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A Methodology for Modeling and Simulating a Thermal Energy System in Colombia

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Abstract

A standard method to improve energy dynamics includes the use of energy models to analyze and decide on courses of action for the energy system. Despite the essential role that electrical energy plays in contemporary societies, the focus of efforts is mainly on analyzing and optimizing these systems, often ignoring another critical energy source, thermal energy. Thermal energy refers to temperature variations and the production and transfer of heat, the physical principle that drives various sectors, including industry, transportation systems, and domestic needs such as cooking and heating. Usually, thermal energy uses primarily non-renewable fossil fuels, serving as the basis for a thermal energy framework. This paper aims to outline a methodology for creating a foundational model of a thermal energy system that illustrates the movement of diverse energy sources denoted by different types of fuel with varying instances of supply and demand on a national level, considering Colombian data. Based on the preceding information, it is proposed to model and simulate energy scenarios in which some thermal consumption is substituted with electricity consumption from renewable generation sources, while considering the national energy transition objectives.

Keywords: Energy modelling, Thermal modelling, Calliope, Renewable energies.

1. Introduction

Thermal power generation plays a fundamental role in the supply of different sectors of the energy matrix of countries, contributing significantly to the stability and reliability of systems that do not depend on the electricity supply on a national scale, such as the transportation or industrial sector [1]. In a context of increasing energy demand, thermal generation has become an essential pillar to ensure the availability of resources across the territories. However, as we move towards a more sustainable and environmentally friendly energy future, the need to evaluate and optimize the deployment of these technologies becomes more important than ever [2].

Establishing a baseline thermal generation that considers daily energy dispatch in Colombia is a crucial step in the transition path towards decarbonization [3]. This baseline provides a foundational reference for understanding and analyzing the current state of thermal generation in the country, encompassing different technical, economic, and environmental considerations. It provides a foundation for objective decision-making in the planning and management of energy infrastructure, enabling a transition to a more sustainable and efficient model.

This article aims to introduce a methodology that uses Colombian data to define and simulate the thermal generation baseline. This methodology is based on a thorough review of current infrastructure, assessment of the efficiency and performance of thermal plants, evaluation of fuel management, and projection of future trend analysis. In addition, it examines the importance of thermal energy production within the Colombian industrial and transportation sector, including its association with other energy sources and the impact of geographical and climatic conditions. Finally, this study proposes a scenario in which a portion of the thermal consumption can be replaced with electricity by incorporating renewable generation sources, including solar and wind power.

2. Related work

Building energy models on a national scale is a critical area of research presently, considering the worldwide significance of the transition to more sustainable energy sources [4]. National energy models offer insight into the dynamics of energy markets and systems. This allows the development of tools that can anticipate future needs and propose policy and technology recommendations. Various strategies and methodologies have been developed to build models that address various energy sources. These models also provide routes to decarbonization of different sectors and consider the complex interactions within an entire country [5]–[9].

Developing baselines that can be compared with real data from the country's energy market is crucial for models to accurately reflect reality. Vuuren et al. [10] propose exploring the evolution of baselines to mitigate CO2 emissions, as the growth of Chinese industry is directly correlated with increased carbon emissions. The implementation of energy efficiency strategies was one of their main findings. Santika et al. [11] have proposed forecasting the energy requirements that will impact the implementation of the Sustainable Development Goals (SDGs) in Indonesia. Using a model built for this purpose, they found that the country can achieve the goals despite the increase in energy demand, provided that the right energy policies are in place. Urban et al. [12] assess the viability of energy transition policies in various countries by building baselines. They compare the behavior of 12 energy models in developing countries, concluding that these models are often biased toward industrialized nations and lack understanding of the complex characteristics within developing countries.

One of the main goals of energy modeling involves the integration of renewable energy sources to achieve decarbonization steps. To achieve this objective, various strategies are considered that analyze objective functions such as cost analysis [13] or strategies that integrate cost and emissions for countries [14]–[16] are considered.

When conducting thermal system modeling research, the focus usually lies on developing more efficient systems that generate thermal resources from renewable sources, such as Qerimi et al. [17] suggesting an alternative to the current water heating systems in Kosovo by building a mathematical model for solar thermal heaters. This plan aims to meet heating needs while reducing carbon emissions. Noorollahi et al. [18] suggest substituting natural gas for buildings in Iran with solar and wind energy sources. After analysis, they concluded that only solar collectors have the economic capability to meet this demand. Furthermore, prior work focuses mainly on the switch to thermal systems to replace water heaters, using solar or wind energy sources for this objective [19]–[21].

Finally, this article proposes a methodical approach to accurately define the baseline for thermal systems at a national level while accounting for their entire transport infrastructure.

3. Proposed Approach

Based on the analysis above, this study proposes a methodological framework to construct the baseline model. The methodology aims to accurately characterize the thermal system and associated resources. One of the proposed steps in the methodology is to choose software based on an evaluation of relevant criteria for modeling, defining the energy system, and determining the simulation resolution. The model's inputs in terms of technical or economic requirements should also be established, followed by validation using scenarios up to 2030. See Figure for further details.

A. Problem definition

In the Colombian context, the generation and consumption of thermal energy is crucial in various sectors, including households, industries, and transportation. Nevertheless, the country's reliance on nonrenewable sources of thermal energy presents significant sustainability and environmental challenges. The combustion of fossil fuels, including natural gas and oil, for the generation of thermal energy in vital applications poses hazards to air quality and

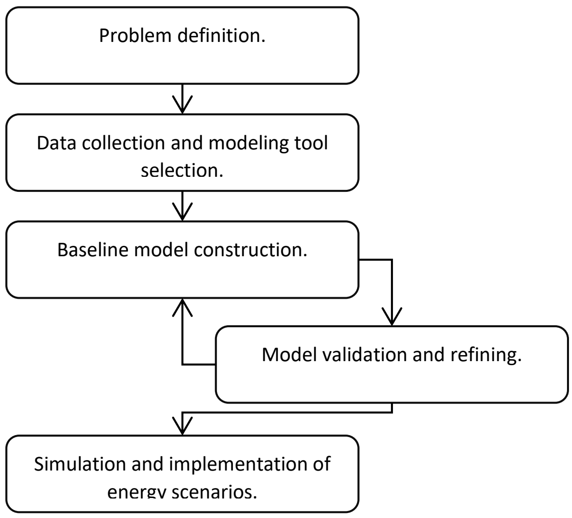

Figure 1. Proposed methodology.

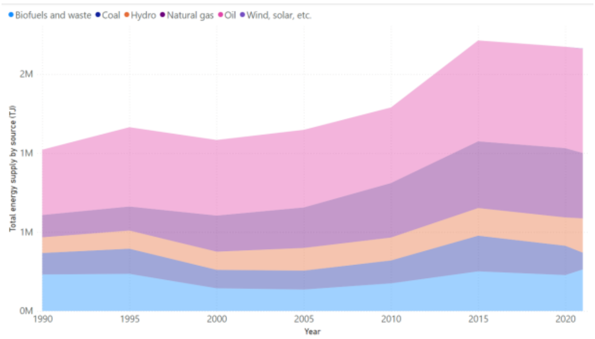

Figure 2. Total energy Supply Colombia.

climate change. However, it is responsible for most of the country's energy production, as shown in **Error! Reference source not found.**, where fuel supplies account for approximately 70% of the energy share. [22].

The focus of this scientific paper is on creating a fundamental model and analyzing its thermal energy transfer. The analysis helps in determining the amount of thermal energy that can be converted into electricity with the use of renewable energy sources. Modelling methodologies are utilized to construct a thermal model for Colombia. This model identifies sectors where thermal energy demand can be replaced with electricity consumption from renewable sources, contributing to a more sustainable and diversified energy matrix while decreasing greenhouse gas emissions linked to climate change.

One issue identified in the research is the country's dependence on imported fossil fuels to meet its energy demands, as illustrated in Figure . This reliance is linked to increased consumption and insufficient domestic production capabilities, leading to elevated fuel and energy expenses associated with their use. This is a concern that may worsen over time without appropriate intervention.

B. Data collection and modeling tool selection.

The initial stage in constructing the model entails specifying the modeling instrument required to create the energy model representation. This is critical because the qualities of the tool or software will determine the minimum input parameters for the simulation. Consequently, several tools were evaluated, including Homer, LEAP, RETScreen, Ihoga, and others, as presented in **Error! Reference source not found.**.

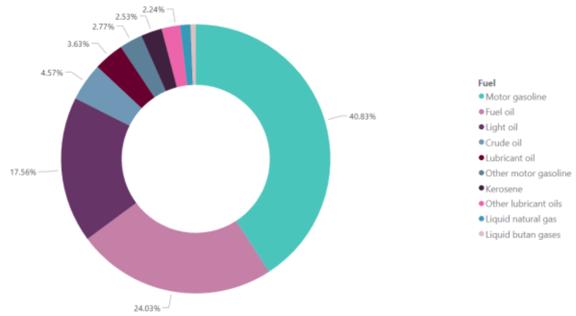

Figure 3. Distribution of fuel Imports 2022.

Table I. Compared Software for energy system modeling.

Software	**Methodology**	**Scale**	**Resolution**
Calliope	Bottom-up	National/Urban	Multiple
OSeMOSYS	Bottom-up	National	Multiple
Homer	Bottom-up	Urban/Rural	Renewable
RETScreen	Top-down	National	Multiple
Ihoga	Top-down	National	Multiple
LEAP	Bottom-up	National/Urban	Multiple
Flextool	Top-down	Building	Building

Regarding the software selection criteria, the simulation scale plays an important role. Our aim is to develop a model depicting Colombia's energy system, requiring the software to have national-level representation. The other criterion is software resolution, which directly impacts optimization. For the dispatching model, using software with hourly resolution is advantageous as it enables precise handling of available resources and facilitates visualization of energy flow behavior based on actual consumption profiles, even when demand cannot be fully met. In addition, an hourly time step is beneficial when combining thermal and electrical systems, as energy sources that rely on environmental factors often vary on an hourly basis.

For various reasons, the Calliope modeling tool was selected to create the baseline model and simulate various scenarios. Calliope is a frequently used framework in energy modeling research and long-term planning. This framework is referenced in the work of Lombardi et al. [23] who created a model to decarbonize the Italian electricity system through the implementation of photovoltaic and storage systems. Their work provides a useful tool for future policymaking.

Other relevant research includes the work of Lombardi et al. [2], to replace traditional gas cookers with induction stoves on a large scale in Italy. They achieved this through a balanced approach that enables the generation of electrical energy for cooking from renewable sources instead of fossil fuel power generation plants. Díaz et al. [24] present an economic model for Switzerland, analyzing the costs of using gas for electricity generation. Their findings suggest that this approach can serve as a pathway toward the transition and decarbonization of energy compared to other fuel alternatives. However, the cost savings associated with this method are not significantly different from a complete shift to wind and solar power. Therefore, it is recommended to quickly integrate renewable sources at an accelerated rate as a viable alternative.

Following software selection, a search and data collection are performed to establish a baseline that adequately represents the dynamics and flows within the thermal sector. A recommended approach to effectively demonstrating thermal energy flows is to utilize various types of fuel as energy carriers within the system. The National Energy Plan (PEN) [25] and the Colombian Energy Balance (BECO) Click or tap here to enter text. identify and track numerous fuels in Colombia. The initial modeling approach focuses on only four fuels. This decision is based on the importance of these fuels in various industries, transportation, and residential areas. The accessibility of data and the traceability of these fuels throughout their production and transport to the final consumption nodes are also considered. Official databases are available from various platforms and entities, which are categorized according to consumption sectors and departmental nodes throughout the country. For fuels of interest, see Table 2, which provides an overview of the BECO data for 2021.

Table 2. BECO fuel data for 2021.

Fuel	Brute offer	Internal production	Imports	Exports
Motor gasoline	88175.7	52137.84	29872.4	97.0833
Diesel oil	87173.11	88582.71	13919.99	22524.57
Jet fuel	13819.31	13610.54	208.77	-
Natural gas	122391.9	187252.41	481.783199	-

On the other hand, to construct the electricity model for proposing and simulating decarbonization scenarios for the thermal sector, data on electricity generation points in Colombia was collected from the company XM [27], along with resource data for solar and wind generation from the NREL National Solar Radiation Database.

These hypothetical scenarios for decarbonization propose changes to the existing system. The scenarios endeavor to replace a portion of fuel consumption with renewable electricity resources. As a result, evaluating the technical feasibility of these scenarios entails essential data on resource behavior and installation capacity of technologies.

Finally, Figure 4 depicts the defined structure of how the data is fed into the model. The thermal baseline model is represented in black, consisting of data on energy demand, carrier generation constraints (fuel production capacity, distribution of polyducts and gas pipelines), and associated operation and maintenance costs and emissions for each fuel. The model's construction does not deal with the economics and emissions aspects of fuel use. Instead, it concentrates on the resource flows accessible to satisfy a specific demand over time.

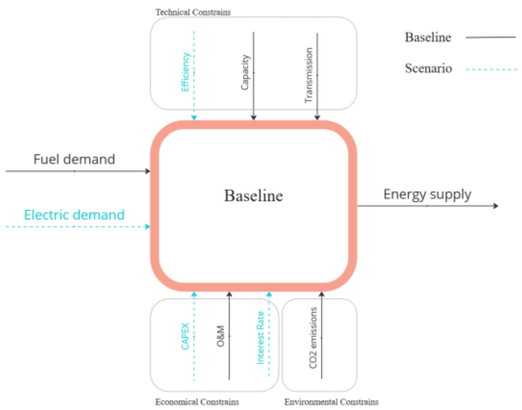

Figure 4. Baseline model data structure.

C. Baseline model construction.

The base model is constructed in several stages. To begin, system nodes are defined. The model's purpose is to analyze decarbonization scenarios and partial replacement of fuel consumption with renewable energy sources, and therefore, a production and consumption node layout is proposed in line with the electric system distribution in Colombia. In this context, the Colombian electric transmission system comprises 17 nodes that function as transportation networks for gases and fuels, distributing them across the country to various regions. To better represent the structure of the polyducts and gas pipelines, three intermediate nodes were added to facilitate the design of the fuel's transportation systems. After setting the nodes, we collected supply and demand data to ensure comparability between the thermal model and electric power dispatch models. The data needed to have high periodicity and be available for the created nodes. Some platforms were found that facilitate the querying of these data with a daily periodicity, which are SICOM [28] for fossil fuel trading and the "*Bolsa Mercantil de Colombia*" BMC [29] with the Natural Gas Market Manager. The study collected daily dispatch volume data from official service stations associated with the liquid fuels system, categorized by the nodes related to Motor Gasoline, ACPM-Diesel, and Jetfuel-Kerosene. Additionally, comprehensive information on natural gas was obtained, including total demand by department, consumption percentages by sector (e.g., power generation, industry, natural gas for vehicles, and residential use). Since there was no available hourly data or typical consumption profiles for any of the fuels, the decision was made to linearly distribute the data for the 24-hour period. Because the initial model approximation does not sectorize the demand but instead takes a general fuel demand per fuel at each node, this approach is deemed appropriate for the system's preliminary analysis. Figure 5 displays the demand profiles for all fuel types in the system and their respective usage in each department. Notably, all fuels, except for Jetfuel, maintain a consistent level of demand throughout the year.

Supply data is determined by utilizing a fuel management report from UPME (Unidad de Planeación Minero-Energética) to ascertain the daily average national fuel production capacity. **Error! Reference source not found.** outlines the average capacities, in thousands of barrels per day, for the Reficar-Cartagena and Barrancabermeja refineries.

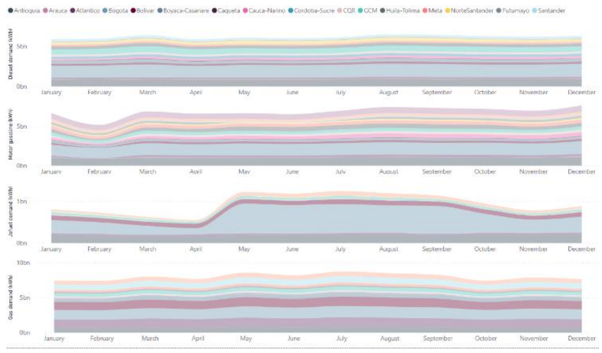

Figure 5. Demand profile for thermal carriers.

Table 3. Refining capacity per plant.

Refinery	Fuel	Capacity (kBD)
Cartagena	Motor gasoline	29.2
	Diesel	77.8
	Jetfuel	10.9
Barrancabermeja	Motor gasoline	50.7
	Diesel	61.1
	Jetfuel	19.7

Although the annual import data [30] indicates global entry of diesel oil, possible imports of this fuel are not being considered due to local demand being met through domestic production and storage. This same practice applies to Jetfuel. On the other hand, the domestic demand for motor gasoline rounds 150 kilo-barrels per day, whereas the domestic supply averages just 80 kilo-barrels per day. As such, imports play a crucial role in meeting the nation's demand for this fuel. When it comes to natural gas supply, information exists about active extraction fields, gas regasification plants that receive gas imports, and the amount of energy injected into the natural gas transportation system. Using the production data of each gas field, Figure 6 displays a distribution graph that plots the maximum value. This value defines the installed capacity on the model since it is assumed to be the highest amount that each field can extract and inject into the system.

Next, the transport systems for moving fuel from extraction/refining sites to consumption nodes are defined, ss shown in Figure 7. First, the electric transmission system is defined including its network capacities; however, this system is solely utilized to support energy scenarios, so no technology is included in the base model. Following this is the consolidation of the polyduct system for transporting various liquid fuels. The sections, links, and abilities are received from CENIT, the agency responsible for nationwide fossil fuel transportation. The fuel availability report from UPME [30] illustrates the distances and ground transport routes between departments that are not served by the pipeline network. The gas transport system is distinct, comprising an inland system and a coastal system that operate autonomously to provide distinct regions in the nation [29].

Figure 6. Gas fields capacity

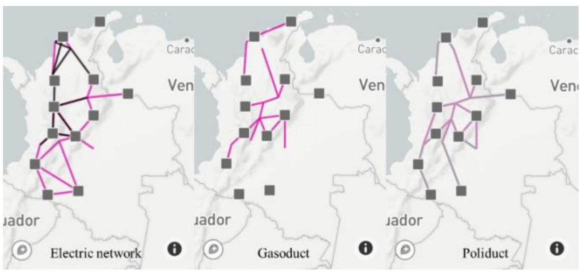

Figure 7. Electric Grid – Gas transport system – Polyduct system.

With the given parameters, the model is run to establish the system's baseline and ensure accurate representation of energy carrier behavior during the analysis period, as shown in Figure 8. The aim is to provide an objective evaluation of the data and dynamics.

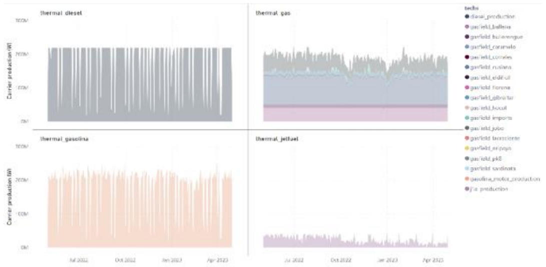

Figure 8. Baseline model - simulation of the carrier behavior

Fig. 8 shows that only gas utilizes distinct technologies to model various extraction fields within the country, as opposed to other fuels that rely on the two refineries, which are modeled in the same manner and located in their respective nodes. The maximum capacity of the refineries is established based on data from Table 3.

When compared to the BECO annual totals (Table 2), the internal supply data displays a striking similarity.

Furthermore, the model's sum of supply closely resembles the actual data for the period. However, it is worth noting that there is a significant unfulfilled demand for most fuels, with diesel and motor gasoline experiencing the largest shortages.

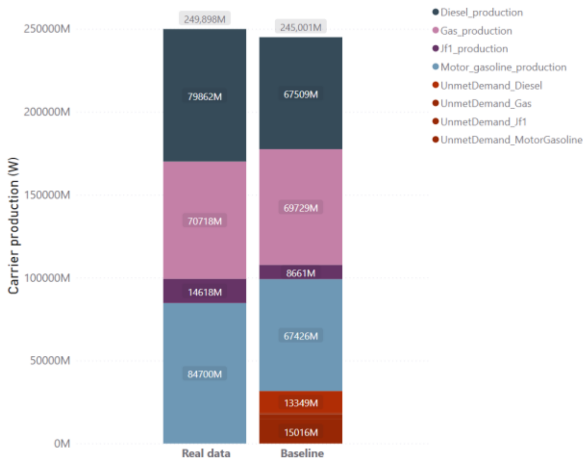

Figure 9. Real data comparison of carrier production.

This stands in contrast to the real system, where all registered demand was met, as it is observed in Figure 9.

It is necessary to develop a storage system to save surplus energy produced during times of excess, which can then be utilized to accommodate future occasions with higher demand that surpass the capacity of the existing system. This storage system adds reliability to the energy model and is a mechanism commonly utilized in actual supply systems to deal with intermittent offers or unexpected demand peaks. On the demand side, it is conventionally used to account for periods of unavailability.

D. Model Validation and refining.

Figure 8 illustrates that certain carrier experience deficits on specific days, while on other days, the production level exceeds the consumption rate. This is due to the lack of storage mechanisms, which are commonly utilized to counterbalance consumption peaks or supply variations. The refining model incorporates storage technologies for motor gasoline, diesel, and jetfuel. These technologies have a fixed maximum production rate, which enables the generation of a surplus. This surplus can then be utilized for meeting higher demands in subsequent periods. Figure 10 illustrates how the storage system works, indicating that during periods of low fuel demand, fuel can be stored, and during periods of high consumption, it is supplied from the storage.

Table 4 contains a detailed description of the total storage capacities of the system. for production and high consumption nodes such as the SubAntioquia and SubMeta nodes, both of which experience natural gas consumption caps during peak periods of use imposed by the transmission system. To ensure total production can be stored and prevent losses in the model, the aforementioned storage capacities were decided based on production capabilities.

Table 4. Storage capacity by region.

Locations	Techs	Storage capacity (kW)
SubAntioquia	gas_storage	10000000
SubBolivar	diesel_storage	200000000
SubBolivar	gasolinamotor_ storage	175000000
SubBolivar	jetfuel_storage	150000000
SubMeta	gas_storage	10000000
SubSantander	diesel_storage	200000000
SubSantander	gasolinamotor_ storage	175000000
SubSantander	jetfuel_storage	150000000

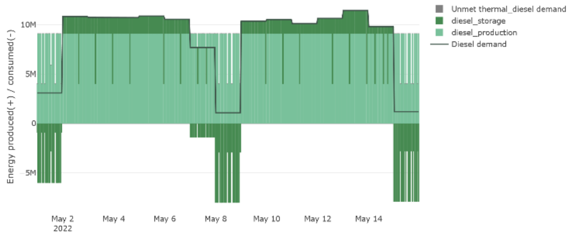

Figure 10. Storage system behavior on carrier production/demand.

The incorporation of storage reveals the modeled baseline productions align closely with the actual production of the real system. After comparing the baseline plus storage results to the real data, a discrepancy of 1% for diesel, 2.7% for motor gasoline, 25% for Jet fuel, and 1% for gas was found, illustrated in Figure 11. This analysis indicates that the constructed baseline for the 2022-2023 period mirrors the actual thermal market behavior. The exception is Jetfuel, which had a higher percentage difference. This may be because even small production variances result in high percentage differences due to its low production. Additionally, the baseline data does not account for fuel imports. However, since demand is always met, the model development is not hindered.

E. Simulation and implementation of energy scenarios.

Before simulating and detailing the energy scenarios, an estimation of the renewable resources to be incorporated in the electric model for fuel substitution was undertaken. In this case, the resource was predicted using the Typical Meteorological Year (TMY) for the scenarios. The Finkelstein-Shafer (FS) statistical model was utilized, which enables the construction of a typical meteorological year based on an accumulated distribution of the solar and wind resources over the last 20 years. Refer to Figure 12 for details. To establish the efficacy curves which are included in the model's dataset to depict resource behavior, a 1W power was assumed to achieve the normalized value. Subsequently, they were computed using energy sizing models described for both wind and solar energy [31].

Considering the construction of the model and all the constraints of both the fuel transportation system and the electricity transmission system, two scenarios are proposed to evaluate the technical feasibility of replacing part of the thermal consumption with renewable electricity consumption, mainly in sectors destined for electricity generation from fossil fuels. The year of simulation is 2030, identified in the national sustainable development plans as the initial objective to decarbonize the electricity sector. In the proposed scenarios, the focus is on reducing the consumption of natural gas - the second largest source of fuel consumption in the country. Not only does the electricity grid rely heavily on natural gas, but also the industrial system, which could have potential technical and economic implications in the medium- and long-term.

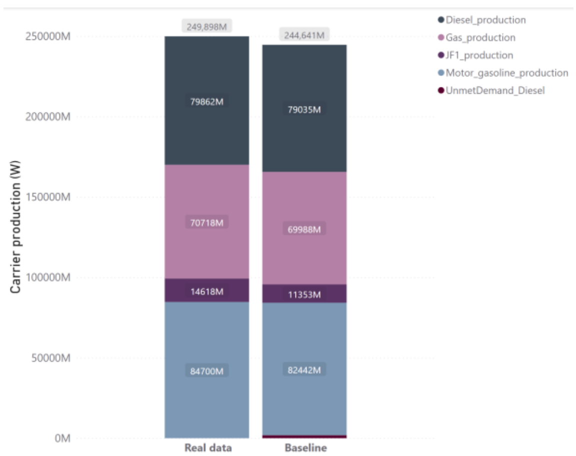

Figure 11. Fixed production capacity pos model refinement.

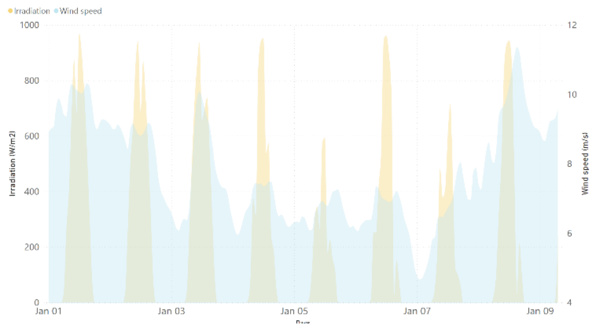

Figure 12. Wind and solar profile in SUBGCM region.

Regarding other fuels like motor gasoline and diesel, they are primarily linked to the transportation sector. The National Development Plan (PND) has explored certain transition scenarios in order to decrease the reliance on imports and limit the consumption of these fuels in the sector. Hence, these fuels will not be taken into consideration in the proposed scenarios. Based on the current gas reserves projections, it is estimated that by 2030, gas extraction capacity will decrease by 60%, as depicted in Figure 13.

For simulation purposes, the initial step is to establish growth projections for natural gas consumption. According to UPME's forecasts [30], the annual increase rate in gas demand from 2023 to 2030 is estimated to be 0.41%. Using the percentages by sector in each department given by the Natural Gas Market in Colombia [29], it is proposed for the scenarios that the resources coming from the fields, supported by imports from abroad, will try to supply the consumption of industrial sectors, vehicles and refineries, which account for about 50.9% of total gas consumption at the national level, while the remaining percentage, which is mainly related to residential, commercial and electricity generation, will switch and be supplied by electricity coming from renewable sources. In both scenarios, no cost estimates will be made, but rather the technical feasibility of supplying this new consumption with renewable electric energy facilities will be explored.

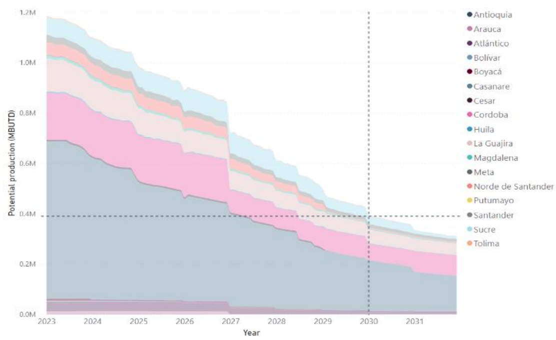

Figure 13. Forecasting of natural gas resources depletion.

Scenario 1: In this scenario, 50.9% of natural gas demand, which accounts for industry, refinery, and natural gas vehicles, is aimed to be supplied with the domestic natural gas resources. If the demand cannot be met, gas will be imported through the regasification plant located at the SubBolivar node of the coastal system. The remaining unmet electricity demand will be met with large-scale solar technologies and wind farms, utilizing the ample solar radiation available in various regions of the country and the wind resources in the north. The approach emphasizes installing these plants to satisfy both generation and residential needs. It is noteworthy that the electric power demand is re-evaluated based on the proportion of each node linked to electricity generation through gas-fired power plants. To avoid oversizing power requirements, an average efficiency of 45% for these types of plants (OCGT and CCGT) is set.

Scenario 2: In this scenario, the goal is to fulfill the natural gas demand of the same sectors mentioned in scenario 1. However, we have calculated the total unmet demand for natural gas for all sectors. It has been determined that 30% of this unmet demand can be met via imports through the regasification plant located at the SubBolivar node and the currently inactive inter-American pipeline leading to the SubSantander node (which can be reactivated due to the ongoing socio-political circumstances in the country). Importing gas would result in an excess supply to the main cities of the country, specifically the SubAntioquia, SubAtlántico, SubBogotá, SubSantander, and SubValle nodes. The remaining demand for energy is then filled by renewable technologies, as in scenario 1, following the same calculations and considerations for electric power demand.

4. Scenarios results

Based on the proposed models, the results for the two scenarios are obtained. The primary aim of this analysis is to identify energy behavior with the inclusion of new technologies and assess the technical feasibility of implementing this type of thermal sector decarbonization.

A. Scenario 1

The initial scenario demonstrates a shift in the original gas demand, with 45% now allocated to electricity consumption and 55% to gas demand. The average electricity demand of approximately 3.43E+10 kWh is primarily met by 70% wind power and the remaining 30% through photovoltaic installation, as shown in Figure 14.

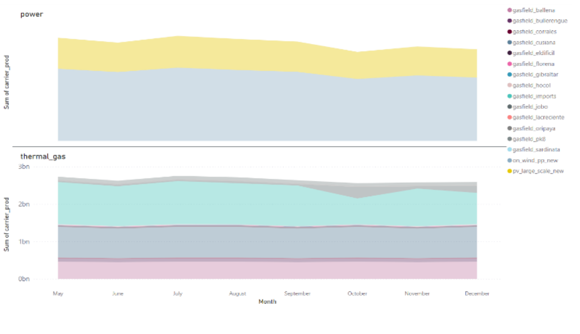

Figure 14. Scenario 1 - Electricity and gas supply.

Figure 15 illustrates an unmet demand in the production of both gas and electricity. Specifically, certain coastal gas fields, such as Hocol and Jobo, from the SubCordoba-Sucre node operate below their maximum capacity. On analysis, it was discovered that imports through the Bolivar node occasionally result in a surplus of resources along the coast. However, due to the separate independent operation of the coastal and inland systems, this surplus does not reach the inland nodes where there is a greater deficit. This is demonstrated in Figure 15, which shows SubAntioquia and SubSantander with nearly all their demand unmet.

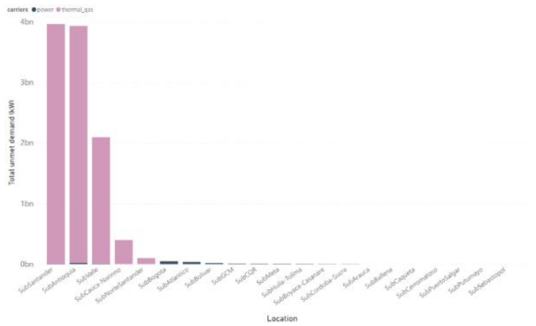

Figure 15. Scenario 1 - Unmet demand per Region.

This issue was addressed in the development of Scenario 2, which suggests the possibility of resuming imports through an international pipeline to meet the increasing demand for the resource within the inland system, given the current political environment in the region.

Figure 16 depicts the significant role that wind energy could have on gas reduction scenarios, although the requirements of gas imports are still crucial in meeting the demands of various sectors. It is also noted a smaller but still relevant portion of solar power on the energy supply.

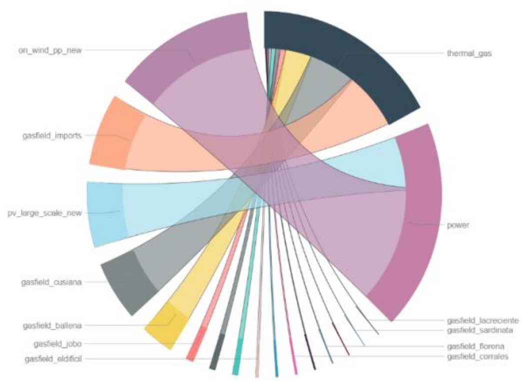

Figure 16. Scenario 1 - Share by power plant.

Scenario 2: As previously stated, in this scenario, approximately 30% of the unmet gas demand is fulfilled by gas imports from two sources, which supply both coastal and inland systems. The split between the coast and inland is approximately 23% and 77%, respectively. Due to the higher percentage of gas consumption, the demand for electricity decreases, as indicated in Figure 17. Nevertheless, the percentage distribution of newly installed technologies remains the same with 70% and 30% for wind and solar generation, respectively.

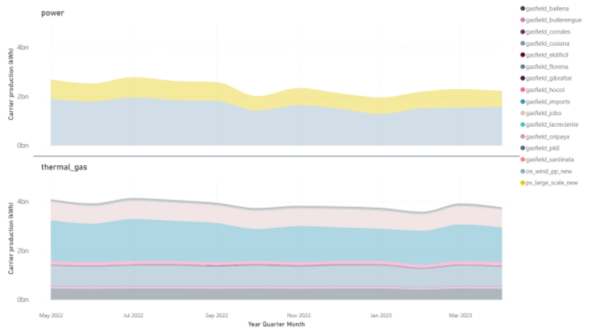

Figure 17. Scenario 2 - Electricity and gas supply.

In relation to system demand, Figure 18 illustrates that the unmet demand in this scenario is significantly lower than that in the previous scenario. The unmet demand level drops to as low as 0.19%, which is attributed to the electric power supply and primarily to random hourly peaks that cannot be met by the available renewable resources.

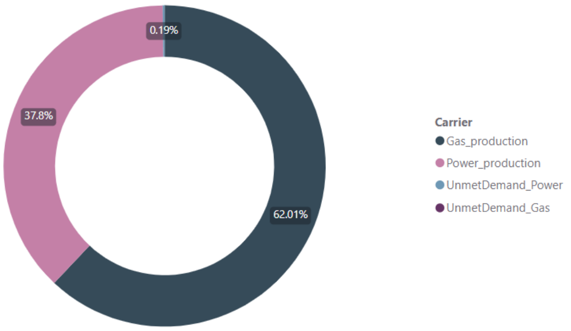

Figure 18. Scenario 2 – Total Unmet demand

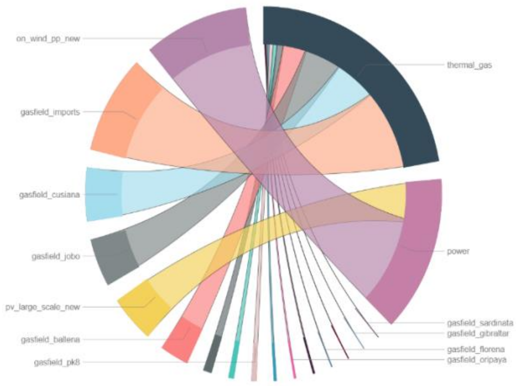

Figure 19. Scenario 2 - Share by power plant.

Finally, Figure 19 indicates that wind power and gas imports are comparable in energy contribution, suggesting that wind power may gradually replace gas resources. However, the overall energy supply's reliance on photovoltaic technology has decreased as larger percentage of demand is still met by gas, unlike the previous scenario.

5. Conclusion

The construction of the baseline of the thermal system in Colombia has established a reliable foundation for comprehending the intricate dynamics of the current energy landscape. Analysis of the data has facilitated identification of consumption patterns, generation factors, demand peaks, and most importantly, fuel behavior, which is converted into thermal consumption for various applications, ranging from industry to residential heating. This starting point enables proposing strong energy scenarios in the future, which aim to replace a considerable portion of thermal consumption with renewable sources.

One of the primary discoveries of this model pertains to the challenges associated with the reduction in fuel extraction and production over the next several years. By 2030, about 60% of the existing gas production will be unavailable, necessitating costly imports of this resource.

To address this issue, the model proposes the incorporation of storage systems capable of meeting demand during consumption spikes. This was discovered during the model creation without system integration, demonstrating up to a 20% demand deficit in total supply. However, with the incorporation of storage systems and the subsequent model refinement, variances in fuel supply of only 1% were observed for gas and diesel. Although Jetfuel showed a substantial difference of around 25% from the reported data, it is possible that the model did not take into account some sectors that UPME reported with regard to the sale of this fuel.

The developed energy scenarios indicate that transitioning to renewable sources is a viable and sustainable long-term option for the decarbonization of the Colombian thermal system. Incorporating solar and wind technologies shows significant potential for reducing greenhouse gas emissions. This demonstrates that up to 40% of fuels that cannot be produced domestically can be replaced with these sources.

However, it has been emphasized that certain challenges must be addressed, including the temporal variability of renewable sources and the need to adapt existing infrastructure to effectively integrate these new technologies. Additionally, future scenarios could involve the implementation of solar thermal systems that supply thermal consumption directly without the need for energy conversions, as well as the utilization of biomass systems. The latter is particularly promising given the country's vast agricultural area. Finally, while the implemented scenarios served as demonstrations of the technical feasibility, it is important to implement scenarios that align with public policies, include strategic investments, and involve various actors in the energy sector.

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