the decision-making process, because since it directly affects the production costs, they will feel motivated to adjust their consumption patterns and invest in efficient equipment. (ii) *Establishment of Minimum energy performance standard (MEPS)*: outline minimum performance standards for the EE of end-use equipment while advancing the design, implementation, and strengthening of the energy labeling strategy for equipment, vehicles, and buildings. (iii). *Implement innovative financial instruments*: the promotion of financial tools and tax incentives to support investments in the acquisition of BAT (Ministry of Mines and Energy et al., 2020).

In the particular case of better-informed end users, it represents a tremendous opportunity to open the way to digitization. The data collected by digital devices can be managed and transformed into information that makes it possible to identify the drivers of consumption and use them to develop optimal response strategies (Ministry of Mines and Energy et al., 2020). The ability to have metering and data collection devices and to communicate them almost instantaneously allows the end user to understand the conditions that affect their energy consumption and to have a greater range of response (Ministry of Mines and Energy et al., 2020). On the other hand, consumers have the opportunity to directly control energy consumption and sell services to the grid, so they are able to demand a higher level of quality, personalize their products according to their convenience, and earn an income for their energy production (Ministry of Mines and Energy et al., 2020). This represents a challenge for the energy plan itself. Digitization and decentralization are complementary (and inevitable) trends that will bring more information, new actors, new ways of solving problems, and empowerment of end users. In this context, energy planning must innovate the way it proposes future scenarios and clearly communicate the purpose and limitations of its models (Ministry of Mines and Energy et al., 2020).

In 2021, the third version of PROURE was launched in Colombia, whose objective is to gradually apply for programs so that the energy sectors comply with the minimum EE requirements (Guerra & Guillén, 2021). Unlike PEN 2020-2050, the program is not a roadmap, instead, it is an instrument that allows decision-makers to focus on designing medium and long-term strategies to enhance energy use from the demand side.

The long-term energy modeling displayed in PEN 2020-2050 (Ministry of Mines and Energy et al., 2020) used the simulation tool LEAP, as mentioned in Chapter 2. The model allows "bottom-up" and “top-down” structuring and integrates the energy and environmental dimensions through analysis such as "what would happen if", allowing the study of all the impacts of each of the proposed scenarios on the electric system, the environment, and the communities. However, unlike other modeling instruments, LEAP has some limitations in terms of automatically identifying the systems with the lowest cost or market share in terms of prices and other variables. As a result, the factors that influence consumer behavior, such as energy policy, can be difficult to parameterize or are very sensitive to possible variations and initial assumptions. Figures from the modeling of the Colombian framework indicate that for all the evaluated scenarios, a significant increase in installed capacity of the electric grid is required by 2050, from 17 GW in 2019 to more than 40 GW, a growth of 135% in 30 years (Ministry of Mines and Energy et al., 2020). That growth is proposed in the Energy Plan's scenarios to be supported by the promotion and incorporation of new non-conventional renewable sources, such as solar power, onshore wind power and offshore wind power; but also, the country bets on the development of green hydrogen; while the share of fossil fuels in the matrix is carefully reduced. Given that each scenario sets different targets, assumes different risks and has different costs; the simulation exercise also identifies which is the most ambitious scenario while remaining realistic, which is the one that should be considered by regulators for designing public policy and decision-making (Ministry of Mines and Energy et al., 2020).

3.2 Theoretical Framework of PEN 2021-2050

The PEN 2020-2050 was thought to approach five primary challenges of the Colombian electrical sector for the next three decades as it is summarized in *Figure 20*. Of those, there are particularly three that are closely related to the EE framework. Challenge 2, because it requires better informed consumers, setting minimum EE, reviewing market schemes and their tariff systems, and monitoring EE results achieved. Challenge 3, because it has a direct impact on the reduction of GHG emissions. Challenge 4, demands stronger efforts aligned with decarbonization, digitalization and decentralization, especially the second one is linked with the EE measures (Ministry of Mines and Energy et al., 2020).

Own construction

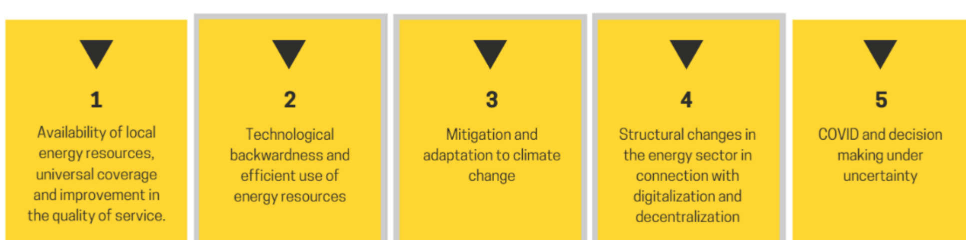


Figure 20 Set of challenges faced by the PEN 2020-20250

Once the existing challenges of the national electric system were identified, a sequence of phases was established to structure the general body of the plan. The first phase requires a clearly defined vision that serves as the philosophy of the plan. The second phase identifies strategic areas that serve as pillars to enable the vision. The upper phase establishes the goals, which must be ambitious, specific, measurable, achievable, relevant and timely for the next 30 years. Finally, the last phase proposes all the initiatives necessary to promote the achievement of the goals (Ministry of Mines and Energy et al., 2020).

3.2.1 The Vision

An energy transformation that enables sustainable development is characterized by: (i) the use of clean energy sources and low emissions; (ii) the use of cutting-edge technologies on both the demand and supply sides; (iii) the use of digital, information, and communications technologies for management and decision-making; and (iv) increased empowerment of the end users; that at the same time enables the achievement of the sustainable development goals (SDG). *Table 4* is displayed the targets drawn in the PEN 2020-2050 for those SDG by 2030 (Ministry of Mines and Energy et al., 2020).

Table 4 Summary of the targets for the SDG related to the energy transition set in PEN 2020-20250

Own construction

7	**National Indicator:** Electricity coverage (% of households) **Base line (2015):** 96.9%	**National target (2030):** 100%
8	**National Indicator:** Labor formality rate (% employed population) **Base line (2015):** 50.8%	**National target (2030):** 60%
9	**National Indicator:** Households with internet access (%) **Base line (2015):** 41.8%	**National target (2030):** 100%
10	**National Indicator:** GINI Coefficient **Base line (2015):** 0.522	**National target (2030):** 0.480
11	**National Indicator:** urban households with a quantitative housing deficit (%) **Base line (2015):** 6.7%	**National target (2030):** 2.7%
12	**National Indicator:** Recycling rate (%) **Base line (2015):** 8.6%	**National target (2030):** 17.9%
13	**National Indicator: Total emission reduction of GHG** (%) **Base line (2015):** 0%	**National target (2030):** 20%

3.2.2 The Pillars

The defined pillars in the PEN 2020-2050 are the following:

(i) *Pillar 1 - Safety and reliability of the energy supply:* Ensure that Colombia's energy system improves its ability to meet demand reliably, safely, and efficiently, complying with established quality standards. This includes adequate infrastructure for the supply,

transportation, and distribution of all energy sources. In addition, government policies should foster an attractive business environment for investors, regulate prices that reflect the conditions of a competitive market, and lead to efficient consumption decisions.

(ii) *Pillar 2 - Mitigation and adaptation to climate change:* To present the actions that the energy sector must take to make a significant contribution to mitigating climate change by reducing GHG emissions in accordance with the commitments made in the Paris Agreement and managing the risks associated with climate variability.

(iii) *Pillar 3 - Competitiveness and economic growth:* Incentives for the various market players to integrate the best available technology for the efficient use of energy resources, accompanied by better information for end users about their energy performance and the setting of standards and minimum requirements for EE by public authorities. This pillar is particularly important because it has a direct impact on the competitiveness of the productive sector and the budget of households, which ultimately leads to a significant contribution to the economic growth of the country. In addition, this pillar places a high priority on the circularity of production processes, both in minimizing the use of virgin materials and in the generation of waste.

(iv) *Pillar 4 - Modernization and Innovation:* Promoting a country where innovative solutions and the development of new technologies have a place in the state budget, to support projects and research groups that are able to use the latest technological advances to propose transversal changes that create added value and solve problems of the energy sector and society in general. This pillar also contributes to the country's productivity.

Of the four pillars, the last two will have a direct influence on strengthening the country's EE policy, which is why this study will only focus on the goals and initiatives established for these two pillars.

3.2.3 The Objectives

As control and follow-up mechanism for the pillars, the targets have been established against which their compliance will be evaluated. The targets are evaluated against a set of indicators that have been established according to *Table 5*, where the objectives of the selected pillars are displayed (the numbering of the objectives was kept from the PEN 2020-2050 to be consistent with the document). For the purpose of this work, and because they are most relevant to the subject of the study, objectives 5 and 7 were selected for analysis.

Table 5 Objectives associated with the challenges in EE

Own construction

PILLAR 3	Objective 5	Adopt new technologies for the efficient use of energy resources
	Objective 6	Promote a competitive market environment and the transition to a circular and inclusive economy
PILLAR 4	Objective 7	Advance in the digitization and use of data in the energy sector
	Objective 8	Stimulate research and innovation and strengthen human resource skills

(i) *Objective 5 – Adopt new technologies for the efficient use of the energetic resources:* The modernization of infrastructure, machinery and equipment to produce and efficiently use energy. The emphasis is that efficiency from production to energy consumption itself is not only a strategy to reduce production costs and increase competitiveness, but also has a direct impact on reducing GHG emissions. The indicators proposed for monitoring progress are listed in *Table 6*.

(ii) *Objective 7 - Advance in the digitization and use of data in the energy sector* Enabling digitization and progress in the effective and analytical use of collected data. This is a disruptive process that brings significant changes in the mindset of end users, but leads to automation, cost reduction and optimization of decision making. *Table 7* shows the indicator to be used as a reference.

Table 6 Indicators to measure Objective 5 defined in PEN2020-2050

Objective 5

Own construction

	Tracking Indicator	Baseline 2019	Vision 2050
1	Percentage of useful energy (in relation to total energy consumption).	31%	Potential between 50% and 70%
2	Energy Intensity	2.29 kJ/COP	Potential between 1.08 and 1.32 kJ/COP

Table 7 Indicators to measure Objective 7 defined in PEN2020-2050

Objective 7

Own construction

	Tracking Indicator	Baseline 2019	Vision 2050
1	Percentage of users with a smart meter (AMI)	1.2% - 2.4%	Potential between 90% and 100%

3.2.4 The Initiatives

The PEN 2020-2030 identified a number of technological alternatives that could be used to achieve the set goals. They were classified based on three criteria, as shown in *Figure 21* (zoomed in *Appendix 1*): (i) their technological uncertainty (the rightmost mapped elements have greater uncertainty); (ii) their contribution to climate change mitigation (the topmost mapped elements have greater contribution); and (iii) their implementation challenge (the largest elements have a greater challenge). In addition, the elements framed with an orange line correspond to those for which policy guidance already exists.

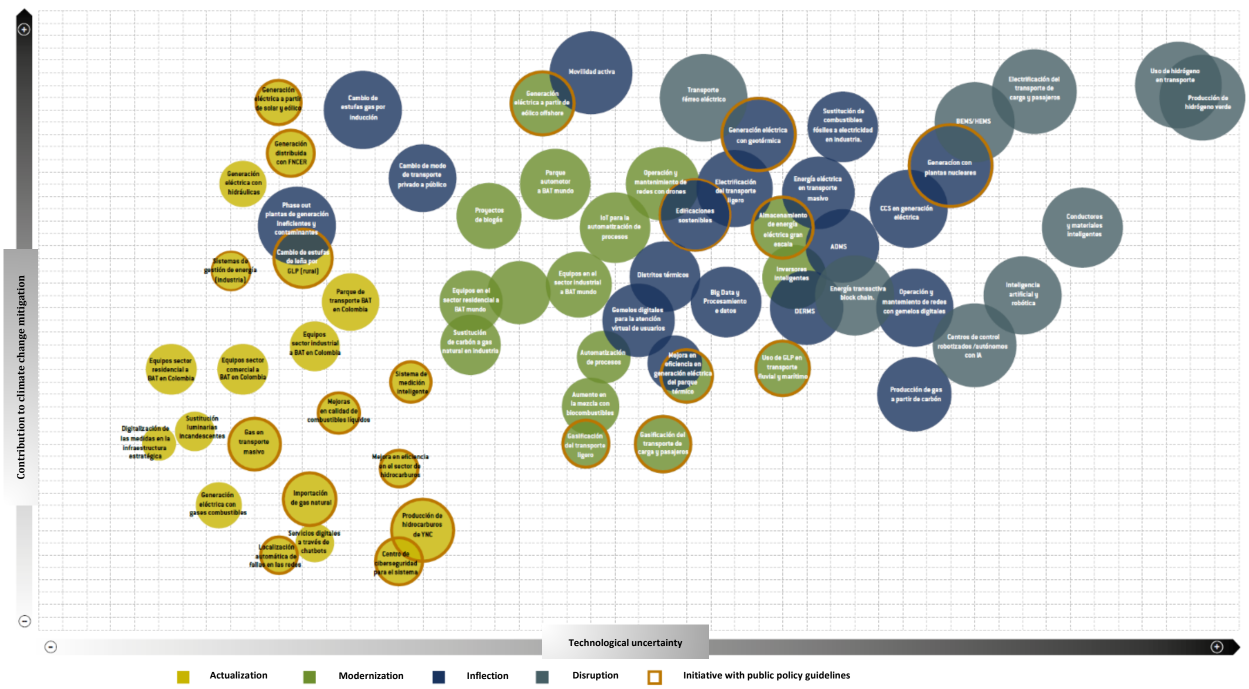


Figure 21 Set of Initiatives proposed in PEN 2020-2050, (Ministry of Mines and Energy et al., 2020)

It is not realistic that all initiatives will be implemented at the same time or that they can all be implemented. Therefore, the initiatives have been grouped into four hypothetical scenarios to be evaluated in the framework of achieving the overall 2050 vision. In *Figure 21*, the initiatives that belong to each scenario are distinguished by the color of the element. The initiatives colored yellow are part of the Update scenario, which aims to align technologies to current global trends. Those colored green belong to the Modernization scenario, which is characterized by an emphasis on gasification as the primary technology to achieve decarbonization of the economy in 2050. The initiatives colored blue are part of the Inflection scenario, which implements the technologies necessary to begin electrifying the economy. The gray initiatives are part of the Disruption scenario, where innovative technologies are the protagonists to achieve carbon neutrality by 2050.

The four scenarios were the strategy designed to play with the different initiatives that form combinations and introduce new technologies into the energy system, to be able to analyze rigorously with strategic and critical thinking the impact of each of them. This will be the compass that will allow decision makers to select the proper instruments to align the market with the overall vision. The initiatives shown in *Figure 21* have been grouped into more compact initiatives that facilitate modeling of each of them at LEAP. The alternative scenarios represent various future transformation configurations that reflect alternative assumptions about policies and technologies. *Table 8* summarizes the profile of each scenario in a comparative way, in order to understand the differences between the four scenarios just considering initiatives involved on the demand side but in a compacted way.

The scenarios were designed after a rigorous analysis of the environment using the SWOT technique to identify strengths, weaknesses, opportunities, and threats related to the plan in each scenario (Ministry of Mines and Energy et al., 2020).

Considering all the variables involved and the several actors and factors that must be included in the analysis, the model was carried out in LEAP, structuring before the whole energy system and assumptions required to model the scenarios the most realistic possible understanding of the uncertainties of the future and applying different “what would happen if” assumptions.

Table 8 Profile of the scenarios proposed in PEN 2020-2050

Own construction

	Update scenario	Modernization scenario	Inflection scenario	Disruption scenario
	Aligned to current trends	**Gasification as driver of carbonization**	**Gradual electrification of the economy**	**Innovation as a driver of carbon neutrality**
Long term GDP	**3.1%**	**3.1%**	**3.5%**	**3.5%**
Demand Side Initiatives	• Adoption BAT Colombia 2050 • Replacement of firewood by GDP in the rural areas • Current vehicle electrification goals • Change of luminaires in the residential sector	• Adoption BAT Colombia 2050 • Gas in mass transportation and industry • Greater participation of electricity in the transport sector	• Adoption BAT Colombia 2040 • Change of gas stoves for induction • Total elimination of the use of firewood for cooking in the rural sector by 2050 • Higher levels of electrification in the industry and transportation sectors	• Adoption BAT Colombia 2030 • Use of low-emission hydrogen in the transport sector • Accelerated renewal of the vehicle fleet with zero and low emission technologies
Contribution to mitigation	●●●○○○○○○○	●●●●○○○○○○	●●●●●●○○○○	●●●●●●●●○○
Technological uncertainty	●●●●○○○○○○	●●●●●○○○○○	●●●●●●●○○○	●●●●●●●●○○
Transformation challenge	●●●●●○○○○○	●●●●●●○○○○	●●●●●●●○○○	●●●●●●●●○○
Technological lock-in risk	High	Medium - High	Medium - Low	Low
Potential environmental risks	Medium - High	Medium	Medium - High	Medium
Skilled Labor Risk	Low	Medium	Medium - High	High

3.3 PEN 2020 - 2050 Structure of the Modeling on LEAP

This section analyzes how PEN 2020 - 2050 was modeled in LEAP, including the structure, considerations, assumptions, and obtained results. Independent variables were used to "drive" the calculations in Demand, Transformation and Resource analyses.

After building the philosophy of the National Energy Plan, with clarity on the global panorama and responsible analysis of the opportunities that the country has to decarbonize the economy from the demand side by 2050, the model is structured in LEAP, trying to achieve an accurate representation of the behavior of the energy system and taking into account the variables that act as drivers, such as population, number of households, socioeconomic level, rural-urban distribution and household size.

First, it is important to describe how the PEN 2020 - 2050 model was constructed at LEAP. The modeling tools allow the system to be defined in terms of a hierarchical outline (Stockholm Environment Institute, 2011), which is used to organize and manipulate the main data structures for analysis. The tree diagram has predefined main branches that can be edited, added or deleted to allow the organization of the power system. *Figure 22* shows the first level of branches from PEN 2020-2050, which consists of the following categories.

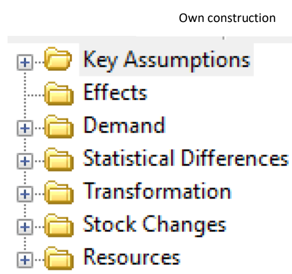
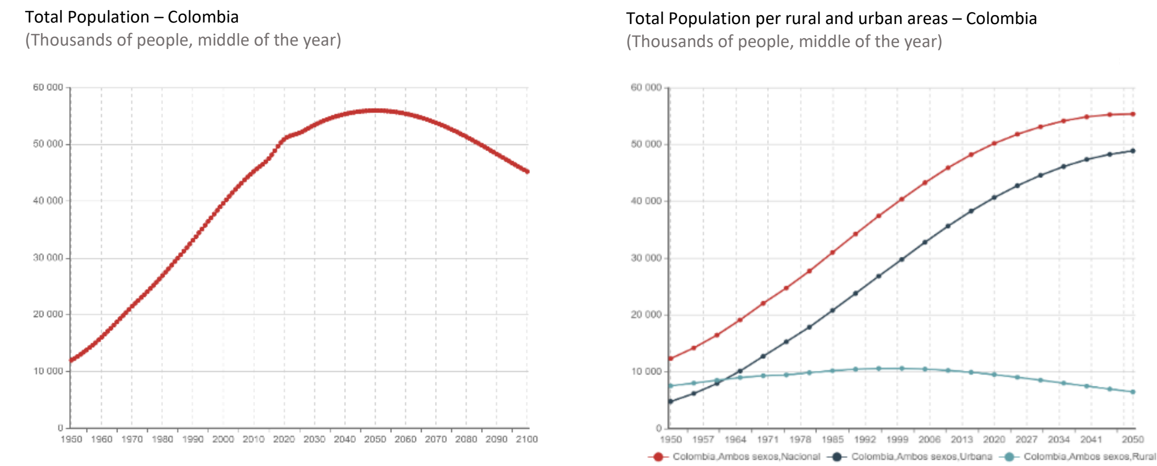


Figure 22 Branches structure overview of PEN 2020-2050 on LEAP, (UPME, 2020a)

(i) *Key assumptions branch:* Under this category, it is included the independent time series variables that drive the calculations for the future scenarios of the demand, transformation, and resource analyses. Basically, the key variables are associated with macroeconomic variables related to GDP, demographics such as population growth and rural-urban distribution, and fuel markets. The key variables in this branch are displayed in *Figure 23*. Regarding the assumption about the population, the projection shows that the maximum number of Colombians would reach 55.9 million, which will gradually decrease to 45.2 million in 2100. This means that between 2050 and 2055 the curve in Colombia will be inverted, with more deaths than births (Cepal, 2022). Those figures reflect that Colombia's population is expected to increase by 11% by 2050 and become more urbanized (Climate Transparency, 2020). The General scheme of this branch is shown in *Figure 24* and *Figure 25*.



(a) Total Population ***(b) Population per rural and urban areas***

Figure 23 Key assumptions branch, (Cepal, 2022)

(ii) *Demand branch:* under this category, the disaggregated structure of energy demand analysis is produced, based on end-use requirements, to model the final energy consumption for each economic sector in accordance with the energy utilized for their uses. The energy demand analysis is the starting point for guiding the integrated energy analysis, as all Transformation and Resource calculations depend on the calculated levels of final demand. *Figure 24* and *Figure 25* show how the sectors are articulated and allow to understand the structure in which each of the subsectors has defined energy uses, the type of energy source to meet demand, and in some cases the technology and emissions data per gas. The demand branch is broken down into different levels of disaggregation. *Figure 24* and *Figure 25* display the general scheme of this branch. The structure consists of Colombia's main economic sectors, including industry, transport, tertiary, and households, each of which is subdivided into different subsectors, end uses, and fuel-using devices. These can range from highly disaggregated end-use oriented structures to highly aggregated to allow overall analyses.

(iii) In the *Transformation branch*, the structure is created to simulate the conversion and transportation of energy forms from the extraction of primary resources and imported fuels to the final fuel consumption. This branch, as well as the other branches shown in *Figure 22*, are not displayed because they are not the focus of this study.

Own construction

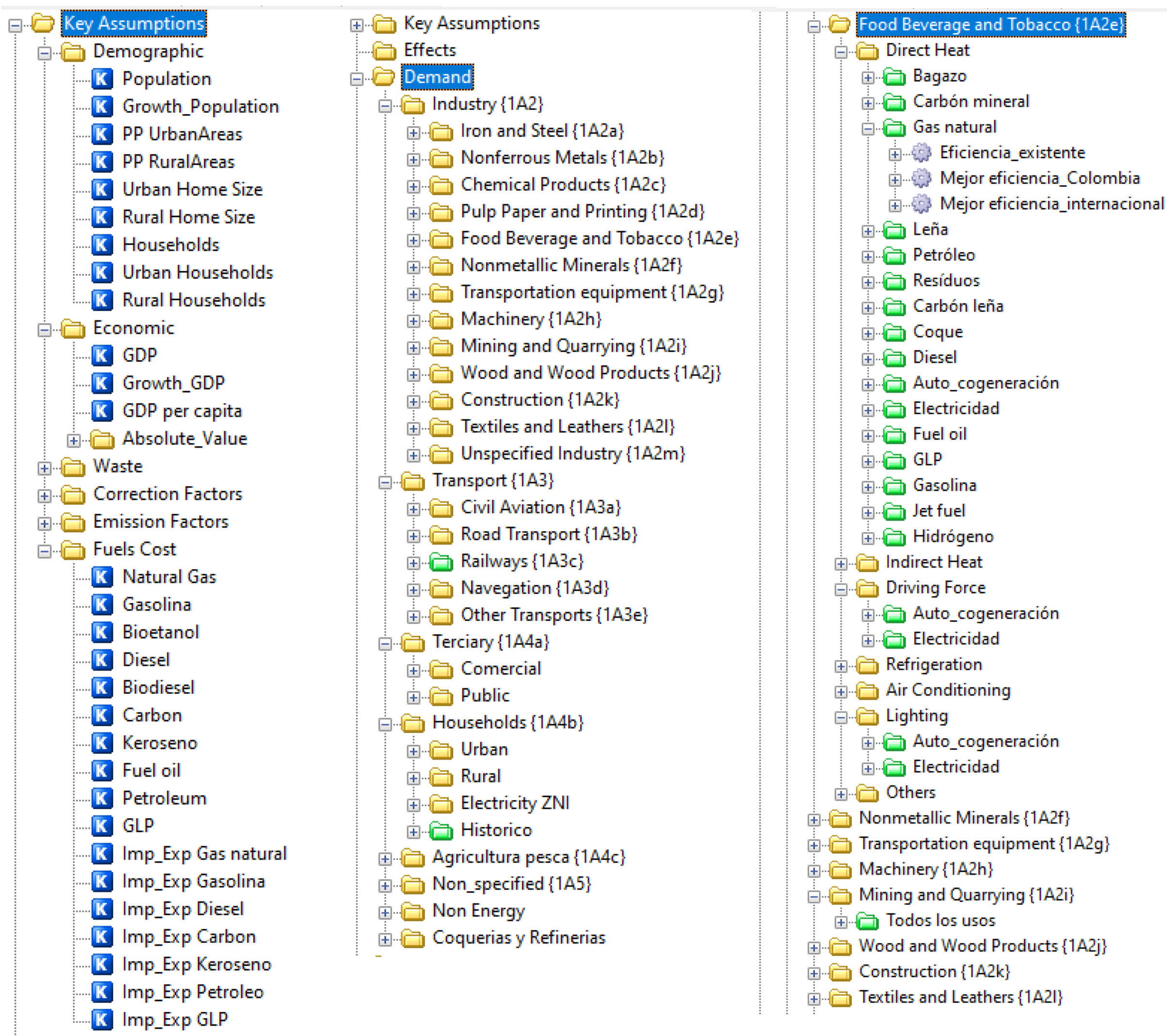


Figure 24 Detailed Branches structure of PEN 2020-2050 on LEAP – Part (a), data source (UPME, 2020a)

Own construction

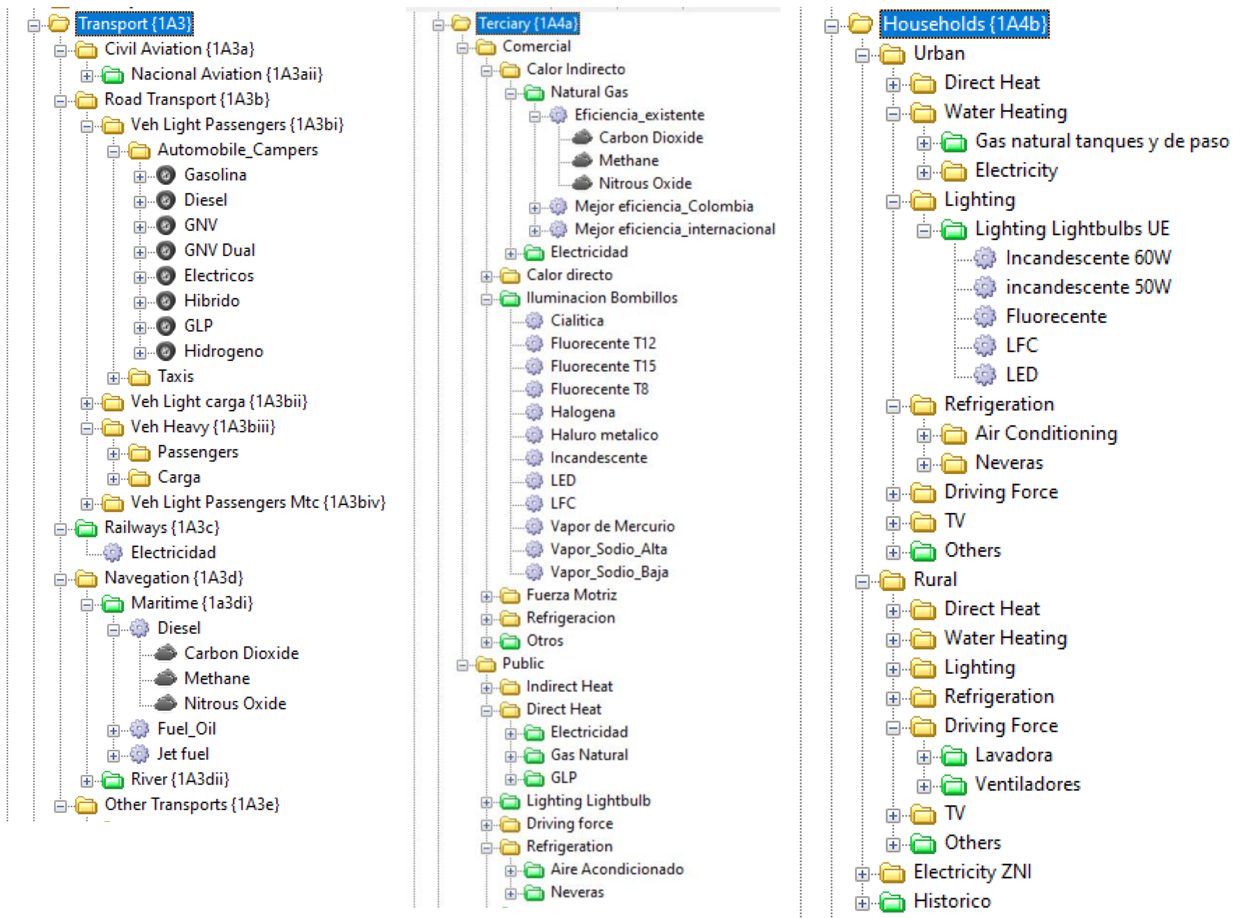


Figure 25 Detailed Branches structure of PEN 2020-2050 on LEAP – Part (b), data source (UPME, 2020a)

Applying economic, demographic and energy-use historic and projected information, PEN 2020-2050 examined how total and disaggregated energy consumption evolve over time in all sectors of the economy; also the costs and environmental implications of each scenario. The results obtained with the simulation and presented in PEN 2020-2050 are divided into three broad categories: Energy, Environment, and Economy.

3.3.1 Energy Outcomes

This category is divided into energy consumption, use of fuels per consumption sector, and primary energy supply composition. The last category is not considered for the purpose of this study due to the magnitude of the analysis and due to time limitations.

(i) *Energy consumption:* It was found, as expected, that in all scenarios energy consumption increases as a result of population growth and economic activity of the country. However, energy intensity decreases due to the inclusion of EE measures. Those trends are displayed in *Figure 26* comparatively with the four scenarios presented in section *3.1.4.* and illustrated in *Table 8*. In addition, it is presented in *Figure 27* how energy consumption varies by economic sector and scenario. In such a figure, it is noted that the energy consumption does not present any difference between the "Modernization" and "Inflection" scenarios, but it should not be forgotten, from *Table 8*, that the Inflection scenario considers a higher GDP, which means that its energy intensity is lower.

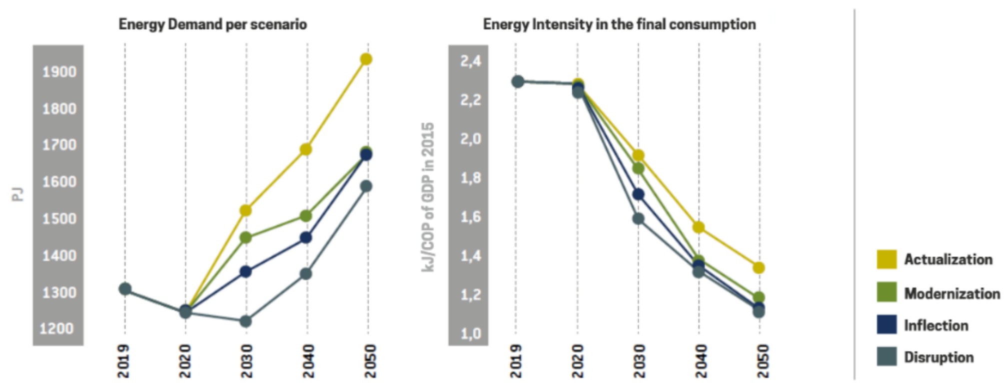


Figure 26 Energy demand Vs Energy intensity per scenario, (Ministry of Mines and Energy et al., 2020)

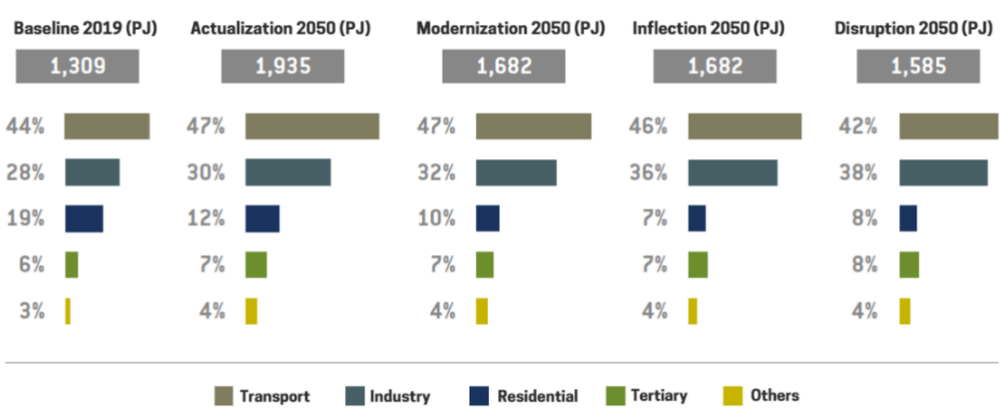


Figure 27 Energy consumption per sector per scenario, (Ministry of Mines and Energy et al., 2020)

(ii) *Fuels per consumption sector:* In the industrial sector, the Updating and Modernization scenarios envision larger amounts of natural gas, while the Inflection and Disruption scenarios focus on electrification of direct heat use. The Disruption scenario also relies on coal substitution in the industrial sector. *Figure 28* provides a general overview of how the different fuels will be used from 2019 to 2030 and 2050, depending on the scenario for the *(a)* transport, *(b)* industry, and *(c)* household sectors (Ministry of Mines and Energy et al., 2020). In the case of Industry, natural gas plays a larger role in the modernization and inflection scenarios, while hydrogen is only considered in the Disruption scenario, making natural gas and fossil fuels less representative; electricity gains share in all scenarios, with the highest share in the disruption; it is also observed that coal does not play a role in the power generation matrix. From another angle, the transport sector shows an evident increase in the use of natural gas by 2050 in all scenarios, even larger than the electrification share in all scenarios. The use of hydrogen in this sector is only considered in the disruptive scenario with a relevant share in 2050. In contrast, the household sector increases the electrification share in Inflection and Disruptive scenarios, almost doubling the percentage by 2050.

On the other hand, the household sector promotes higher penetration of natural gas and substitution of wood by GLP in the updating and modernization scenarios, while the replacement of induction stoves is the basis for the inflection and disruption scenarios.

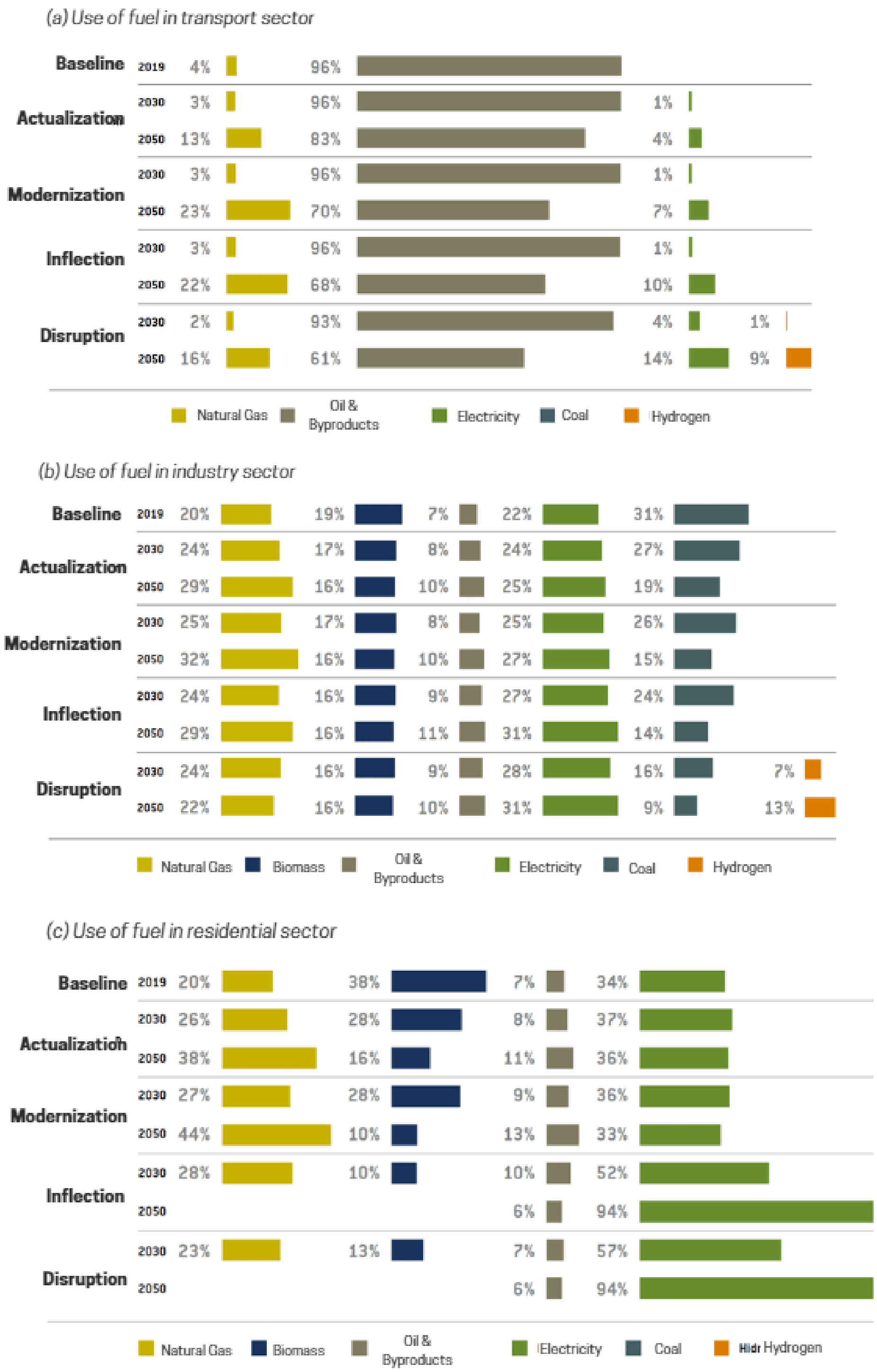


Figure 28 Use of fuels per consumption sector 2019, 2030, 2050, (Ministry of Mines and Energy et al., 2020)

3.3.2 Environmental Outcomes

Looking only at the GHG emissions associated with the demand side in *Figure 29*, the transport sector is the main emitter of GHG in all scenarios, as expected. In the Disruption scenario, emissions will peak before the end of the decade, due to the accelerated penetration of electric vehicles and the introduction of hydrogen technology starting in 2030. In the Modernization scenario, industry-generated GHG emissions begin to decline as international BAT adoption accelerates. In the Inflexion and Disruption scenarios, GHG emissions from the household sector decline significantly from 2030 and reached near zero by 2050, driven by improvements in cooking energy efficiency (Ministry of Mines and Energy et al., 2020).

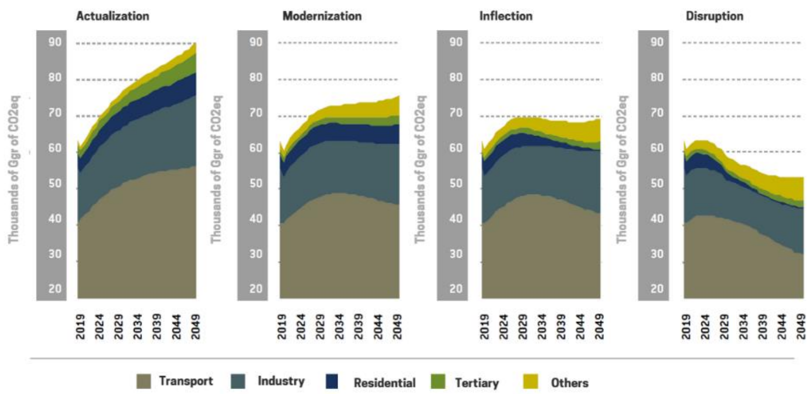


Figure 29 GHG emissions per consumption sector (Ministry of Mines and Energy et al., 2020),

3.3.3 Economic Results

With the adoption of the BAT to boost energy efficiency and the consequent reduction of energy losses in end-use equipment, a reduction in costs in the consumption sectors will be achieved. Nevertheless, the net present value (NPV) of the investment is high and implies a higher financial cost as is represented in *Figure 30.* The cost associated with the modernization and inflection scenarios could be similar in magnitude measure even though, the inflection scenarios can reach more significant results in the national decarbonizing goal.

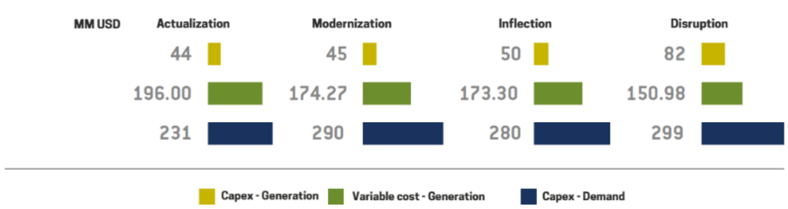


Figure 30 NPV of the total cost of each scenario, (Ministry of Mines and Energy et al., 2020)

Chapter 4
Evaluation of Alternative Scenarios focused on the Demand Side

4.1 Modeling of the "*Alternative Scenario*" on LEAP

To test the model's sensitivity to certain variables and policies, a new scenario was created at LEAP based on the original from PEN 2020-2050 with its four scenarios (Actualization, Modernization, Inflection and Disruption), whose original model can be obtained in the UPME website (UPME, 2020b). The new scenario, shown in *Figure 31*, was named "Alternative" and inherits the data and assumptions of the Inflection scenario, which was selected because it is considered ambitious but remains achievable with a lower level of technological uncertainty (compared to the Disruptive scenario). In addition, micro-scenarios were created to provide the option of grouping the changes and evaluating the modified Inflection scenario with some of the changes or with all of them.

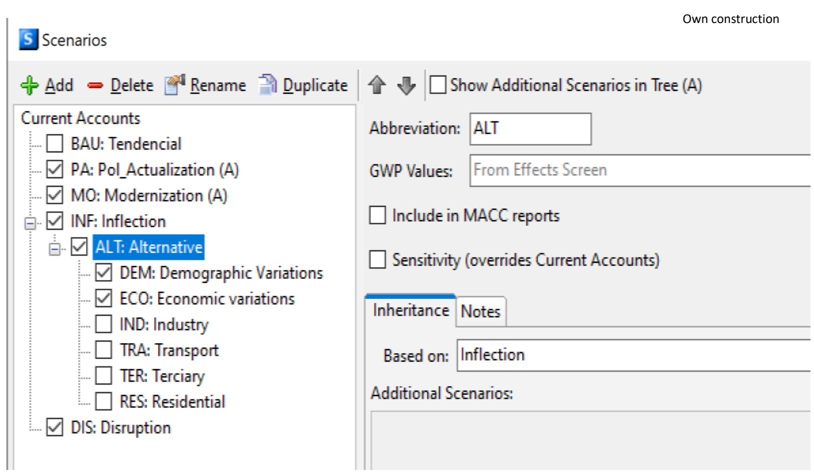


Figure 31 Proposed scenario to make variation to the model on LEAP

This new simulation is not intended to propose new policies or initiatives that differ from those in the original model PEN 2020-2050. This would require a rigorous scope of work for future work. On this occasion, some changes are proposed with the sole purpose of validating their impact on the model and thereby identifying sensitivities. The methodology process to estimate energy demand proposed by Angel Gonzalez Salazar et al. (2014), presented in *Figure 32*, is going to be applied to identify the primary actors in inefficiency in the main sector of the economy in order to be taken into consideration in the Alternative scenario.

Own construction

Figure 32 Methodology to assess energy demand, (Ministry of Mines and Energy et al., 2020)

4.2 Demographic Variables

The data for the years 2020 and 2021 have been updated with the official population data, nevertheless, the growth rate projected for the following years until 2050 is maintained. It is evident that the growth in 2020 and 2021 was slightly lower than expected, but this does not mean significant changes as observed in *Figure 33.*

Own construction

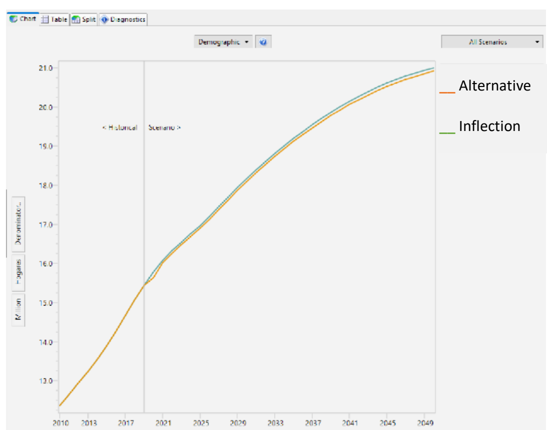
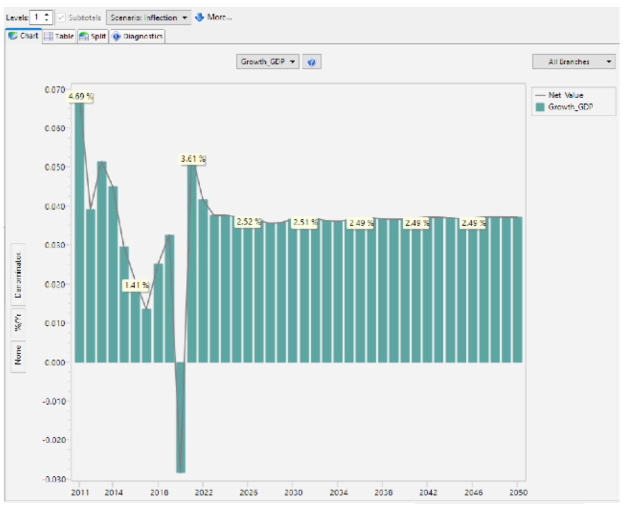


Figure 33 Demographic Variation 2020-2050 - Inflection Vs Alternative, data source (UPME, 2020a)

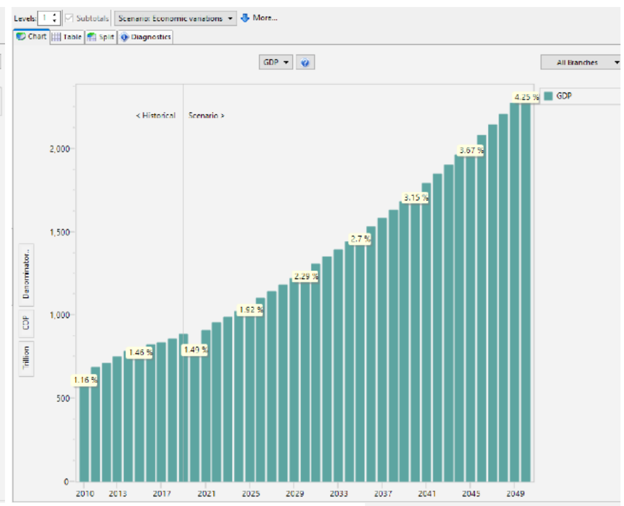
4.3 Economic Variables

Gross Domestic Product GDP: The main microeconomic variable GDP of this set is modified. The data for this variable inherited (from the inflection scenario) to the Alternative scenario, corresponded to an optimistic projection, which was then modified by a conservative projection. The data considered for that alteration was also available in the supporting documents of PEN 2020-2050 on the UPME website (UPME, 2020b) with figures calculated annually for the entire 2020-20250 assessment period. In the same way, the growth rate was modified. The data for these variables for the years 2020 and 2021 was updated with official information registered for those years (The World Bank, 2021), updating the projection for 2022 and 2023 (OECD, 2022) and the rest of the years are left with the conservative forecast Considering that this is one of the main components for calculating energy intensity, this change has led to a reduction in total energy consumption, the total amount of GHG emitted, and consequently energy intensity and carbon intensity. Variations are illustrated in *Figure 34,* where “Inflection” conditions are always indicated on the left and “Alternative” conditions on the right.

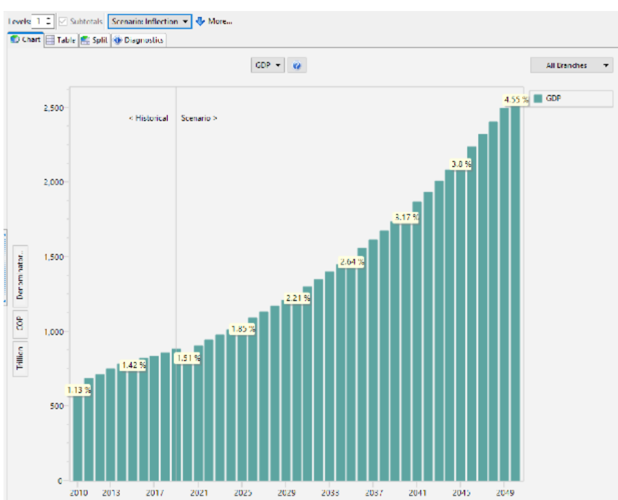
Own construction



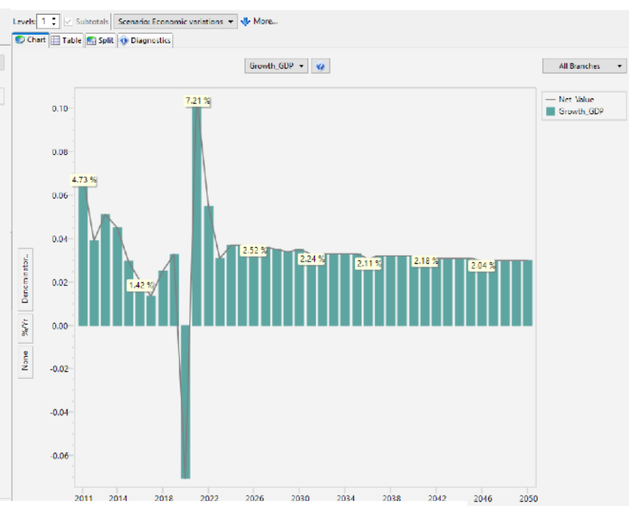
(a) GDP assumed in “Inflection”



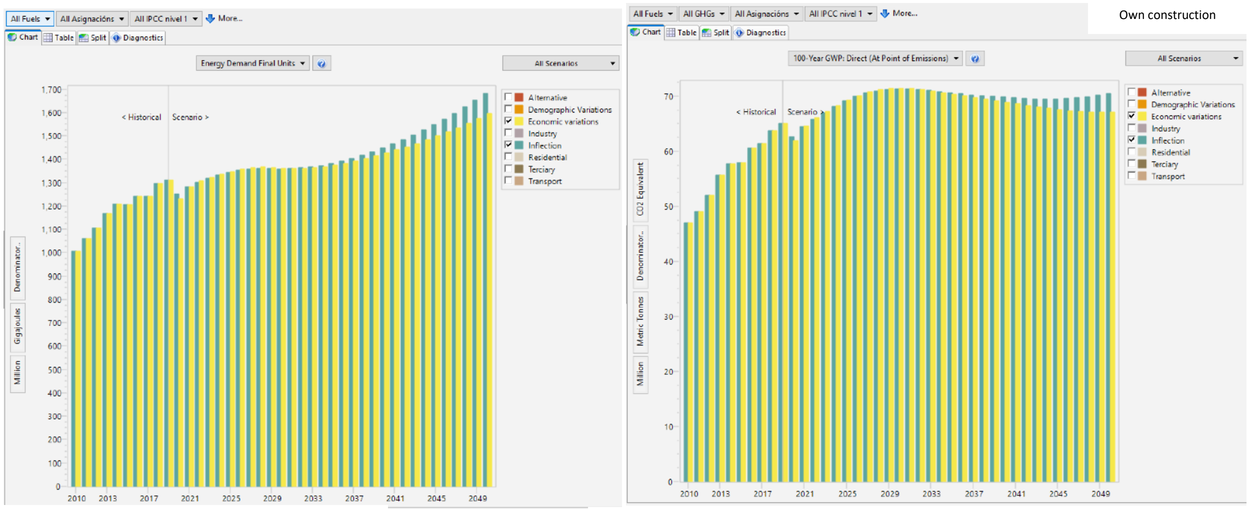
(b) GDP assumed in “Alternative”



(c) GDP Growth assumed in “Inflection”



(d) GDP Growth assumed in “Alternative”



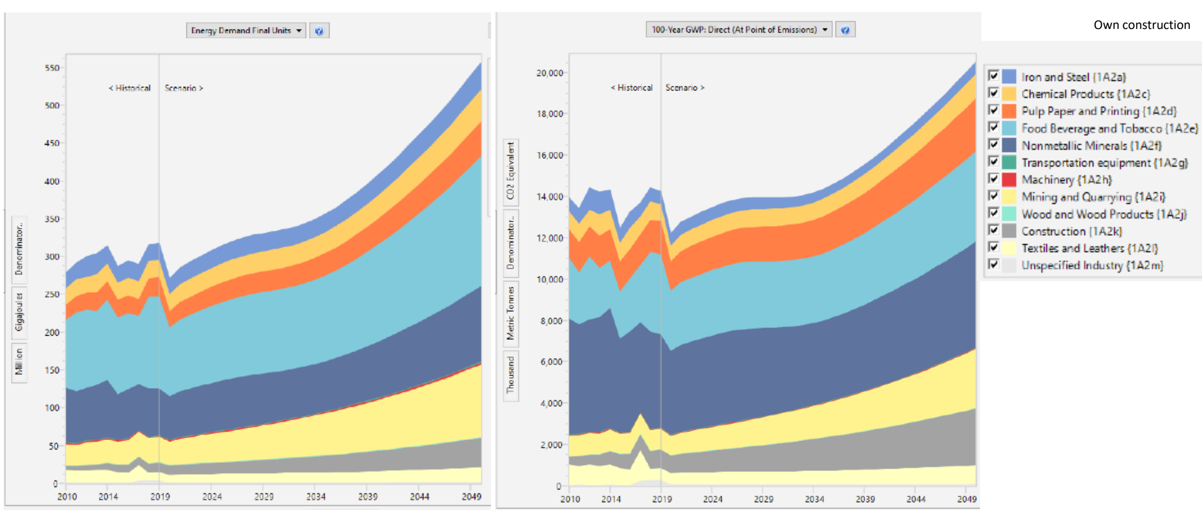
(e) Final energy Demand Inflection Vs

(f) Final GHG Emissions Inflection Vs

Figure 34 Effect of the GDP variation on Energy Demand and GHG emissions, data source (UPME, 2020a)

4.4 Industry Sector Variables

According to Pen 2020-2050 – LEAP Model, 67% of the energy demand of the industrial sector is concentrated in “Food and beverage”, “non-metallic Minerals”, and “Mining and quarrying”, being also the most pollutants in the sector, as it could be observed in *Figure 35*. One of the main challenges for those industries is the optimization of thermal processes, as they account for 88% of the energy consumed in the sector. The introduction of better technologies to replace the current boilers and furnaces would mean a 20% improvement in efficiency (Ministry of mines and energy & Mining-Energy Planning Unit, 2021).



(a) Energy Demand (GJ)

(b) GHG emissions (Mt $CO_{2\ eq}$)

Figure 35 Industry 2020-2050 by sub-sector, data source (UPME, 2020a)

In the case of the "Alternative" scenario, all the energy intensity figures in all subsectors were modified, in order to identify at the end with all the changes done, how much improvements in the total energy demand and total GHG emissions could be achieved. *Figure 36* illustrates the variations made in energy intensity in the three main industries, on the right the graphs resulted from the Inflection scenario and on the right, the graphs resulted from the Alternative scenario. As it could be noticed, the energy intensity dropped off to the minimum level reached in the last 15 years in those industries.

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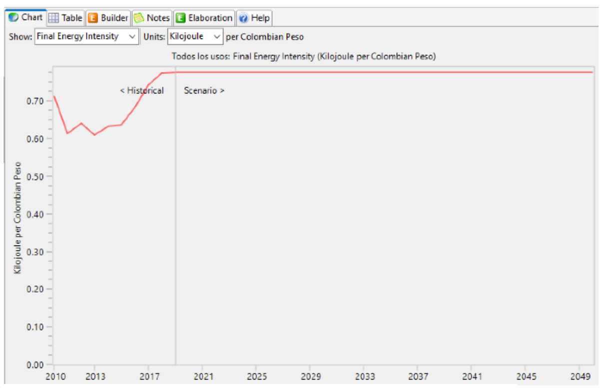
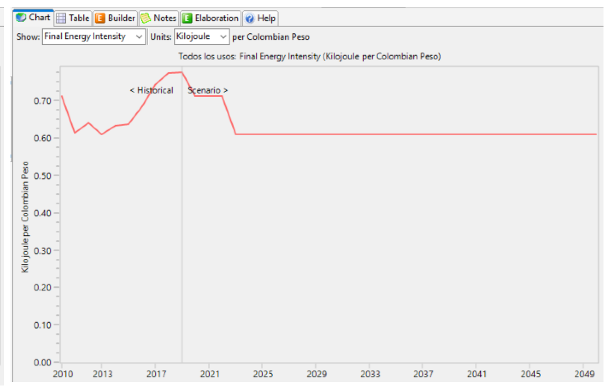
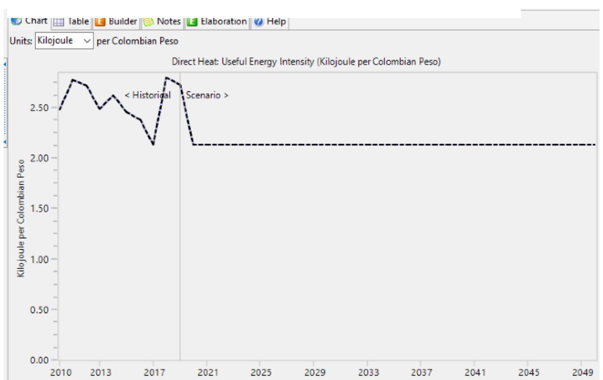


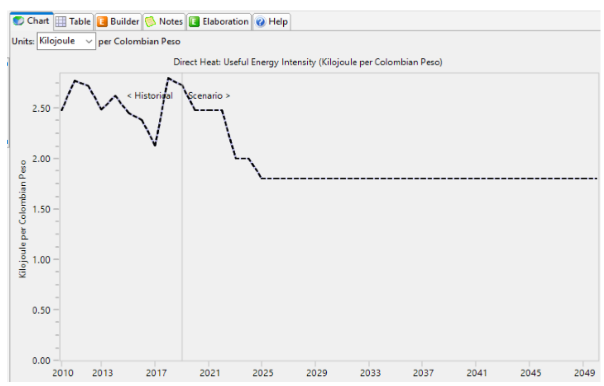
(a) Energy Intensity – Mining and Quarrying industry - Inflection



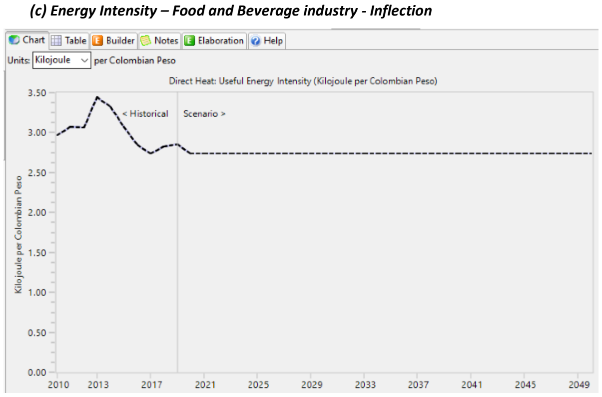
(b) Energy Intensity – Mining and Quarrying industry - Alternative



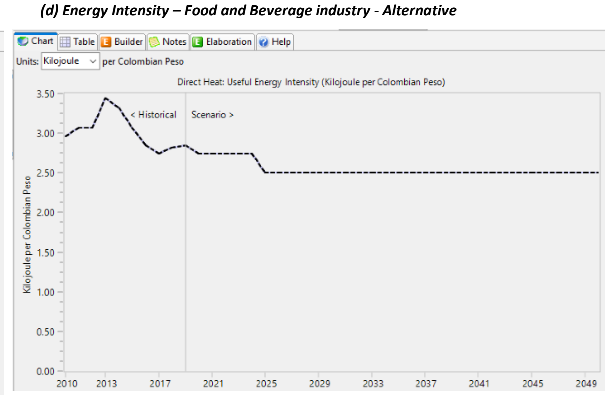
(c) Energy Intensity – Food and Beverage industry - Inflection



(d) Energy Intensity – Food and Beverage industry - Alternative



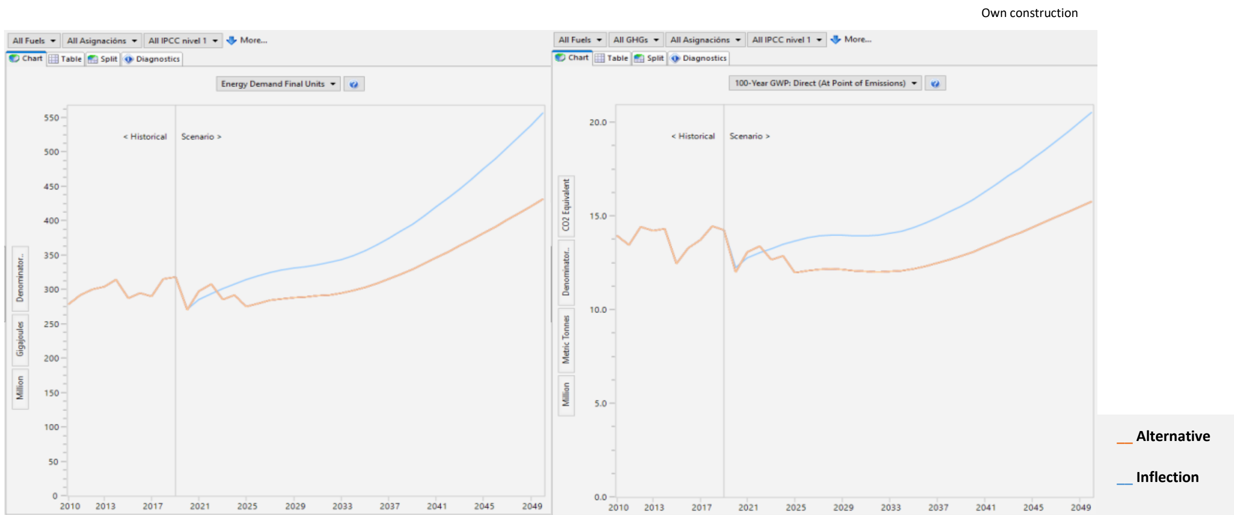
(e) Energy Intensity – Pulp paper and Printing - Inflection



(f) Energy Intensity – Pulp paper and Printing - Alternative

Figure 36 Energy intensity levels in main Industries 2020-2050, data source (UPME, 2020a)

As a result of the modeling, it was noticed that the alterations made in the energy intensity variable would represent a decrease of 18% in the final Energy Demand of the sector by 2050 (*Figure 37a*), resulting in a reduction of 25% of GHG emissions generated by the industries (*Figure 37b*).



(a) Energy Demand (GJ) ***(b) GHG emissions (Mt $CO_{2\,eq}$)***

Figure 37 Industry sector 2020-2050 - Inflection Vs Alternative, data source (UPME, 2020a)

4.5 Transport Sector Variables

According to the Colombian Energy Balance (BECO), the transport sector accounts for the highest share of the country's final energy consumption, at around 40% (Ministry of environment and sustainable development et al., 2019). Road transport accounts for the largest share of energy consumption at 88%, of which 36% is freight transport, 34% is passenger transport, 16% is vehicles and vans, and 14% is motorcycles. The most representative uses are interurban passenger transport with 27%, private urban passenger transport with 22%, and interurban freight transport with 16%. Ferry transport, on the other hand, accounts for 10%, while rail, river, and sea transport account, each, for less than 1% (National Planning Department et al., 2019).

It is expected that by 2028, the number of zero- and low-emission vehicles in the Colombian fleet will increase to 2.85%; similarly, 100% of mass transportation systems in operation will be equipped with electric and natural gas vehicles; and the number of diesel vehicles will increase by 22% (complying with the Euro VI emission standard) (National Energy Department et al., 2022a).

(i) *Urban passenger massive transport:* It is proposed the acceleration of electrification from 2037, and reach 2% more share at the end. The remaining vehicles correspond to those bought during this decade. This variation is represented in *Figure 38*, showing on the right the base of the inflection scenario and on the left the alternative variation, in order to analyze at the end "what would happen if" this change is achieved.

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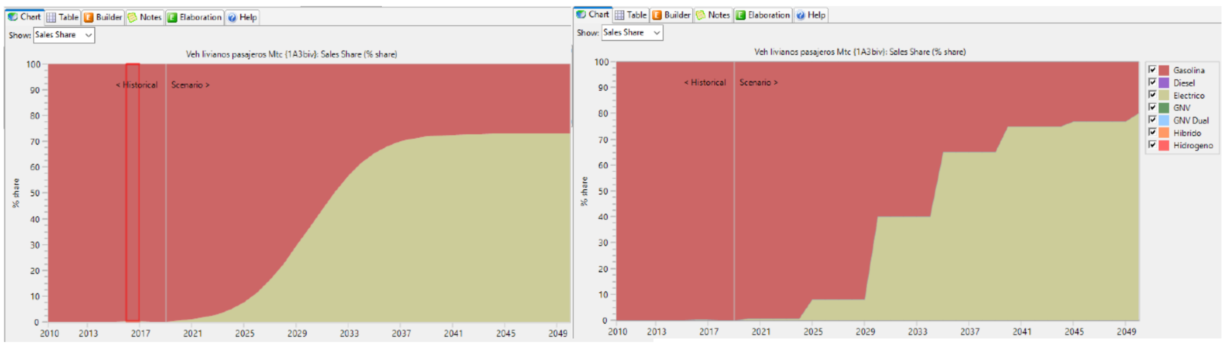

(a) Inflection ***(b) Alternative***

Figure 38 Electrification of urban passenger transport (%) 2020-2050, source (UPME, 2020a)

(ii) *Private urban passenger transport:* The alternative scenario includes also a slight acceleration of the penetration of electric vehicles as observed in *Figure 39*.

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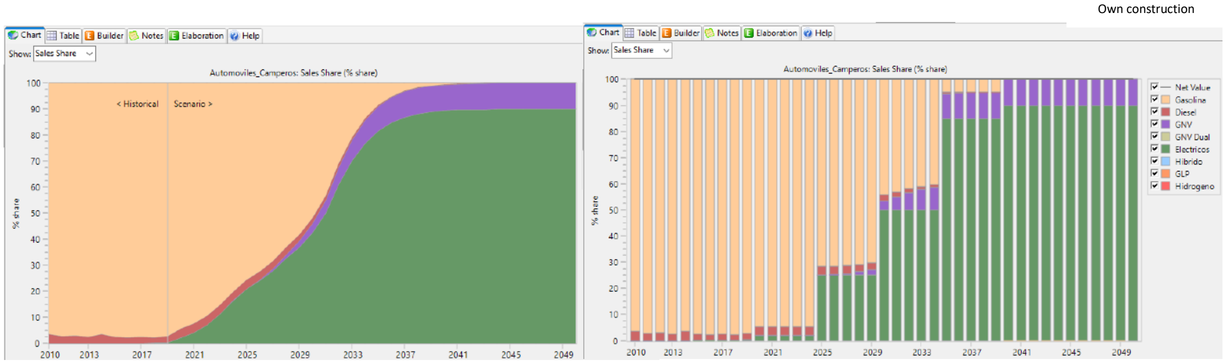

(a) Inflection ***(b) Alternative***

Figure 39 Electrification Private urban passenger Transport 2020-2050, data source (UPME, 2020a)

(iii) *Aviation, navigation and railways:* In the Alternative scenario, *all graphs* on the left, the energy intensity level is dropped off, as illustrated in *Figure 40*, in order to identify how much this variation could impact in the whole scenario.

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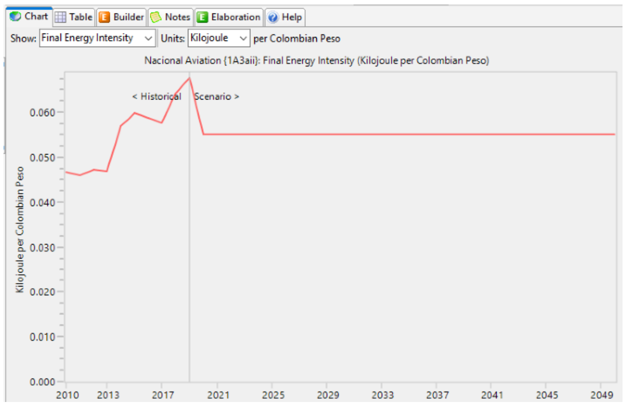
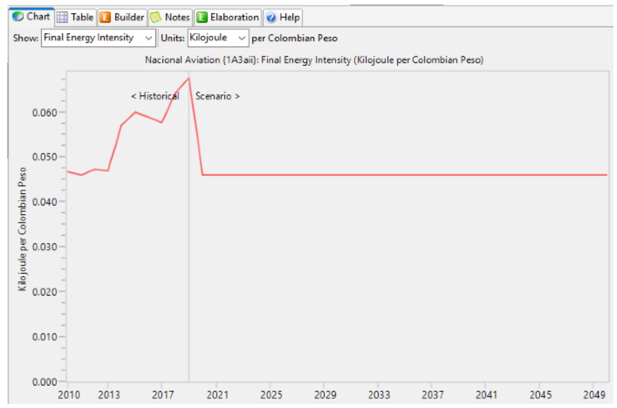
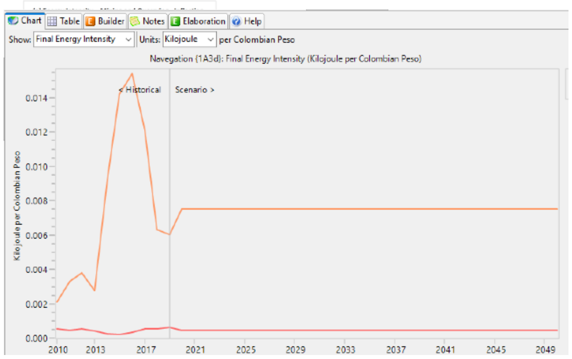


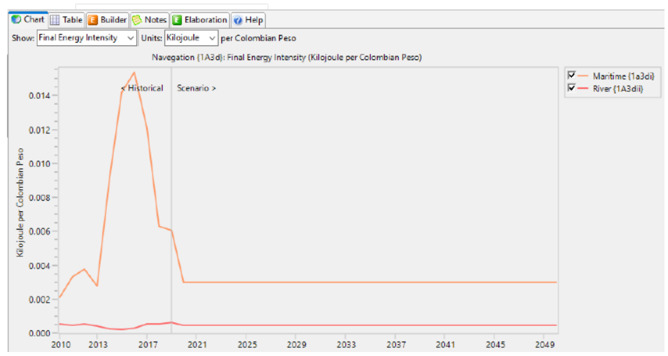
(a) Energy Intensity – Aviation sector - Inflection



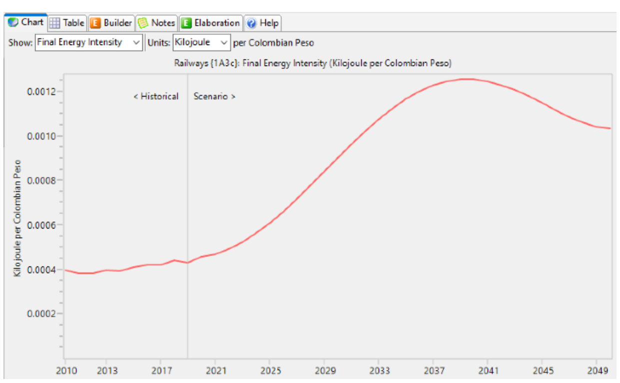
(b) Energy Intensity – Aviation sector - Alternative



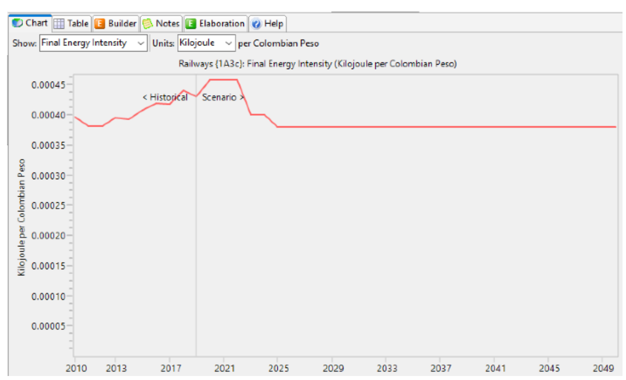
(c) Energy Intensity – Navigation sector - Inflection



(d) Energy Intensity – Navigation sector - Alternative



(e) Energy Intensity – Railway sector - Inflection



(f) Energy Intensity – Railway sector - Alternative

Figure 40 Energy intensity of Aviation, Navigation, and Railway sectors 2020-2050, data source (UPME, 2020a)

If those Energy efficiency levels were achieved, it would result in 7% less final energy demand and 8% less GHG emission to the environment caused by the transport sector as shown in *Figure 41*.

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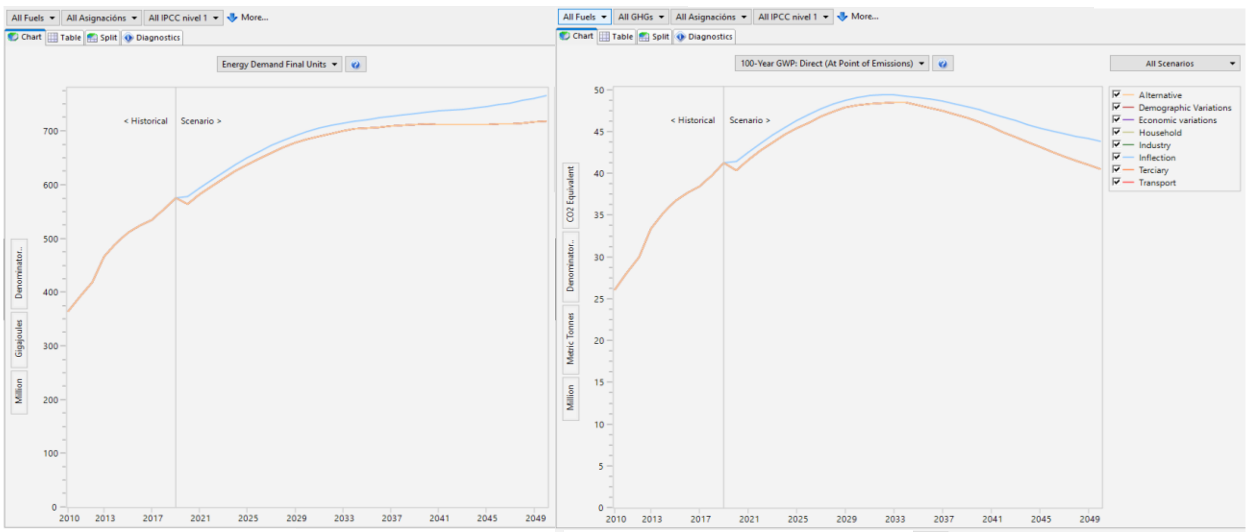

(a)* Energy Demand (GJ)** ***(b) GHG emissions (Mt $CO_{2\ eq}$)

Figure 41 Transport sector 2020-2050 – Inflection Vs Alternative, data source (UPME, 2020a)

4.6 Household Sector Variable

In the household sector, there are two key elements: the use of firewood in the rural sector, which requires increasing efforts to eliminate its consumption before 2040; and appliances used for refrigeration that does not accomplish energy efficiency standards.

(i) *Use of firewood in rural areas:* Currently, 10.74% of households in Colombia cook with firewood and other solid fuels. This situation causes high health costs that exceed USD 200 million due to exposing the population to particulate matter (National Planning Department et al., 2018). Considering this fact, the Alternative scenario simulates a faster decrease in the use of firewood in rural areas (*Figure 42*), even though this change is expected to not have a significant impact on the whole panorama, given that the rural population is also projected to decrease in the coming decades.

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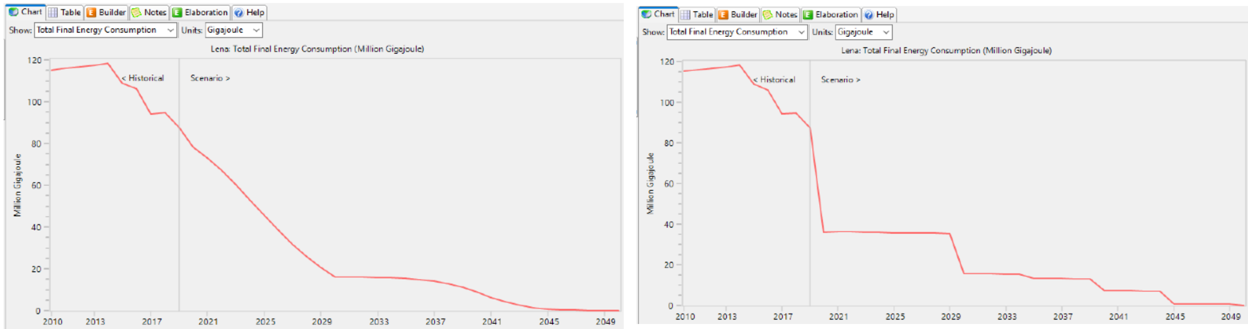

(a) Inflection ***(b) Alternative***

Figure 42 Use of firewood (%) in rural areas 2020 - 2050, data source (UPME, 2020a)

(ii) *Refrigeration Appliances in urban and rural areas:* According to the energy characterization studies carried out by UPME in the household sector, The majority of household refrigerators in Colombia are energy inefficient. Depending on the thermal floor in which the appliance operates, refrigerator energy consumption can account for between 40% and 60% of the total bill. It is estimated that 45% of refrigerators in the country do not have optimal energy consumption (category A and B) and have an average life of 5 years (National Energy Department et al., 2022a). It has been found that replacing an inefficient refrigerator with an energy-efficient appliance (category "A") can reduce the electricity consumption of that appliance by up to 67%, which represents a significant economic benefit to end-user, as they perceive a savings of 20-30% on their energy bill (OECD, 2022). Considering this fact, the Alternative scenario simulates the acceleration of substitution of refrigerators from 2025, reaching 100%

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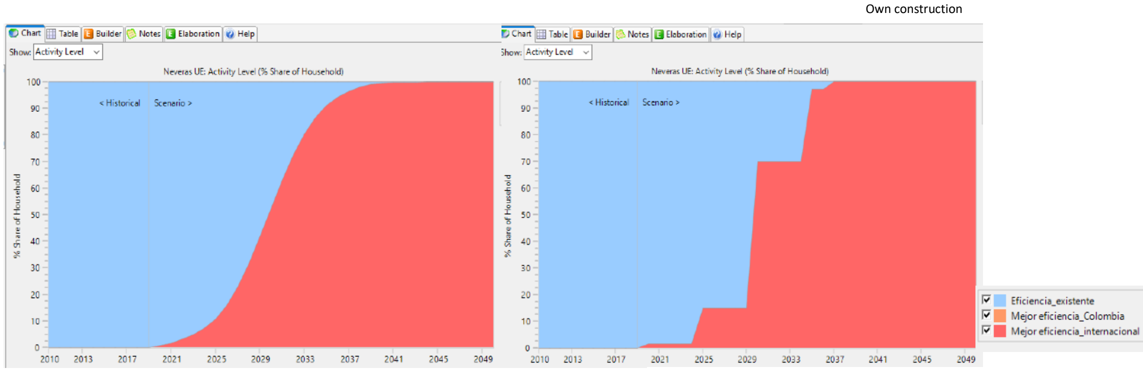

(a) Inflection ***(b) Alternative***

Figure 43 Substitution Refrigeration appliances (%) - Urban areas (international BAT), data source (UPME, 2020a) two years earlier than in the Inflection scenario as it is illustrated in *Figure 43* for urban areas and in *Figure 44* for rural areas. The difference between both is insignificant.

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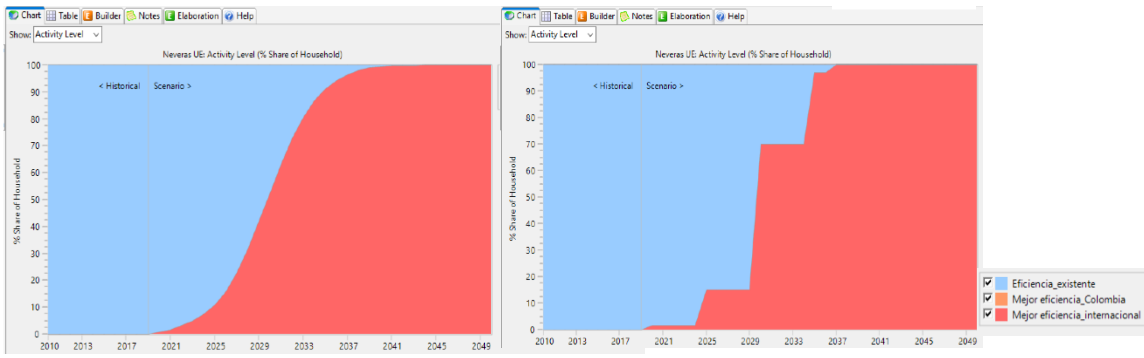

(a) Inflection ***(b) Alternative***

Figure 44 Substitution of refrigeration appliances (%) in Rural areas (international BAT), data source (UPME, 2020a)

As a result of the variations (i) and (ii) in the household sectors, the resultant graphs on LEAP to compare the Alternative with the Inflection scenario are shown in *Figure 45*.

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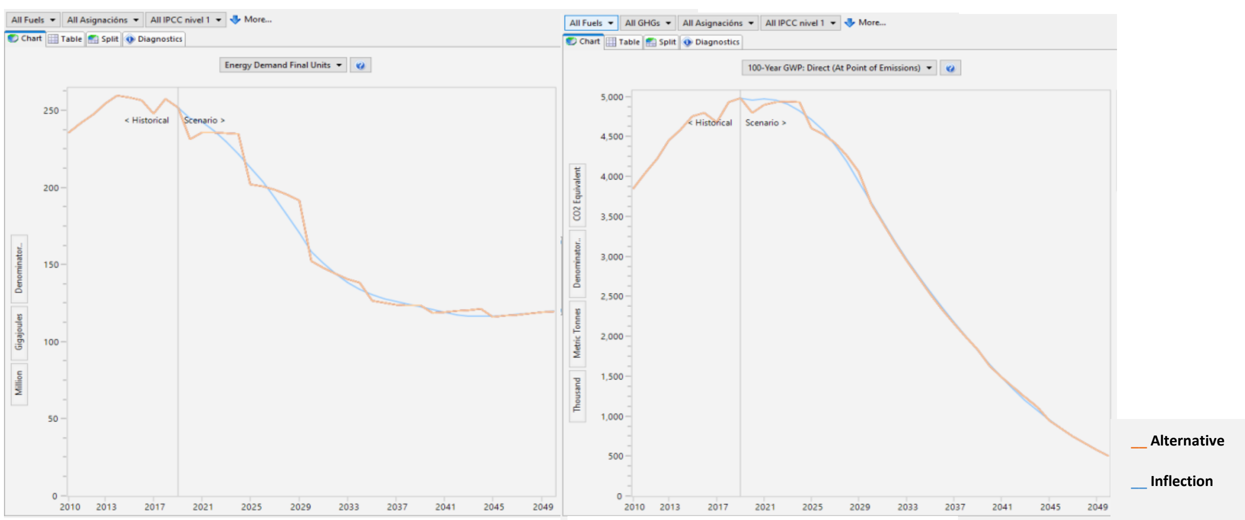


(a) Energy Demand (GJ) ***(b) GHG emissions (Mt $CO_{2\,Eq}$)***

Figure 45 Household sector 2020-2050 – Inflection Vs Alternative, data source (UPME, 2020a)

Running those changes on the model, it was noticed that they did not have a significant impact on the end result of the energy demand figures and the amount of GHG emissions (*Figure 45*). However, the use of firewood is not just a matter of energy consumption and energy efficiency, but also it is a matter of health issues and forest degradation. Even when those last factors are not considered in the PEN 2020-2050 LEAP model, they should not be ignored.

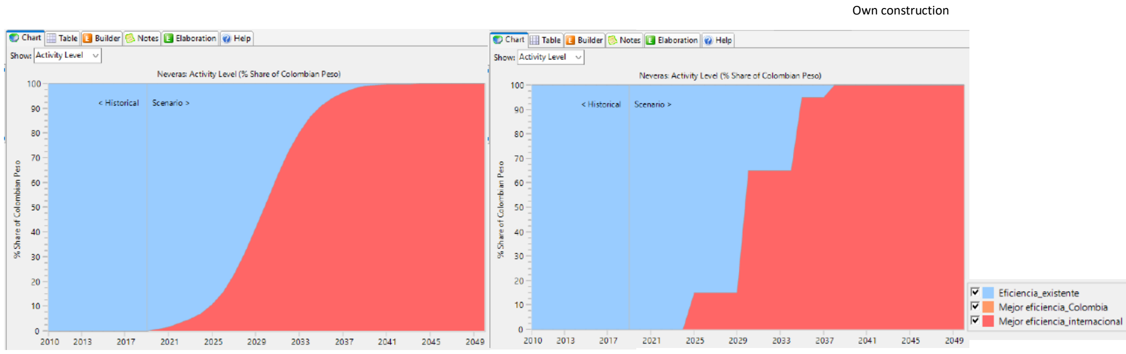
In parallel, the NDC update (Colombian Government, 2020) proposed to strengthen the conversion of national refrigerator production lines, launch environmentally friendly refrigerators, establish a national household refrigerator replacement program, and promote refrigerator disposal.

4.7 Tertirary Sector Variables

This sector is formed basically by two actors: Commercial and Public. The first one has had a better performance in terms of incorporation of BAT for their operation. Meanwhile, the public sector requires high investments to implement measures for efficient energy management. Public administrative, health and educational buildings have an electrical energy demand of about 2,264 GWh/year, but the facilities, equipment and appliances used by public entities are very inefficient and some have exceeded their useful life, resulting in higher-than-average energy consumption, considering national and international BAT. On the other hand, the country is lagging behind in the introduction of thermal districts (centralized and demand-controlled air conditioning systems). These are more efficient than the thermal air conditioners currently used and become relevant when considering that air conditioning in buildings is one of the main sources of energy consumption in Colombia (National Energy Department et al., 2022a)

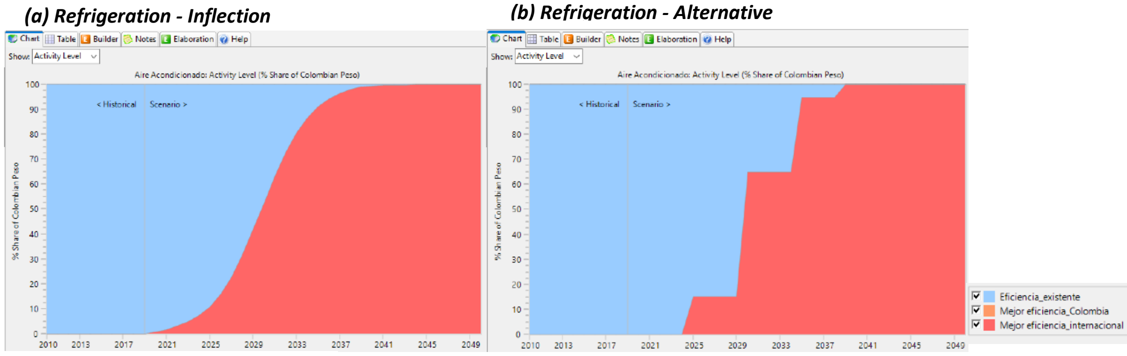
The alternative scenario varied the activity level of air conditioning and refrigeration of the tertiary sector accelerating the implementation of international BAT and trying to identify the impact of reducing energy consumption in those two activities. Changes are shown in *Figure 46.*

If the acceleration of international BAT were viable in the coming years, it would represent a decrease of 12% in the final energy demand and as a result, 12% less GHG emissions accounted for by this sector, as observed in *Figure 47*.



(a) Refrigeration - Inflection

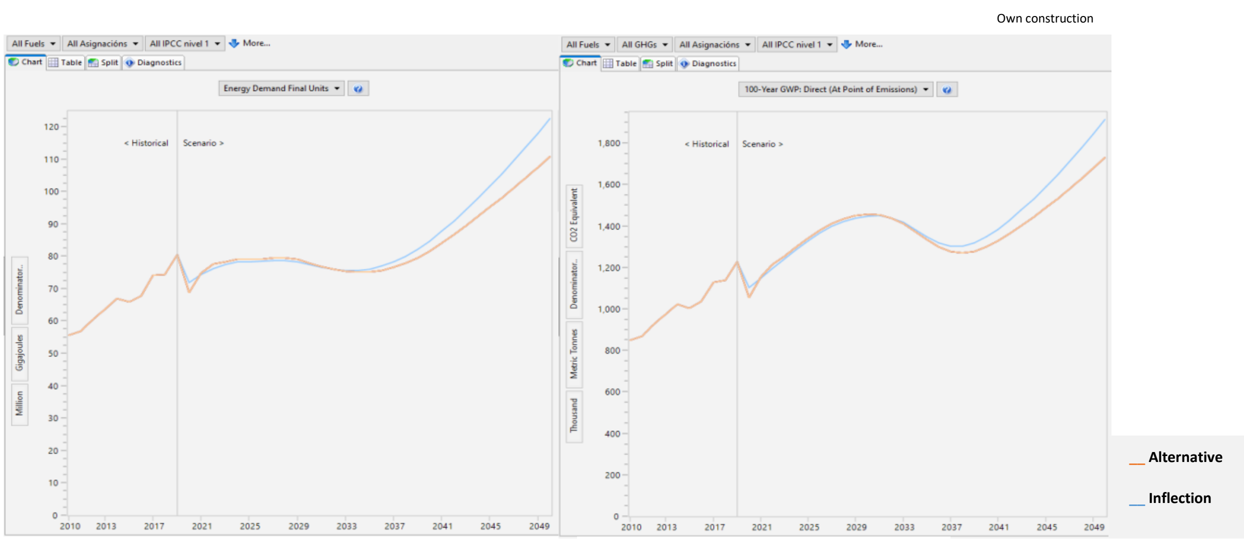
(b) Refrigeration - Alternative



(c) Air Conditioning - Inflection

(d) Air Conditioning - Alternative

Figure 46 Activity Level (%) - Refrigeration and Air conditioning - BAU and BAT in the Tertiary sector, data source (UPME, 2020a)



(a) Energy Demand (GJ)

(b) GHG emissions (Mt $CO_{2\ eq}$)

Figure 47 Tertiary sector 2020-2050 – Inflection Vs Alternative, data source (UPME, 2020a)

As one of the most important measures to achieve greater energy efficiency in the sector, the NDC update proposes the promotion of thermal districts for the replacement of cooling systems in cities, allowing energy savings through the replacement of old and inefficient air conditioning systems, the centralization of the generation and distribution of thermal energy (heating/cooling), the use of residual energy, renewable energy or from directly available thermal sources, among others. According to the NDC update (Colombian Government, 2020), the country should support these initiatives to increase the number of thermal districts in different cities of the country.

4.8 Overview of Demand-Side Results with the Alternative Scenario

Bringing together the alterations made in each of the main economic sectors, the overview of the demand-side is that energy consumption could be reduced by 11% which is linked with a reduction of 14% in GHG emissions as it could be noticed in *Figure 48*. The actions taken in the Household and tertiary sectors do not have a significant impact on the whole panorama when it is just considered the amount of energy demand or the GHG emission reduced as could be observed in *Figure 49* and *Figure 50*. Nevertheless, the effects of the actions taken household sector regarding the use of firewood, as an example, could have significant impacts on public health, which is a dimension that has not been considered in the analysis on LEAP.

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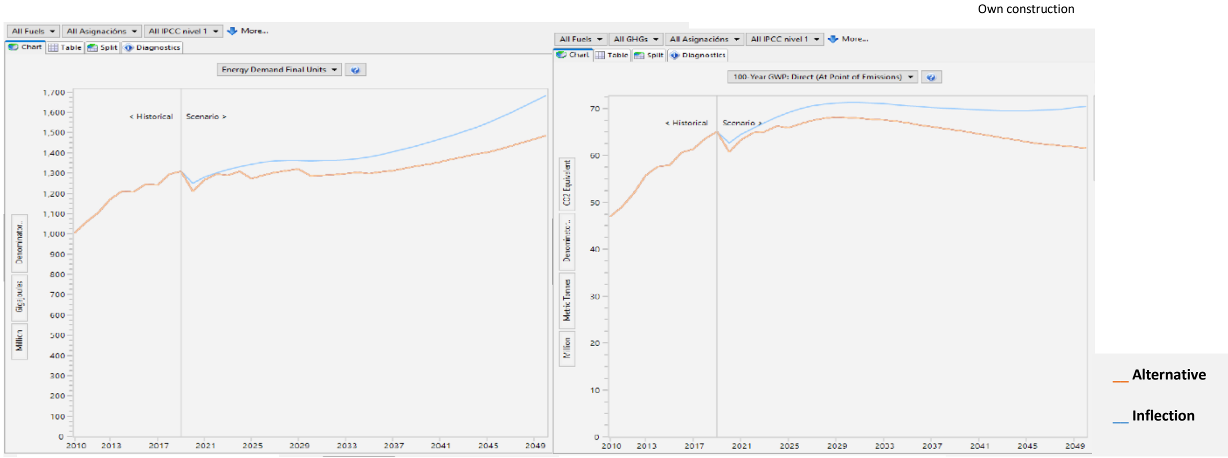

(a) Energy Demand (GJ) ***(b) GHG emissions (Mt $CO_{2\ eq}$)***

Figure 48 Demand Side Overview 2020-2050 – Inflection Vs Alternative, data source (UPME, 2020a)

Given the importance that the industrial sector has in the overall result, as can be seen in *Figure 49* and *Figure 50*, which target the second position, there is no doubt that Colombia should focus on promoting energy management and energy efficiency projects in the sector, which include:

Identification, structuring and implementation of good operating practices projects and implementation of process improvements Energy sources and use of energy sources with a lower emission factor as it was already proposed in the update of *National Determined Contribution* (NDC) signed by Colombia in 2020 (Colombian Government, 2020) .

For its part, the transport sector, which is the main actor in terms of energy demand and GHG emissions (*Figure 49* and *Figure 50*), as mentioned earlier in this work, requires immediate and effective action. The NDC update also indicated 7 specific strategies for the sector: (i) Optimization of freight/route logistics by the industry, which would have a direct impact on reducing emissions and fuel consumption. (ii) Creating a regulatory environment and accelerating the transition to electric mobility. (iii) Promote the use of the Performance-Based Navigation (PBN) system in 100% of the country's airports and flights. (iv) Strengthen the modernization program for automotive freight transport for vehicles with a gross vehicle weight of more than 10.5 t and more than 20 years old. (v) Promote the shift of freight transport from road to the river until the target of 8 Mt of freight per year is reached. (vi) Increase the percentage of bicycles in all cities. (vii) Rehabilitation of the rail corridor, which will allow the transportation of at least 5 Mt of freight per year in this way (Colombian Government, 2020).

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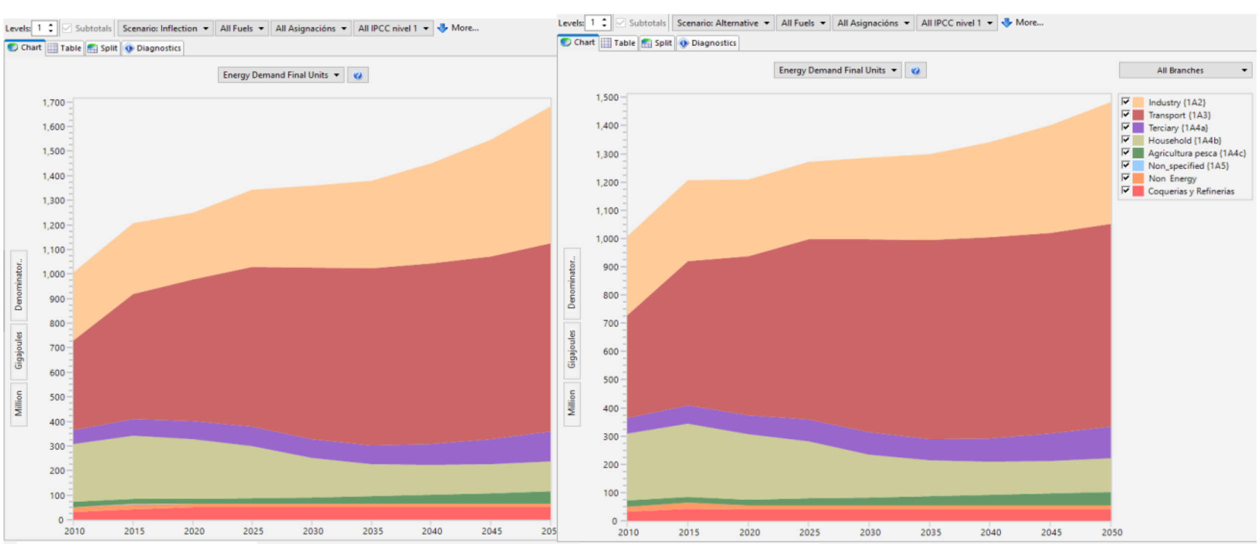

(a) Inflection ***(b) Alternative***

Figure 49 Total Energy Demand by sector 2020-2050, data source (UPME, 2020a)

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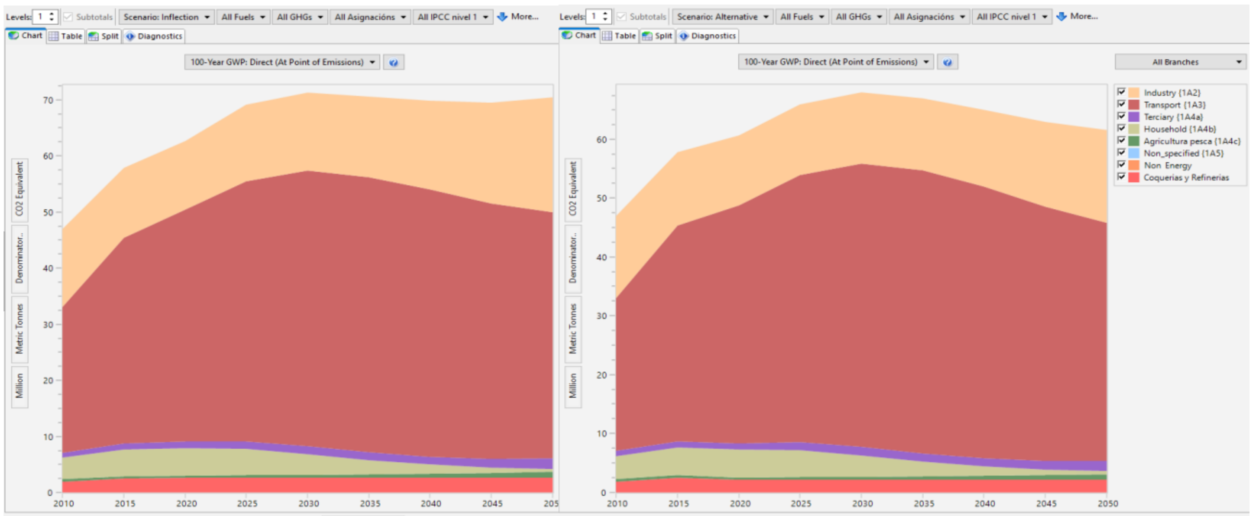

(a) Inflection ***(b) Alternative***

Figure 50 Total GHG emissions by sector 2020-2050, data source (UPME, 2020a)

4.9 Analysis and Discussion

First of all, it is important to clarify that the "Alternative" scenario does not correspond to a set of proposed policies, instead, it was a way to analyze which drivers improve or influence the results for the targets set in PEN 2020-2050 regarding EE. In the second place, with the variations on the model, it was possible to identify the sectors that have a higher potential in terms of energy savings, the variables that have more or less incidence, and the factors that were not considered in the original analysis. Future studies could approach the design of particular policies that have a cross-sector effect in order to promote one of the results mentioned in the Alternative scenario.

Due to the dynamics of economic growth and urbanization of the country, it is imperative to find appropriate strategies to better manage the energy demand and optimize generation resources as much as possible. The demand sector presents interesting challenges that, if addressed with the right policies, would lead to results in the decarbonization process of the country's economy in the short and medium term. Thus, it is crucial developing strategies and actions to improve knowledge and innovation related to the energy transition, applied across sectors, to promote the adoption of new, more efficient and cleaner technologies. The items in the Demand-side framework that could be considered relevant to achieving a near 50% reduction in carbon emissions by 2030 and achieving carbon neutrality by 2050 are summarized below.

(i) As it is concluded in the OECD Economic Surveys (OECD, 2022), informed consumers who are more aware of their role in the electricity system make better decisions. The use of digital metering and control devices that take into account energy consumption behavior is a first step toward optimizing energy use.

(ii) Metering must be accompanied by the approval of tariff systems that vary with electric system conditions to produce optimal demand response to improve the integration of intermittent renewable generation.

(iii) Price is one of the most important variables for consumers. It must not only show the relative scarcity or abundance of resources, but also take into account the negative externalities associated with the production and use of the goods consumed.

(iv) International experience shows that the introduction of minimum energy efficiency standards has been effective (National Planning Department et al., 2019). Thus, Energy labeling initiatives and minimum energy performance standards (MEPS) for end-use appliances, vehicles, and buildings must be continued, strengthened, and implemented. It is essential to have progress in the implementation providing users with information on energy consumption.

(v) The interplay of digitization, hourly tariff systems, the carbon price, and an energy labeling system can be the basis for shaping profound and long-term changes in energy consumption.

(vi) Lighting is an area where energy efficiency gains can be capitalized rapidly and easily thanks to LED technology. On the one hand, it is a technology with high penetration and commercialization in the market, so its acquisition does not require major expertise, thus its implementation could be fully spread.

(vii) Deployment of Energy Management Systems based on ISO 50001 could be an important driver to achieving constant improvements in energetic performance in the industry. By adopting ISO 50001, organizations are provided with a structured, clear, flexible and achievable systematic energy management program that enables gradually identifying what improvements can be made at facilities and the potential savings that they could represent.

(viii) In developed countries, there are standards limiting pollutant emissions from the transportation sector, as well as energy efficiency standards for the automotive market.

These policies induce manufacturers to produce cars with better fuel efficiency (and thus lower GHG emissions), making more efficient alternative fuels (such as electricity) competitive (Ministry of environment and sustainable development et al., 2019).

(ix) The challenge of transforming the automotive sector is no small one, because making the technological transition a reality and enabling fuel substitution requires a coordinated set of signals that create an environment conducive to that transition. Fiscal incentives aim to overcome one of the main barriers to technological switch, which is the purchase price of new vehicles. However, this signal must be complemented by other measures aimed at reducing the risks perceived by end consumers regarding progress (OECD, 2022).

(x) The old age of the road freight fleet in Colombia is currently one of the main obstacles to the transformation of this sector, even if this situation has a negative impact on the efficiency of freight transport. On average, the fleet of freight vehicles in Colombia is twenty-one years old. This figure is higher than the average in Latin America (15 years) and more than double the average in developed countries (8 years) (National Planning Department et al., 2019)

Chapter 5
Conclusions and Future Work

5.1 Conclusions

Through the analysis of the Colombian Energy Transition Plan and its complementary policies and programs to strengthen EE performance, as well as the hypothetical scenarios developed to evaluate the different possibilities that arise from the implementation of different initiatives with varying degrees of difficulty, this work has demonstrated the usefulness of energy system planning tools for decision-makers tasked with defining the public policies that will make the energy transition in Colombia feasible.

Modeling and verifying the sensitivity of the different variables and evaluating new potential policies with these tools makes it possible to identify the real cross-sectoral impacts while reducing uncertainties. This can, directly and indirectly, influence policy making in the country around the electricity system.

PEN 2020 - 2050 is not a finished document, but rather an initial roadmap to address the energy transition in Colombia. Such a roadmap should not depend on the political will of the incumbent government, but on the result of detailed studies based on those of countries that have already come closer to their carbon neutrality. Nevertheless, it is a document that must be constantly updated with the realities of the country in relation to its national power grid.

After studying the global panorama, approaching the Colombian framework to the worldwide trends, and analyzing the scenarios proposed in the PEN 2020-2050 to assess the Colombian Energy Transition Plan and the Energy Efficiency Potential to Decarbonize the Economy, as an object of this thesis work, it is possible to set the following conclusions:

(i) The role of electrification is vital in the energy transition process. However, the use of fossil fuels will continue to be needed in the next 30 years. Achieving fossil fuel independence in Colombia by 2050 will require increasing renewable energy generation by up to 8 times, assuming energy demand is held constant, which trends

suggest is not reasonable. The most reasonable strategy to manage the demand side growth is more aggressive energy efficiency policies.

(ii) The energy transition is feasible, but expensive. It entails a significant investment to deploy all the strategies and programs designed for the BAT and to fully develop the disruptive technologies that have appeared in the panorama. Therefore, to make the transition a reality, it requires solid financial resources and mechanisms.

(iii) It should be considered that further investment funds and innovative technologies do not ensure the success of the transition, it is a process that takes time and with a large number of uncertainties.

(iv) The transportation sector, as the largest energy consumer in Colombia and in the world, is expected to increase its energy demand. The technological capabilities that allow to optimize energy use and reduce GHG emissions are critical to transforming the energy sector in general.

(v) The scenarios in PEN 2020-2050 LEAP led to a higher degree of substitution of liquid fuels for natural gas, electricity and hydrogen in the transportation sector. Nevertheless, it is estimated that the renewal of the national fleet will take about 25 years, thus conventional vehicles are still expected to be on the roads by 2050, whether considered the vehicles that will be launched in the next few years.

(vi) Natural gas plays a fundamental role in allowing the country to keep its energy self-sufficiency in the coming decades, as was observed in the foreseen scenarios in PEN 2020-2050. This represents a competitive advantage for the country avoiding having to face the price volatility of this fuel as other countries have had to do with the natural gas crisis of 2022 derived from the war in Ukraine.

(vii) It was noticed that international aviation was not considered in the PEN 2020-2050 LEAP analysis, understanding that is not easy to define which country should assume the GHG emissions. Even though, this activity contributes also to GHG emissions and makes aviation a key player in the deployment of disruptive technologies such as green hydrogen.

(viii) The tertiary and industrial sectors in Colombia have significant barriers regarding EE to overcome. The high costs associated with the acquisition of international BAT; and contracting specialized companies to do energy audits; are in contrast to the low cost

of some polluting energy sources. In this sense, empowering and preparing university centers to carry out the audits in those economic sectors could be a winning strategy not only to reduce costs but also to have professionals in the country with high-value training on the subject.

(ix) Cost-effectiveness analysis from the standpoint of return on investment for the private sector and the need to provide tax incentives or not, were not included in the analysis of PEN 2020-2050, which correspond to one of the weaknesses of the model because it is not possible to visualize the cost implication of each variation.

5.2 Future Work

Understanding how Colombia has designed its National Energy Plan and which are the initiatives proposed to strengthen the rational use of energy; future works could take advantage of the amount of available official information for the country on the government agencies' websites including the model of PEN 2020-2050 on LEAP to simulate the policies proposed for the incoming government, which will govern the next four years starting in January 2023. It has proposed a set of measures aimed at expanding the use of decentralized solar energy; toughening taxes for those sectors responsible for the largest carbon emissions; stopping contracting new exploration of natural gas; among other measures. Modeling the new policies in the framework of the PEN 2020-2050 and assessing how they impact the demand side and how contribute to the reduction of energy intensity of the country through energy efficiency; also their positive and negative effects in comparison to each of the published scenarios could be an interesting analysis.

Likewise, the availability of information allows future works to study the viability of a policy that generates strong progress in terms of energy efficiency. This demands more time, considering the collateral effects that a policy has on the entire national scenario. Therefore, it would require a prudent time to design police analyzing its viability, and its compatibility with other existing policies, besides its effects on all sectors of the economy.

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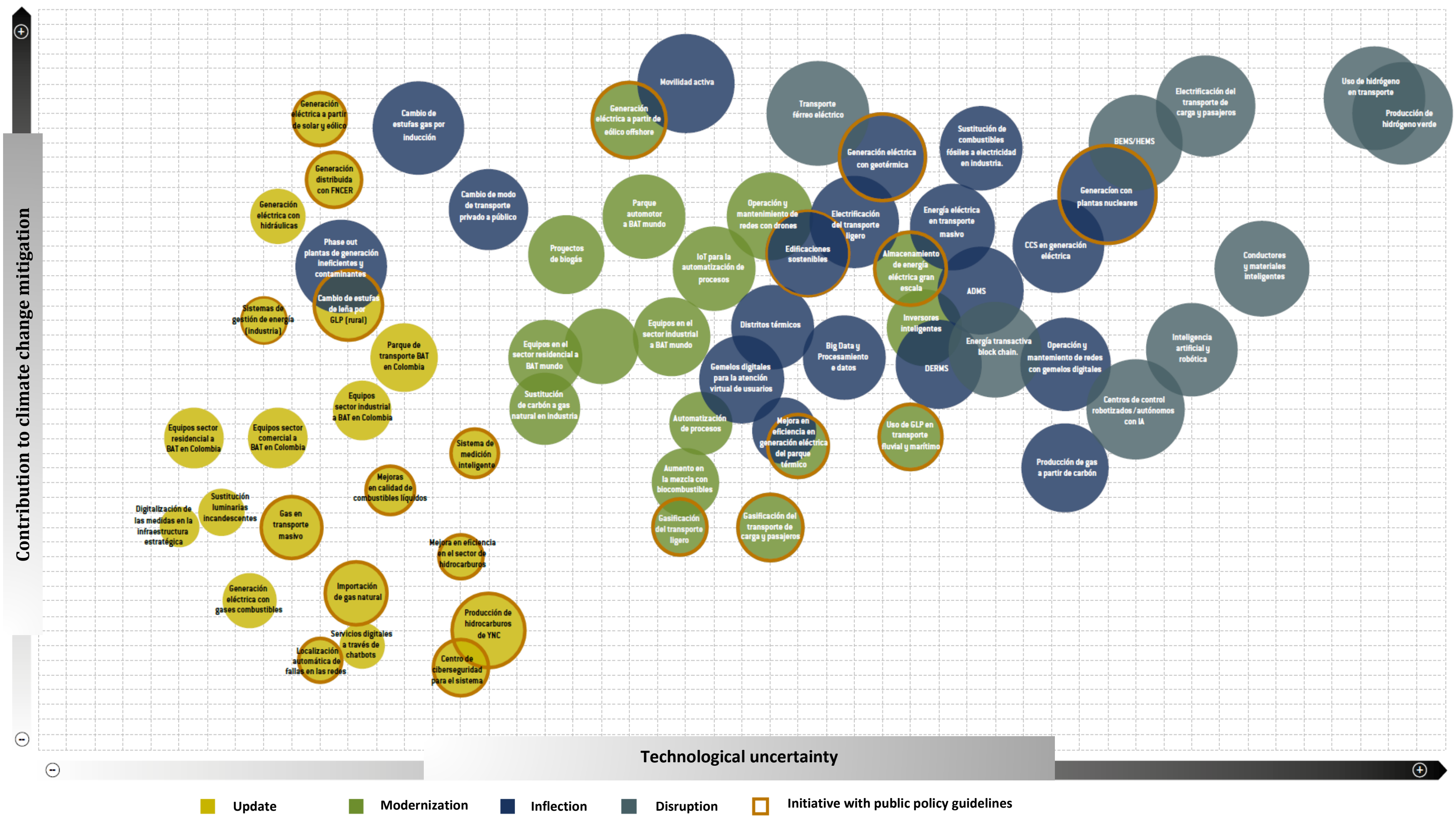
APPENDIX 1 – Initiatives proposed in PEN 2020-2050



Zoom of Figure 21: Set of Initiatives proposed in PEN 2020-2050, (Ministry of Mines and Energy et al., 2020)