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Article

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International Journal of Energy Economics and Policy

Reference: Insuasty-Reina, Jeniffer Guadalupe/Osorio-Gomez, Juan Carlos et. al. (2022). A system dynamics model for the analysis of CO2 emissions derived from the inclusion of hydrogen obtained from coal in the energy matrix in Colombia. In: International Journal of Energy Economics and Policy 12 (2), S. 72 - 82.
https://econjournals.com/index.php/ijeep/article/download/12538/6658.
doi:10.32479/ijeep.12538.

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2022, 12(2), 72-82.

A System Dynamics Model for the Analysis of CO_2 Emissions Derived from the Inclusion of Hydrogen Obtained from Coal in the Energy Matrix in Colombia

Jeniffer Guadalupe Insuasty-Reina*, Juan Carlos Osorio-Gómez, Diego Fernando Manotas-Duque

School of Industrial Engineering, Universidad del Valle, Cali, Colombia. *Email: jeniffer.insuasty@correounivalle.edu.co

Received: 10 October 2021 **Accepted:** 05 January 2022 **DOI:** https://doi.org/10.32479/ijeep.12538

ABSTRACT

The environmental effects generated by the energy sector worldwide have become increasingly evident, raising the concerns of governments, industries and the research sector for addressing this problem. In the search for alternatives, hydrogen technology has drawn attention for its benefits as a new energy vector, since it is highly efficient and clean, and has multiple sources of generation. In Colombia, the possible generation of this energy vector from coal gasification has been estimated, since coal is a resource that is abundant in the territory. However, as a technology that uses a fossil resource, an analysis of the environmental effects of its implementation is necessary. The present work uses a system dynamics model to analyse the carbon dioxide (CO_2) emissions that would be generated in this process in the national context. Through simulation scenarios, a comparative analysis is carried out of the effects of the current use of coal within the energy matrix versus the use of this resource for hydrogen generation in the medium and long term. The results indicate that the implementation of this technology accompanied by a minimum CO_2 capture process would represent a reduction in the total emissions of the energy matrix.

Keywords: Hydrogen Production, Coal Gasification, Energy System, CO_2 Emissions, System Dynamics
JEL Classifications: C63; Q42; Q51

1. INTRODUCTION

Population growth has brought with it an increase in energy demand worldwide. Although this energy has various sources of origin, today the largest source of energy generation in the world still comes from non-renewable sources or fossil fuels such as oil, coal and natural gas. Over time, the harmful effects on the environment of its extraction, processing and use have become more evident (Keçebaş and Kayfeci, 2019). This problem has lately drawn the attention of governments, industries, and the educational and research sectors to jointly study alternatives that help to face this environmental problem and find economically viable options.

Recently, hydrogen technology has gained increased attention in many countries as an environmentally sustainable alternative for power generation (Moreno and Vargas, 2013). This is because hydrogen (H2) is an abundant element in nature, simple, light and, as a fuel and energy generator, based on its origin, it does not produce harmful emissions to the environment. In addition, hydrogen sources are very diverse, ranging from fossil fuels, biomass, nuclear energy and renewable energy sources, such as wind, solar, geothermal and hydroelectric; thus, hydrogen has great future energy potential (Nastasi, 2019).

Depending on the source, there are various techniques for obtaining hydrogen. These generally have an inverse relationship between the emissions they can generate and the costs they incur. In other words, the most favourable for the environment tends to be economically unsustainable on a certain scale; in contrast, the least expensive alternatives, which are indeed the most widely used, are those that have caused the greatest environmental damage over the years.

Hydrogen then receives a classification depending on the generation source and the emissions that are emitted during its production. The most notable are blue hydrogen and green hydrogen. The first one is obtained using non-renewable sources; however, in this process, there must be a minimum capture of the emissions generated. Conversely, green hydrogen is generated using renewable sources (Morante et al., 2020).

Therefore, to address this problem, it is necessary to further analyse the viability of the existing techniques, study their possible improvement and even explore new alternatives. These analyses should take into account aspects of capacity, versatility, transportation, storage and the environmental, social and economic impacts of each (Abdalla et al., 2018).

Among the forms that lead the production of hydrogen, coal gasification (CG) is a technology that is currently characterized by its high development and low costs compared to other technologies (Moreno and Vargas, 2013). The low costs of implementing this technology occur mostly in regions where there is a relative abundance of coal. However, as well as other technologies, it still has the disadvantage of a high CO_2 release, and therefore, it is still necessary to find a trade-off between processing costs and the capture and reduction of emissions (Hydrogen Council, 2020).

In Colombia, the government has invited the scientific community to study the production of hydrogen from coal and its inclusion as an energy vector in the country (Minciencias, 2020). This factor, combined with the recent development of policies that promote participation in alternative energy projects, tends towards a research opportunity. In addition, it is necessary to address the issue from different disciplines and perspectives, considering future energy planning not only in the economic and technical fields but also in the environmental and social fields (Deenapanray and Bassi, 2015).

In a review of the literature, it is found that energy systems have been modelled, among other methods, by means of system dynamics. This is an approach that, through simulation modelling, allows the analysis of complex systems, the interactions of their processes and the impact on their elements over time. Authors such as (Mutingi et al., 2017); (Momodu and Kivuti-Bitok, 2018) and (Shari and Moumouni, 2020) stand out on this issue, as they have developed studies in different countries and have used system dynamics models to analyse topics such as energy planning, capacity management and measurement of environmental impacts over time of technologies employed in the energy sector, among other related aspects.

Based on the aforementioned, in this work, system dynamics is used to address the problem, model the energy system in Colombia and analyse the inclusion of hydrogen generated by CG from an environmental perspective. The analysis focuses on comparing the CO_2 emissions of the current energy matrix, as the main indicator, against the behaviour that it would have when part of the coal is transferred to the production of hydrogen. It is taken into account that this will be an energy vector that seeks to supply part of the electric power (EP) demand before conventional sources.

2. METHODOLOGY

The model developed in this work is based on the systems thinking methodology, which initially integrates problem identification. This was addressed in the previous section. This is followed in this section by the description of the system and its representation through a causal loop diagram. Subsequently, a stock-flow diagram (or Forrester diagram) is presented, as well as the characterization of the main processes in the system, the parameter estimation and the model validation (Bala et al., 2017).

It is taken into account that some of the variables of the model were abbreviated for space issues in this document. The main abbreviations are: EP - Electric Power; EDC - Electricity Demand Coverage; Conv - Conversion; NCS - Non-Conventional Sources; HP - Hydropower Plants; TP - Thermal Plants; CP - Coal Plants; CG - Coal Gasification.

2.1. Energy System in Colombia

The energy system in Colombia is made up of four main processes: generation, transmission, distribution and commercialization; together, these processes make up the well-known National Interconnected System. Different actors participate in each of these processes, which allows the generation of energy through different technologies and from different sources and allows it to be transported to homes and industries.

The country is characterized by its great geographical qualities and global water wealth. For this reason, the country's main technology for power generation is hydroelectric, currently covering 68.3% of the total energy demand. The use of mostly renewable resources such as water, makes it one of the cleanest energy matrices. This technology is followed by thermal technology, which covers 30.7% of demand and today uses fossil sources such as natural gas (13.3%), coal (9.6%) and diesel (7.8%). Finally, on a small scale, it is followed by certain clean energy technologies, such as photovoltaics and wind, that make use of renewable or unconventional sources and cover the other 1% of the energy demand in the country (Grupo Bancolombia, 2019).

The coverage of the demand is carried out initially using unconventional sources such as solar and wind, maximizing the effective capacity of these technologies. Subsequently, the demand for energy is covered by the available capacity of hydroelectric plants and finally the available thermal sources are used. Thus, the model to be developed intends to be a representation of the Colombian energy system that includes its main variables and processes, as well as their relationships, to analyse how the inclusion of a new energy source, such as hydrogen from coal, would affect the system.

2.2. Causal Loop Diagram

The following is a representation of the system to be studied using a causal loop diagram generated in Vensim software.

The main variables to be studied are identified, and causal relationships between them are found. The blue lines represent direct causality, while the red lines between the variables represent reverse causality. The diagram is shown in Figure 1, where the following stand out as main variables: Available Coal, Available Hydrogen, EP and CO_2 Emissions. It is pertinent to mention that the production of electrical energy with TP in this model excludes the energy generated in coal-fired power plants, since this variable is studied separately.

Within this diagram, it can be seen that under the influence of one variable on another, reinforcement feedback loops (snowball) and/or compensation loops (balance) are formed. This shows that the action on one of the variables can affect itself over time and one of the advantages of system dynamics is that it allows these feedbacks to be considered over time. The figures below more specifically show the feedback loops present in the system for better analysis.

2.2.1. Feedback loops

The first two feedback loops can be seen in Figure 2. The generation of CO_2 emissions causes a concentration of greenhouse gases in the atmosphere and in turn increases the environmental effects. This, when becoming evident, increases the concern of governments to increase measures to reduce these emissions, which increases investment in alternative technologies. Those that stand out in this work are CG and CO_2 capture. With the first one, coal would be used in an alternative and cleaner way; however, this process would continue generating certain emissions, and a reinforcement loop is closed here. If CO_2 capture technology is developed, this would ultimately help reduce the emissions generated by the use of coal in the gasification process, creating a compensation loop or balance.

In Figure 3, two compensation loops are shown. The situation is similar to the previous one, but here the investment in alternative technologies would displace and therefore reduce the energy production that is done directly with thermal sources such as coal and others. It is clarified that the production of EP with TP in the present work refers to the use of thermal sources except for coal since this is set aside as one of the main analysis variables of the model.

In Figure 4, 3 compensation loops are shown that occur due to the use of available resources such as coal and hydrogen. With the greater availability of these resources, more production processes can be accomplished, and by making use of these resources, there will naturally be less availability of them.

2.3. Stock-Flow Diagram

The Stock-Flow or Forrester Diagram represents the system in terms of stocks and flows. It allows us to have a physical structure of the system for simulation, taking into account its dynamic behaviour through differential equations. The variables used in this diagram are stock variables, flow variables (inflow, or outflow), and auxiliary variables. The graphical representation of these main variables in the Vensim software is shown in Figure 5.

Equation (1) presents the mathematical representation and the main relationship between the stock and flow variables (Bala et al., 2017).

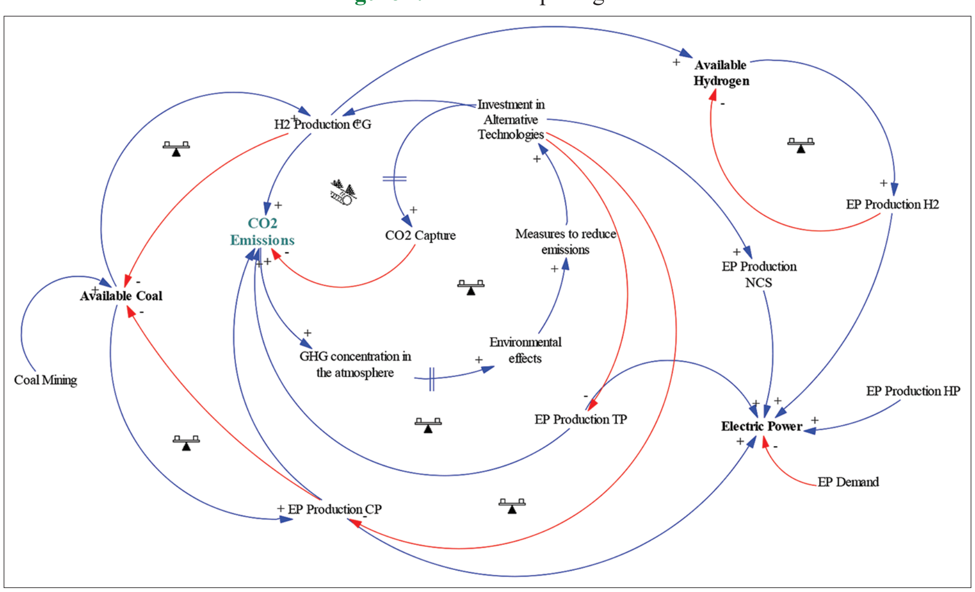
$$\text{Stock}(t) = \text{Stock}(to) + \int_{to}^{t} [\text{Inflow}(t) - \text{Outflow}(t)]dt \quad (1)$$

The Forrester Diagram in the present work has been divided into three sections to improve its understanding and visualization: "Demand and generation of EP," "Production and distribution of coal and hydrogen" and "CO_2 emissions."

2.3.1. Demand and generation of EP

Figure 6 shows the section of the model in which the demand for electrical energy and its production through the different active technologies in Colombia are projected. It is recalled that the demand for energy in Colombia is first covered by unconventional sources such as solar and wind, and would then be covered by

Figure I: Causal Loop Diagram



energy generated with hydrogen. The rest and most of this demand would be covered by hydroelectric sources and finally by thermal sources (such as gas and diesel) and coal.

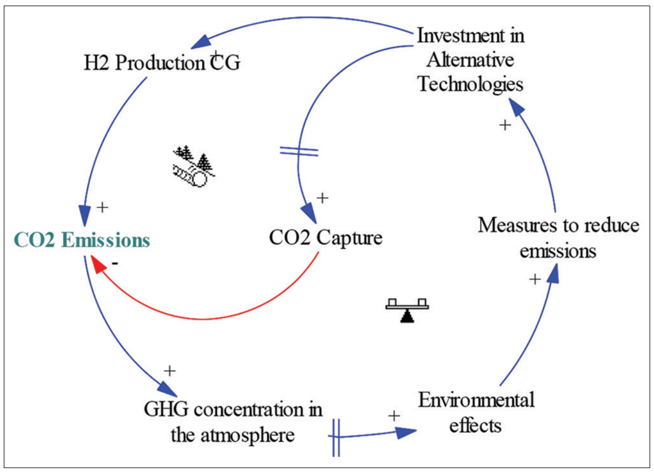
2.3.2. Coal and hydrogen production and distribution

Figure 7 shows another section of the model that corresponds to the production of coal and its distribution, as well as the production and distribution of hydrogen. In the process of hydrogen production through CG, CO_2 emissions are generated. These must be captured, which will be one of the important analysis points of this work.

2.3.3. CO_2 emissions

Several of the production processes analysed in the model have different levels of CO_2 emissions. Figure 8 shows the last section of the model that contains these main emissions in the system, which in turn feed CO_2 into the environment, the main variable of the work.

Figure 2: Feedback loop – Coal gasification and CO_2 capture



2.4. Assumptions and Characterization of Processes

The main processes to be analysed in the model are CG for the production of hydrogen and the generation of EP from this resource. The results of these processes can vary and are determined by various parameters. For this work, specific parameters are assumed under which these processes are managed. In this section, a brief description of the main parameters of each process is made, with the purpose of defining the base assumptions for the realization of the model.

2.4.1. CG process

CG is one of the most widely used technologies today for hydrogen production. In a typical CG process, pulverized coal enters a gasifier, in which, after the application of oxygen and steam, a reaction is generated, obtaining synthesis gas (composed mainly of CO, CO_2 and H2). This gas then undergoes several component separation processes, with the purpose of purifying the hydrogen required at the end (Benavides, 2015). Although this is a process with high CO_2 emissions, currently it is necessary to manage a process of capturing this gas at the same time, which, after being separated from hydrogen, is destined for storage or industrial use.

There are several parameters to determine the Conv efficiency and emissions generated in the process, such as the type of gasifying agent, the pressure and the working temperature. In addition, it must be taken into account what type of reactors will be used. The CG process assumed in the present work uses a drag flow reactor, the process temperature is in the range of 1000–1500°C, and the working pressure is between 30 and 70 bar (Damen et al., 2006).

Figure 3: Feedback loops – EP Production with coal and other thermal plants

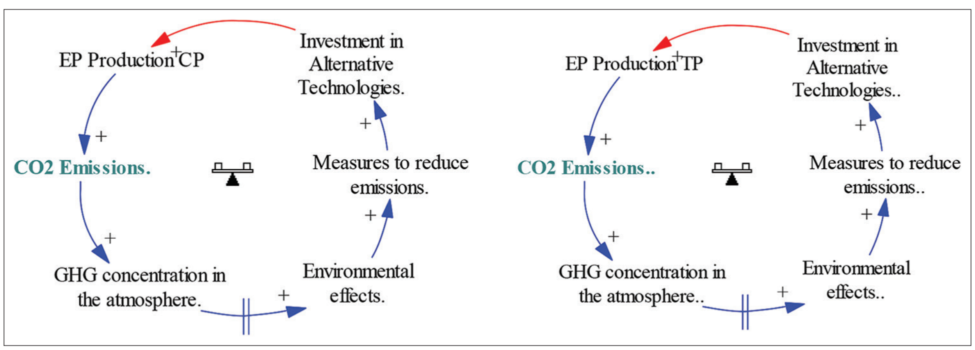
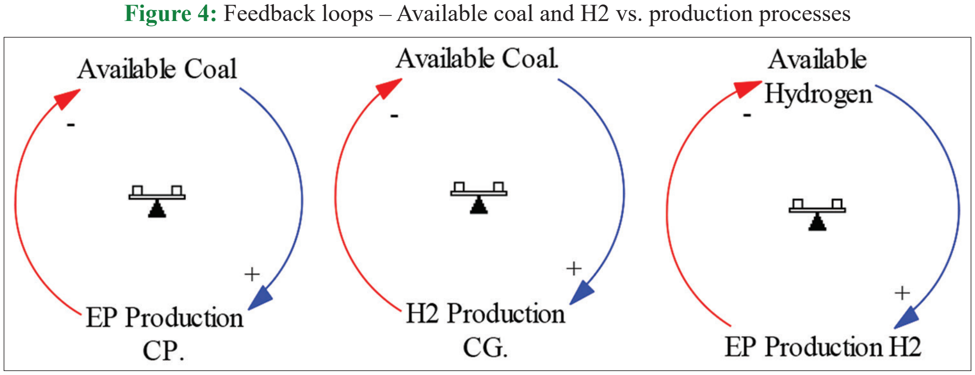


Figure 4: Feedback loops – Available coal and H2 vs. production processes



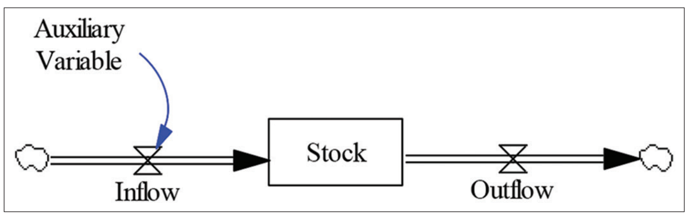
In addition to the parameters mentioned, it is relevant to give important attention to the characteristics of the main input of this process, which is coal. Depending on its characteristics, a certain efficiency can be achieved and emissions into the environment will also be generated. For this model, the use of bituminous thermal coal is assumed, whose characteristics are within the following ranges: fixed coal 60–80%; volatile matter 16–37%; ash 5–10%; humidity 2–15%. It is worth mentioning that the characteristics of the coal classified as "generic" by the UPME (Colombia's Mining and Energy Planning Unit) are within these ranges.

At the end of the CG process, it is assumed that hydrogen is completely free of CO_2, the main component to be analysed. Therefore, for the present work, in the subsequent production of EP with this hydrogen, there are no CO_2 emissions.

2.4.2. EP generation process from hydrogen

Once hydrogen is available, it can be used in different ways, among which the generation of EP and the generation of heat stand out.

Figure 5: Variables – Stock-Flow Diagram



The generation of EP can be carried out by means of fuel cells and by gas turbines, which are typically used in thermal power plants, while heat can be generated by gas engines (Morante et al., 2020). This work considers that this resource would be used for the production of EP by means of gas turbines. These are thermal machines with a combustion system where the energy of a fluid or gas is converted into mechanical or electrical energy. It should be emphasized that, given the characteristics of the hydrogen obtained in the previous process, its combustion would not generate CO_2 emissions.

2.5. Variable Definition, Parameter Quantification and Validation of the Model

This section presents the variables used in the model with their respective units and equations. For the quantification of the model, national data sources were mainly used for the EP demand, the capacity of current technologies and the Conv of some parameters. In addition, it was necessary to consult external sources regarding the process of CG for the production of hydrogen and the process of generating energy with hydrogen because neither technology has been developed within the country at this time.

Tables 1-3 show the main stock variables, the flow variables and the auxiliary variables with external data requirements. In this last table, the references of the data used are also presented. The auxiliary variables that support the model by means of equations are annexed in Appendix A at the end of the document.

Figure 6: Stock-Flow Diagram – Demand and Generation of Electric Power

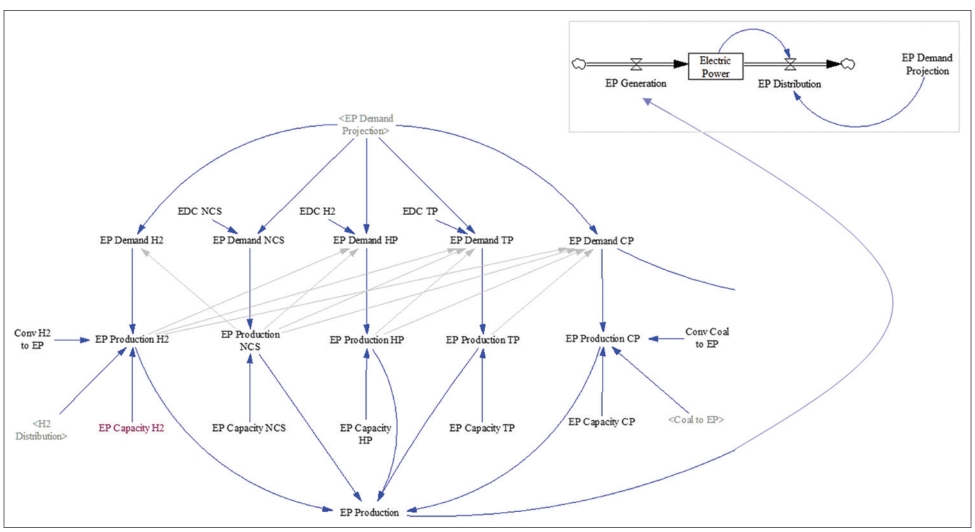


Figure 7: Stock-Flow Diagram – Coal and Hydrogen Production and Distribution

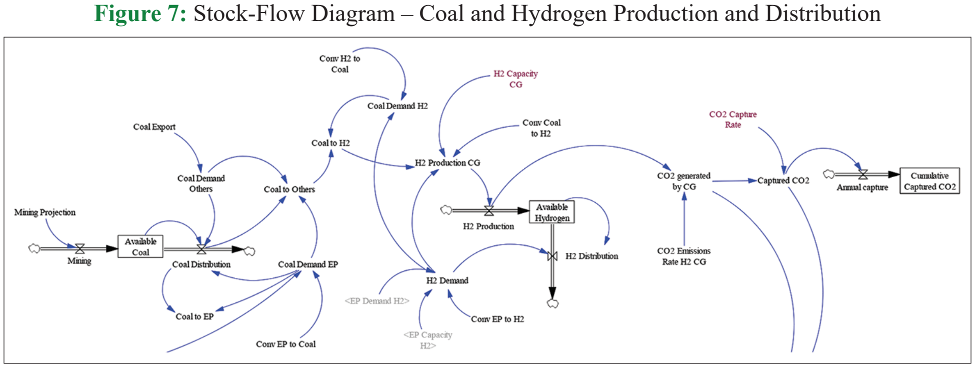


Figure 8: Stock-Flow Diagram – CO_2 Emissions

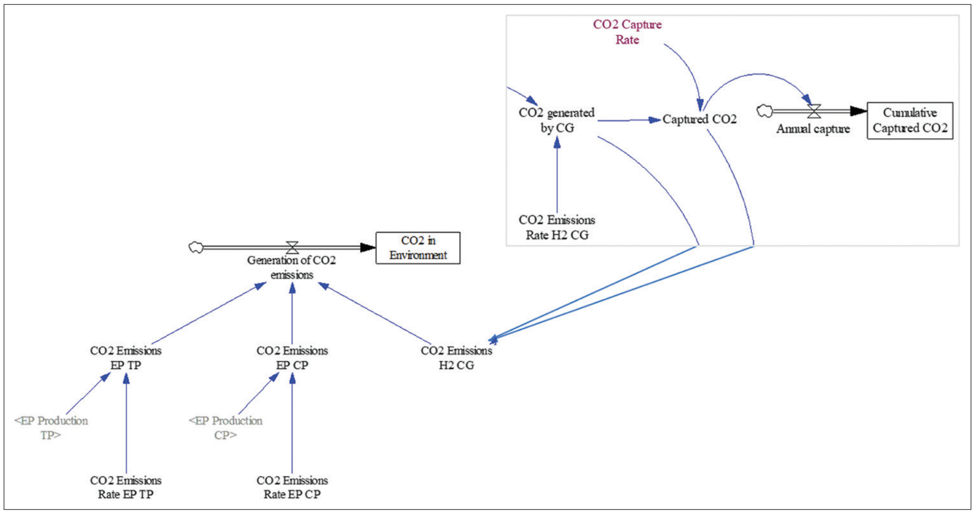


Table 1: Main state variables

Main state variables	Units	Equation	Initial value
EP	[GWh]	*EP Generation-EP Distribution*	76327.1
Available Coal	[t]	*Mining-Coal Distribution*	8.94
Available Hydrogen	[t]	*H2 Production-H2 Distribution*	0
CO_2 in Environment	[t]	*Generation of* CO_2 *emissions*	0

EP: Electric power

Table 2: Flow variables

Flow variables	Units	Equation
EP Generation	[GWh]	*EP Production*
EP Distribution	[GWh]	*MIN (Electric Power, EP Demand Projection)*
Mining	[t]	*Mining Projection*
Coal Distribution	[t]	*MIN (Available Coal, Coal Demand EP+Coal Demand Others)*
H2 Production	[t]	*H2 Production CG*
H2 Distribution	[t]	*MIN (Available Hydrogen, H2 Demand)*

EP: Electric power, CG: Coal gasification

2.5.1. Model validation

A model always consists of less than the studied system; for this reason, it is said that no model can be totally "accurate" or "valid." Systems dynamics, however, does not seek to find specific values or results of the variables of a system, but rather seeks to know and understand its general behaviour over time.

In this regard, after having quantified the model and to verify the validity of its results, structural and behavioural tests were performed (Bala et al., 2017). Initially, the structure of the model was reviewed in detail with energy system experts, and the parameters were verified. Simulation runs were carried out in which important parameters were varied with extreme values, and a certain immediate behaviour of some variables was expected. With this, it was possible to adjust some restrictions of the model to ensure certain conditions within some processes.

In addition, using actual historical reference data, runs were performed, and the results were compared with available current and projected data. Finally, congruence and coherence were found in the results that the model yields, showing that these are close to the real data available.

3. RESULTS AND DISCUSSION

Once the model is completed and validated, the analysis scenarios are established to recognize the behaviour of CO_2 emissions from both the current energy generation processes within the Colombian power system and those that would be generated from the implementation of the CG process. Additionally, it seeks to know how the CO_2 capture process influences the analysis.

Before defining the scenarios, some important parameters that are considered in the model and would remain constant during the analysis should be noted. Table 4 shows the fixed generation capacity parameters of the different technologies. Table 5 shows the demand coverage factors for each technology. To establish these values, a percentage of participation of each was estimated based on historical generation data from 1990 to 2019. The references of the data for each table below are presented in Table 3.

3.1. Scenarios

The considerations for creating each scenario will be described below. Then, in Table 6, a summary of the parameters used in each of them is provided.

3.1.1. Base scenario

This scenario represents the current situation of EP generation in Colombia where hydrogen is not yet produced. Therefore, the initial parameters for the hydrogen production capacity by gasification, such as the generation of electrical energy with

Table 3: Auxiliary variables (data)

Auxiliary variables	Units	Values	References
EP Demand Projection	[GWh]	:=GET XLS DATA	(UPME, 2019c); (UPME, 2020)
EDC NCS	%	0.0153	(IEA, 2021)
EDC H2	%	0.7409	(IEA, 2021)
EDC TP	%	0.174	(IEA, 2021)
EP Capacity NCS	[GWh]	177.22*8.76*0.373	(ACOLGEN, 2021); (GeoLCOE, 2021)
EP Capacity H2*	[GWh]	0	(ACOLGEN, 2021); (GeoLCOE, 2021.)
EP Capacity HP	[GWh]	11846.2*8.76*0.7	(ACOLGEN, 2021); (GeoLCOE, 2021)
EP Capacity TP	[GWh]	3700.24*8.76*0.5467	(ACOLGEN, 2021); (GeoLCOE, 2021.)
EP Capacity CP	[GWh]	1626*8.76*0.5106	(ACOLGEN, 2021); (GeoLCOE, 2021)
Conv H2 to EP	[GWh/t H2]	1/83.79888	(Verma et al., 2015)
Conv EP to H2	[t H2/GWh]	83.79888	(Verma et al., 2015)
Conv Coal to EP	[GWh/t]	1/349.64763	(UPME, 2018); (Kumar et al., 2019)
Conv EP to Coal	[t/GWh]	349.64763	(UPME, 2018); (Kumar et al., 2019)
Conv Coal to H2	[t H2/t]	1/7.33	(Burmistrz et al., 2016)
Conv H2 to Coal	[t/t H2]	7.33	(Burmistrz et al., 2016)
Mining Projection	[t]	:=GET XLS DATA	(UPME, 2019b)
Coal Export	[t]	:=GET XLS DATA	(UPME, 2019a)
H2 Capacity CG*	[t]	0	(Laborde et al., 2010)
CO_2 Capture Rate*	%	0	(Verma et al., 2015); (Morante et al., 2020)
CO_2 Emissions Rate H2 CG	[t CO_2/t H2]	19.424	(Verma et al., 2015)
CO_2 Emissions Rate EP CP	[t CO_2/Gwh]	886.29032	(UPME, 2018)
CO_2 Emissions Rate EP TP	[t CO_2/Gwh]	664.71774	(UPME, 2018)

EDC: Electricity demand coverage, Conv: Conversion, NCS: Non-conventional sources, HP: Hydropower plants, TP: Thermal plants, CG: Coal gasification

Table 4: Fixed parameters - effective electric power generation capacity

Technology	Installed capacity [MW]	Plant factor	Effective capacity [MW]	Energy per year [GWh]
Hydroelectric	11846	70.0%	8292	72641
NCS	177	37.3%	66	579
Thermal	3700	54.7%	2023	17722
Coal	1626	51.1%	830	7272
Total	17350		11212	98214

NCS: Non-conventional sources

Table 5: Fixed parameters of demand coverage

Electric power demand coverage	
EDC NCS	1.5%
EDC HP	74.1%
EDC TP	17.4%
EDC CP	7.0%

EDC: Electricity demand coverage, NCS: Non-conventional sources, HP: Hydropower plants, TP: Thermal plants

hydrogen, are 0. Likewise, the capture rate is not activated in this first scenario.

3.1.2. Low scenario – Cmin

For this scenario, the production of hydrogen and the generation of EP from this resource are taken into account. As this last production process would be carried out by means of gas turbines, it is considered to establish the generation capacity as 10% of the capacity of the TP (not counting the CP), which is similar to the current installed capacity of renewable sources. As its name indicates, low values are estimated for both hydrogen production and energy generation from this resource. Additionally, "Cmin" means that a minimum CO_2 capture level is taken into account in the CG process.

This minimum capture level is established based on (Morante et al., 2020) where the maximum CO_2 emissions from the hydrogen generation process are determined so that it is classified as blue, which is defined as "hydrogen generated from non-renewable sources that emits <4.37 $kgCO_2eq/kgH2$." Therefore, based on the emissions per kg of H2 in the process, there is a requirement for a capture rate of 0.775.

3.1.3. Low scenario – CM

This scenario has the same conditions as the previous one (Low scenario - Cmin); however, the capture rate is increased to the maximum possible value found in the literature, which is 0.99.

3.1.4. High scenario – Cmin

In this scenario, the capacity to generate EP from hydrogen is increased in percentage so that it covers 50% of the currently available capacity in TP. This also indicates that this capacity would cover roughly slightly more of what coal currently covers in the power system. In the same way as the "Low scenario - Cmin," a minimum CO_2 capture level was taken into account.

3.1.5. High scenario – CM

This scenario has the same conditions as the previous one (High scenario - Cm), but a maximum capture rate of 0.99 is considered.

3.2. Analysis of the Results

The simulation was executed in Vensim DSS software. The beginning of the simulation or "period 0" is assumed to be 2020; therefore, its values are those estimated for that year. The simulation is carried out between 2021 and 2050 with an annual time step.

3.2.1. EP demand coverage

Figure 9 shows how demand coverage occurs in the simulated period from the base, low and high scenarios. The scale presented on the vertical axis corresponds to GWh year.

One of the aspects to highlight from the base scenario, which considers the total capacity of the current sources of EP generation, is that if they are constant, they will cover the projected demand in Colombia until 2031. If hydrogen is implemented as an energy vector, in the low scenario, the energy demand would be covered for another year. For the high scenario, it is observed that the energy demand would be covered for 5 more years, that is, until approximately 2036.

Figure 9: Electric power demand vs. generation – Base, low and high scenarios

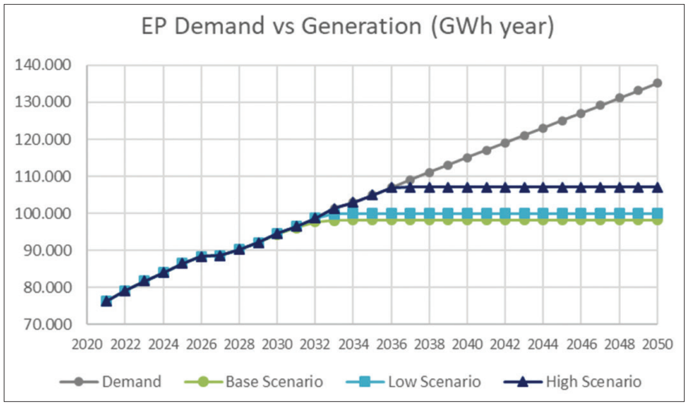
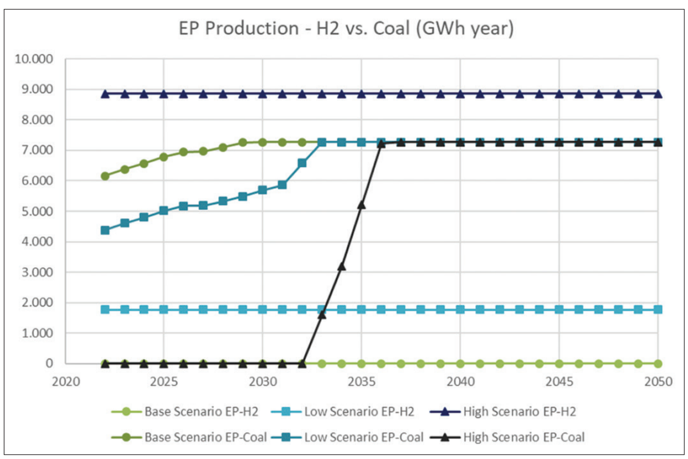


Figure 10: EP production H2 vs. coal – Base, low and high scenario



3.2.2. EP generation - coal versus H2

Figure 10 allows us to appreciate what the production of traditional EP with coal would be like compared to the new alternative proposed for hydrogen, for each of the scenarios. It is observed that with greater participation of the new technology, there is less generation of energy with coal in a conventional manner.

It is observed that in the high scenario, the production of EP with coal would be zero until 2032 because this energy would be covered in its entirety with other technologies and the hydrogen generated. After this year, the installed capacities of the other technologies would reach their maximum, which is where the generation of EP would be required again with coal, seeking to satisfy the demand.

3.2.3. CO_2 emissions

Figure 11 shows the level of total CO_2 emitted each year in the national energy matrix for each of the scenarios considered. The scale presented on the vertical axis corresponds to millions of tons of CO_2.

It is observed that the low scenarios do not present a significant difference compared to the base scenario. However, it must be taken into account that the scale treated corresponds to millions of tons, which from the lowest scenario can represent great emissions savings. In the high scenarios, for a minimum capture level, a considerable reduction in CO_2 emissions is observed over the period of time, while hydrogen technology covers a greater part of the energy demand than the coal source. For the high scenario where a maximum capture of emissions is considered, a significant reduction of these emissions to the environment is perceived.

Analysing the trend of the curves in Figure 12, where the accumulated CO_2 emissions are found, it could be estimated that, projecting the capacities of the technologies, considering the projects under construction in the future and continuing with an investment in energy production technologies with hydrogen, in the production of this input and the capture of CO_2, the generation of these emissions in the energy sector for the high scenarios would be highly placated.

Table 6: Scenarios summary

Scenarios and Technologies	Installed capacity [MW]	Plant factor	Effective capacity [MW]	Energy per year [GWh]	Installed capacity [Ton H2]
Base scenario					
Energy with Hydrogen	0.00	0.0%	0.00	0.00	
Coal gasification					0.00
Low scenarios (Cmin and CM)					
Energy with Hydrogen	370.02	54.7%	202.30	1772.16	
Coal gasification					163355.53
High scenarios (Cmin and CM)					
Energy with Hydrogen	1850.12	54.7%	1011.51	8860.80	
Coal gasification					816777.66
CO_2 Capture Rate					
Cmin scenarios: 0.78					
CM scenarios: 0.99					

Figure 11: CO_2 emissions – All scenarios

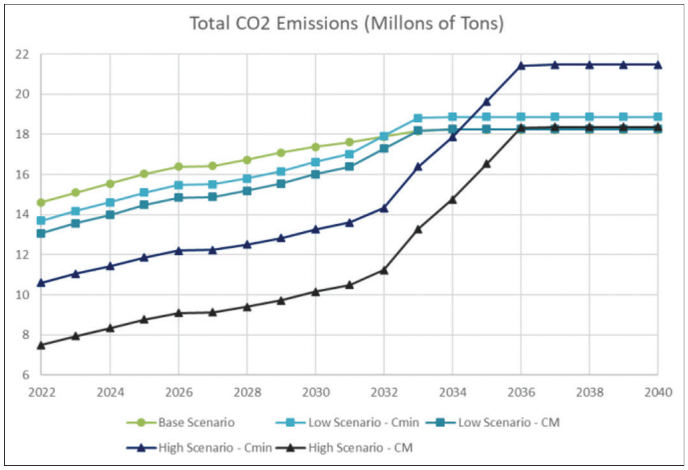
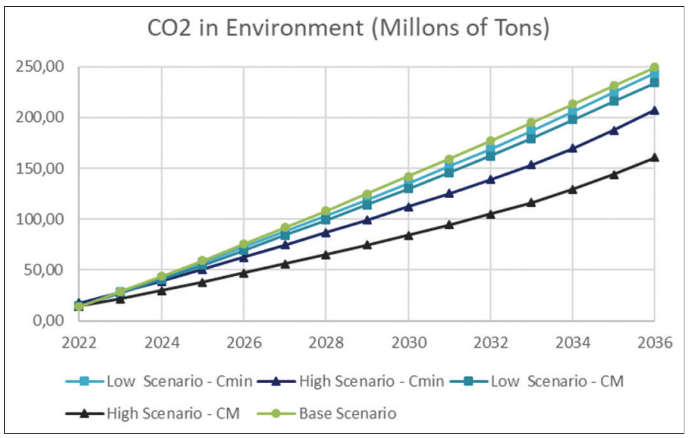


Figure 12: Cumulative CO_2 - All scenarios



4. CONCLUSIONS

Initially, by constructing a causal diagram, an interrelation between the generation of CO_2 emissions to the environment and the incentive towards investment in new energy generation technologies was observed, but it is also known that these events can take some time to yield their effects. For this reason, the importance of knowing the possible long-term outlook of the sector is recognized so that strategies can be sped up to address future problems related to the expansion of the energy portfolio and the mitigation of emissions from the sector.

The CG process analysed in this work can be seen as an alternative for the use of coal, where it goes through a process in which harmful emissions to the environment can be controlled and captured. Through this process it is able to obtain a pure energy vector at the end such as hydrogen, as well as CO_2, which is captured and stored for possible use or disposal. Unlike the coal combustion process, the gasification process would allow the production of hydrogen, which contains a higher calorific value and energy power. In addition, it has the advantage that it can be stored for later use in a combustion process to generate electricity, which would be free of emissions.

As mentioned, in this process, the capture of CO_2 becomes a determining factor, which could be recognized. In the first instance, it is decisive for the fulfilment of the requirements of the process to obtain blue hydrogen, which requires that the emissions generated in the process are not released into the environment. Yet, when analysing the problem from the regulatory and economic scope, the released emissions would have economic effects that may not favour the implementation of the technology. However, if the problem is approached from the use of captured CO_2, this would present various alternatives, which can support the process and make it more viable.

In the base scenario, it was found that the projected electricity demand could be covered with current technologies and their maximum capacities only until 2031. Implementing hydrogen power generation technology with a capacity approximate to that which is currently covered with renewable energies, would allow the coverage of one more period within the matrix, while if the new technology is implemented with a capacity approximately equal to that of coal-fired plants, 5 more years could be covered.

Regarding the analysis of CO_2 emissions from the energy matrix for each of the scenarios proposed, the implementation of the new technology would bring benefits in each of them, showing a reduction in these emissions, conditioned by both the level of production in the gasification process, and the level of CO_2 capture.

Given the technical complexity and the high costs that the implementation of the studied technologies may have, for future work, it is necessary to address the problem from the economic sphere, also considering some technical and regulatory aspects. Additionally, it would be expected to have the projection of the increase in the generation capacity of the energy matrix, considering the projects underway and approved for the future.

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APPENDIX

Tables A-I: Auxiliary variables

Auxiliary variables	Units	Equation
EP Demand NCS	[GWh]	*EP Demand Projection*EDC NCS*
EP Demand H2	[GWh]	*EP Demand Projection-EP Production NCS*
EP Demand HP	[GWh]	*IF THEN ELSE ([EP Demand Projection*EDC H2]<[EP Demand Projection-EP Production NCS-EP Production H2], [EP Demand Projection*EDC H2], [EP Demand Projection-EP Production NCS-EP Production H2])*
EP Demand TP	[GWh]	*IF THEN ELSE ([EP Demand Projection*EDC TP]<[EP Demand Projection-EP Production NCS-EP Production H2-EP Production HP], [EP Demand Projection*EDC TP], [EP Demand Projection-EP Production NCS-EP Production H2-EP Production HP])*
EP Demand CP	[GWh]	*IF THEN ELSE ([EP Demand Projection-EP Production NCS-EP Production H2-EP Production HP-EP Production TP]>0, [EP Demand Projection-EP Production NCS-EP Production H2-EP Production HP-EP Production TP], 0)*
EP Production	[GWh]	*EP Production H2+EP Production NCS+EP Production HP+EP Production TP+EP Production CP*
EP Production NCS	[GWh]	*MIN (EP Capacity NCS, EP Demand NCS)*
EP Production H2	[GWh]	*MIN (EP Capacity H2, MIN [EP Demand H2, H2 Distribution*Conv H2 to EP])*
EP Production HP	[GWh]	*MIN (EP Capacity HP, EP Demand HP)*
EP Production TP	[GWh]	*MIN (EP Capacity TP, EP Demand TP)*
EP Production CP	[GWh]	*MIN (EP Capacity CP, MIN [EP Demand CP, Coal to EP*Conv Coal to EP])*
Coal Demand Others	[t]	*Coal Export*
Coal Demand EP	[t]	*EP Demand CP*Conv EP to Coal*
Coal to Others	[t]	*IF THEN ELSE (Coal Distribution≥[Coal Demand EP+Coal Demand Others], Coal Demand Others, IF THEN ELSE [Coal Distribution≥Coal Demand EP, Coal Distribution-Coal Demand EP, 0])*
Coal to EP	[t]	*MIN (Coal Distribution, Coal Demand EP)*
Coal to H2	[t]	*MIN (Coal to Others, Coal Demand H2)*
Coal Demand H2	[t]	*H2 Demand*Conv H2 to Coal*
H2 Demand	[t]	*MIN (EP Demand H2*Conv EP to H2, EP Capacity H2*Conv EP to H2)*
H2 Production CG	[t]	*MIN (H2 Capacity CG, MIN [H2 Demand, Coal to H2*Conv Coal to H2])*
CO_2 generated by CG	[t]	*H2 Production**CO_2 *Emissions Rate H2 CG*
Captured CO_2	[t]	CO_2 *generated by CG**CO_2 *Capture Rate*

(Contd...)

Tables A-I: *(Continued)*

Auxiliary variables	Units	Equation
CO_2 Emissions H2 CG	[t]	CO_2 *generated by CG-Captured* CO_2
CO_2 Emissions EP CP	[t]	*EP Production CP**CO_2 *Emissions Rate EP CP*
CO_2 Emissions EP TP	[t]	*EP Production TP**CO_2 *Emissions Rate EP TP*

EDC: Electricity demand coverage, EP: Electric power, Conv: Conversion, NCS: Non-conventional sources, HP: Hydropower plants, TP: Thermal plants, CG: Coal gasification

Table A-II: Extra variables

Extra variable	Units	Equation
Cumulative Captured CO_2	[t]	*Annual capture*
Annual capture	[t]	*Captured* CO_2