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A microworld for learning about the diffusion of non-conventional renewable electricity generation technologies in Colombia

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"I've made up my mind to enjoy this drive. It's been my experience that you can nearly always enjoy things if you make up your mind firmly that you will. Of course, you must make it up FIRMLY".

Anne of Green Gables

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Abstract

The speed of changes in the policies and agents of the energy system in Colombia is a conflict when it comes to understanding such a complex system, considering the energy transition towards renewable matrix. This study aims to develop a microworld to learn and understand the dynamics of diffusion of renewable energy technologies in Colombia, and the effect of different incentive policies in such diffusion. We used a system dynamics model to understand the behavior of the available potential and the installed capacity of different electricity generation technologies in Colombia, considering the effect of the regulator's performance over the diffusion. Thereafter, the model was used to develop an online microworld in which the users can play and test different incentives to renewable energy and learn about the systems underlying structure and operation while learning about the process. The main results of the pilot testing suggest that the microworld contributes to improving the knowledge of the users and allowing them to better understand the energy system.

Keywords: Microworld, system dynamics, learning, renewable energy.

Un micromundo para el aprendizaje sobre la difusión de tecnologías renovables no convencionales de generación de electricidad en Colombia

Resumen

La velocidad de los cambios en las políticas y los agentes del sistema energético en Colombia es una barrera para entender un sistema tan complejo, considerando la transición energética hacia una matriz renovable. Esta tesis, tiene como objetivo desarrollar un micromundo para entender y aprender sobre la dinámica de la difusión de las tecnologías de generación renovable en Colombia, y sobre el efecto de diferentes políticas e incentivos sobre dicha difusión. Utilizamos un modelo de dinámica de sistemas para comprender el comportamiento del potencial disponible y la capacidad instalada de diferentes tecnologías de generación en Colombia, considerando el efecto del desempeño del regulador sobre la difusión. A partir de este modelo desarrollamos un micromundo en línea en el que los usuarios pueden jugar, probar diferentes incentivos para las energías renovables y aprender sobre la estructura y la operación subyacente de los sistemas mientras aprenden sobre el proceso. Los resultados principales de las pruebas piloto sugieren que el micromundo aporta al conocimiento de los usuarios y les permite entender mejor el sistema energético.

Palabras clave: Micromundo, dinámica de sistemas, aprendizaje, energía renovable.

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Abbreviations

Abbreviation	Item
AV	Available Potential
BM	Biomass
COP21/23	21/23 Conference of Parties
DANE	Departamento Administrativo Nacional de Estadística
DIAN	Dirección de Impuestos y Aduanas Nacionales
FIT	Feed-In Tariff
GBM	Generalized Bass Model
GHG	Greenhouse Gas
IC	Installed Capacity
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales
IRENA	International Renewable Energy Agency
LCOE	Levelized Costs Of Energy
MADS	Ministerio de Ambiente y Desarrollo Sostenible
MFS	Management Flight Simulator
MinMinas	Ministerio de Minas y Energía
MIT	Massachusetts Institute of Technology
NEA	Nuclear Energy Agency
NIC	New Installed Capacity
PNUD	Programa de las Naciones Unidas para el Desarrollo
RE	Renewable Energy
SHP	Small Hydro Power
SPV	Solar Photovoltaic
UNAL	Universidad Nacional de Colombia
UPME	Unidad de Planeación Minero-Energética

Introduction

In 2014 Colombia started an energy transition process, in the search for a more efficient, sustainable, and reliable energy sector. The main drivers for this transition were the need for reducing greenhouse gases (GHG) emissions and diversifying the energy sources. Different tools, such as simulation models, have been developed to support the decision-making process in the energy transition. However, the changes in the energy sector are happening so fast that updating these models with newly developed policy tools becomes a challenge. What is missing, and of our particular interest, are tools oriented to learning, which allows understanding the constantly changing dynamics of the energy sector. This study proposes the development of a learning microworld to understand the dynamics of renewable energy in Colombia.

In the recent COP23 agreement, Colombia ratified the commitment acquired in COP21 of reducing 20% of the country's projected emissions by 2030 (Barrera et al., 2015). Although Colombia has a relatively clean energy matrix, consisting of 70% hydroelectric power (IRENA, 2018a), the electricity sector has a significant potential for climate change mitigation, given that it contributes 10% to the Colombian greenhouse gas emissions (IDEAM et al., 2016). The country has developed a strategy for transforming the energy sector and reducing its contribution to climate change. One of the measures has been the design of several policy incentives that seek to partially replace generation from fossil fuels with renewable sources. Additionally, the Colombian electricity sector needs to reduce the associated risk of a generation that is highly dependent on water resources. This dependence can generate periods of energy shortage due to droughts and, therefore, high energy prices (UPME & Ministerio de Minas y Energía, 2015). The diversification of the energy matrix with non-conventional renewable energy, such as solar, wind, and biomass, could generate reliability in energy supply and, therefore price stability, and contribute to Colombia's economic development (UPME & Ministerio de Minas y Energía, 2015).

The transformation of the energy sector started in 2014 with the introduction of incentive mechanisms to renewable energy projects through the renewable energy law (law 1715/2014) (Congreso de la República de Colombia, 2014). This law created high expectations about the diffusion of renewable energy in Colombia and created the need to understand how fast or slow will be the penetration of renewable technologies. Understanding this diffusion process is not a trivial task since the energy system and the energy transformation of Colombia involves a high degree of complexity.

The complexity of the energy system is due to the interactions between different actors, delays, the speed of changes, and, in the case of renewable energy, strong learning curve effects. As mentioned above, one approach to studying this complexity has been the development of simulation models. Authors, such as Arias-Gaviria, Carvajal-Quintero, & Arango-Aramburo (2019), Castaneda, Franco, & Dyner (2017), and Henao & Dyner (2020) have tried to explain the behavior of the system considering the complexity of its structure. However, the speed of the changes in the real system has exceeded the modeling capacity. With the complexity of the structure of the system, it is difficult to reproduce a model that represents the exact electricity market situation. Moreover, advanced simulation models do not always generate learning for their users, because they do not involve guided experimentation or feedback. Finally, many of these models are not available for free use, in which case their use for learning purposes is even more limited. Thus, there is still a need to develop learning-oriented tools to understand the dynamics of renewable energy diffusion through incentives in a simplified way.

This work aims to develop an interactive tool, or microworld, that allows the introduction of users, even without previous specific knowledge, to an approximation of the real system, and that generates quick learning about the diffusion of renewable energy in Colombia. This thesis has the challenge of developing a virtual platform that faces the users to the tasks of reaching certain goals related to renewable energy, but at the same time, the platform should be adaptable to the market changes and the users' needs. We considered several methods for developing the platform, including microworlds, simulators, and flight simulators (Boring et al., 2012). We have chosen the microworlds methodology because they are characterized by having a simplified and user-friendly interface that can be played online, facilitating the users' access. Also, microworlds can be adapted to each user's requirements, allowing them to perform many experiments and learn from them. Compared to microworlds, simulators offer unfriendly, advanced interfaces, and flight simulators require the presence of the user in a site to play with real controls (Boring et al., 2012).

Microworlds have been used as a tool for teaching in academic and organizational environments, to confront users with decision-making situations. These tools base their pedagogical contribution on constructionism, which is an educational tendency directed on the self-construction of learning using the computer and virtual instructions. With a microworld, students can solve given challenges, experiencing the situation by themselves, and eliminating the limitations of experimentation in real life, such as high costs and prohibited decisions (Papert, 1986).

Today different microworlds have been highly used for teaching and training. An example for this is C-Roads (MIT et al., 2019) that teach people the effects of climate change by taking actions to reduce greenhouse gas emissions; and En-Roads (Climate Interactive et al., 2019) that is a free and online policy simulator that allows people to explore themselves the consequences of economic growth, land use, and other policies on energy growth. Particularly, the microworld Enerbiz was developed for the Colombian electricity sector (Franco et al., 2012). This game was created to train Colombian energy market agents to learn about the operation and the management of the risks associated with decision making. These platforms are considered learning environments of complex systems (Morecroft, 2007).

This thesis has the following structure: chapter one presents a background on microworlds and renewable energy technologies promotion, the learning, and teaching bases for the microworlds. Based on this background we identified the research problem and defined the objectives of this thesis. Chapter two presents the methodology for developing the renewable energy diffusion model for the learning microworld, and the microworld virtual environment, including all the learning and teaching supporting material. Chapter three presents the microworld's underlying diffusion modeling results Chapter four shows the results of the development of the virtual environment, and the results of the pilot testing of the final platform. Finally, chapter five presents conclusions about this work.

1 Learning in and about renewable energy through microworlds

This chapter presents a literature review on the interactive tools used to support the learning process –microworlds–, and on renewable energy promotion. Later, we discuss the pedagogical foundation of the microworlds, and finally, based on the conclusions of the literature review, we identified the research problem and the objectives of this research.

1.1 Background

To understand the application of a tool for learning about the diffusion of non-conventional renewable energy generation technologies, we developed a literature review divided into two parts: microworlds and renewable energy promotion.

1.1.1 Microworlds

Given the complexity of the systems and the limitation of their intervention in real-time, new technologies allow study through virtual learning environments. These virtual environments are tools with characteristics such as online access, applications, or computer programs that serve as support to professors and students, teaching didactics, and the elimination of time and space barriers, promoting constant participation of users.

Microworlds are simulation tools classified as a virtual environment, which start from an abstraction of the system in a simplified model, with an interface and structure of use that allows users to generate some kind of learning. Microworlds have been widely used as a learning facilitator tool both at an academic and organizational level, some of the most common applications of microworlds are presented in the training of personnel in companies, to face directly decision-making situations that they will have to handle in their work environment. These types of tools reduce the costs associated with errors due to a lack of training in organizations. Papert (1980) proposed the first approximation of microworlds. In his work, he defined microworlds as situations or environments that can be explored in a non-linear way by any type of user and that promote learning by allowing users to modify their environment through decision-making. Other authors define microworlds as business games that provide risk-free environments (Strategy dynamics LTD, 2019c) and offer the opportunities of virtual worlds, such as, the possibility of making forbidden decisions with the sole objective of learning on its result, the immediacy of the conclusions, and the graphical interface that contributes to spatial intelligence for any type of user (J. Sterman, 2000).

Some of the advantages of microworlds are the multimedia information presented interactively (Galvis, 1997), the promotion of collaborative environments between virtual and real media (Galvis, 1997), the ease of manipulating the levels of desired interactivity for the user (Galvis, 1997) the possibility of combining objects or operations of complex shapes and simplifying them (L. P. Rieber, 2002), the possibility of experiencing situations that are impossible in real life (Katsaliaki & Mustafee, 2015) and the ease of personal monitoring of the decisions made (Katsaliaki & Mustafee, 2015). Thus, microworlds facilitate the understanding of the dynamics of the subsystems that compose it and generate learning through experimentation in decision-making, giving the possibility of taking different roles in the real system, but without incurring the risk of decision-making involved in the system. For this reason, microworlds are considered as a complementary tool in learning.

Microworlds have had a high impact on learning and have been applied in areas such as business administration, finance, supply chains, dynamics of market strategies, sustainability, and natural resources management, public policies, among others. One of the first well-known microworlds is the Beer Game (Forrester, 2019), which represents a commercialization and supply chain, where the objective of the player is to minimize the costs related to the operation, deciding how many units to produce or order. While playing this microworld, participants are expected to learn about the bullwhip effect, how structure influences the behavior of systems, and how systems cause their behaviors.

There are also microworlds developed from specific problems that occurred in reality, with which, the microworld seeks to generate learning about that situation to prevent the mistakes made from being repeated in similar situations. This is the case of People Express 2000, described in 1990 (Strategy dynamics LTD, 2019d), a simulator of the commercial operation of an airline based on the information and history of the People Express airline, a low-cost airline, initially very successful, but due to problems in its operation and administration, it had to merge with another airline. This microworld seeks to generate learning about the complexity of the business as social systems, their feedback, and their interactions that generate limits to growth, such as not having airplanes available. And the elimination of mental models that do not allow us to perceive the real problem.

Another microworld used for learning about the management of commonly used resources and the difficulties that this represents is FishBanks, developed in 1996 (MIT et al., 2020), which simulates the fishing carried out by various companies in a common area. The objective of the participants is to maximize their profits. The microworld Beefeater restaurant (or White Label Restaurants) was introduced in 1996 (Morecroft, 2007; Strategy dynamics LTD, 2019a); and later, Brand Management Microworld in 2008 (Strategy dynamics LTD, 2019b), which have similar objectives of profitable growth of a business. On the one hand, Beefeater restaurant confronts users with the challenge of growing a multi-consumer retail business over up to 10 years. On the other hand, Brand Management Microworld simulates the sales and profitability of a high-value consumer brand and the user's goal is to grow the brand profitably. Microworlds have also had different applications in the entertainment industry, with launches such as SIMCITY (Electronic Arts Inc, 2019), a city-building video game in which parts of the city are created to supply and expand it with the budget that is available.

Microworlds have also been used to eliminate paradigms about the diffusion of new products, an example of this is Driving the future, a Management Flight Simulator (MFS) of the US Automobile Market launched in 2017 (Keith et al., 2017). This microworld on strategies and public policies of the manufacturers of alternative fuels automobiles in the United States seeks that the user observes the behavior of different scenarios of diffusion of alternative fuels vehicles. Through this exercise, users learn the concept of diffusion and change their mental models regarding the introduction of alternative fuel vehicles on the market.

Regarding the application of microworlds focused on our topic of interest - learning about the dynamics of adoption and incentives for renewable energy technologies – we know of some relevant developments since the late 1990s. For example, The Electricity Markets Microworld (Vlahos, 1998) allows simulating the deregulated electricity market in the United Kingdom. With this microworld, the user is expected to learn about the operation of the market and the risks associated with its administration. For the Colombian case, Dyner, Larsen, & Franco (2009) presented Games for Electricity Traders: Understanding Risk in a Deregulated Industry, which seeks to train the agents of the Colombian market to know its operation and the risk management involved in making decisions. Later, in 2012, Franco, Velásquez, & Cardona (2012) developed a microworld to simulate a short-term electricity market, which proposes a simulation of the energy market in Colombia, in which the user must obtain the maximum profit.

Finally, the most recent microworlds have been focused on emerging companies in the energy industry, such as CleanStart: Simulating a Clean Energy Startup (J. Sterman, Miller, et al., 2019), where participants take the role of an emerging company in the clean energy sector and must make energy price and resource decisions directed at staff. On the other hand, in the case of a leading company in the market, specifically focused on a generation technology, there is Eclipsing the Competition: The Solar PV Industry Simulation (J. Sterman, 2019), where users play the role of the leaders of a leading Solar Photovoltaic industry and must compete with other simulated companies online, with which it is expected that users learn about price challenges and learning curves, as well as the effect of entry of new competitors to the market.

1.1.2 Renewable energy promotion

There have been different strategies for the promotion of renewable energies (RE) to accelerate their diffusion and mitigate climate change and the diversification of the world energy matrix (Babiker et al., 2018). The global RE capacity increased 7.9% in 2018, in that year, Asia represented 61% of the total of new RE installations with 11.4% growth compared with 2017, Oceania presented a growth of 17.7%, thus being the fastest growth (IRENA, 2019). However, there are still barriers that hinder the entry and operation of these technologies in the energy mix as a representative portion, mainly in Latin American markets. Particularly in Colombia, the main barriers established by the Unidad de Planeación Minero Energética (2015) are the erroneous incentives for conventional technologies, difficulties in financing unconventional technologies, regulations, and institutions traditionally established around conventional technologies, among others. To overcome barriers to the entry and operation of RE, different incentives have been implemented internationally, focused on investment and the generation of these technologies. Next, we present a brief description of the most common mechanisms for promoting renewable generation technologies (Haas et al., 2011; Jacobs et al., 2013; UPME & Ministerio de Minas y Energía, 2015):

- Quotas: establishing a share of renewable energy that must be commercialized can be a goal.
- Emission caps: the number of emissions allowed before generating the carbon tax.
- Feed-in-tariff (FIT or Guaranteed Rate): fixed price of purchase of energy from renewable energy producers.
- Tax incentives: Exemptions or reductions to income taxes, VAT, and duties. Tax credits and/or grants, loans, or direct investments from the state. Or carbon tax as a charge for the generation of Greenhouse gas emissions that can be used for clean energy.
- Bidirectional measurement: measurement of energy surpluses to be remunerated, for the particular case of net measurement, the remuneration rate coincides with the user's consumption rate.
- Auctions: tender for a renewable energy goal, either by generation or by capacity, where the lowest-cost projects are chosen.
- Renewable energy certificates: granting of certificates to renewable energy producers, which can be commercialized, are usually used for disaggregation, verification, and commercialization purposes.
- Contracts for difference: fixed price guarantee for electricity for renewable energy producers, after they participate in the wholesale market.
- Incentives above the market price: granting fixed incentives for electricity in addition to the wholesale market price, can be cash payments or tax credits.
- Operational instruments: priority in the dispatch.

Energy consumption in Latin America has increased in the last decade (Washburn & Pablo-Romero, 2019), this is a sign of the constant economic development and energy transition of the different countries of the region. Also, intending to reduce GHG emissions from non-renewable technologies, Latin American countries have designed and implemented programs and laws specifically focused on the promotion of RE (Washburn & Pablo-Romero, 2019). The countries with the highest number of strategies implemented are Panama, Chile, Mexico, and Nicaragua, while Bolivia, Suriname, and Venezuela are the countries with few or no promotion strategies for renewable energy (Washburn & Pablo-Romero, 2019).

Most of the countries that are implementing promotion programs have established electricity generation goals, rather than capacity goals. For example, Argentina seeks to have 25% of electricity generation from renewable technologies by 2025 and Brazil, 86% by 2023 (including large hydropower) (Washburn & Pablo-Romero, 2019). Colombia, particularly, has a target of 15% by 2030 (UPME & Ministerio de Minas y Energía, 2015). Argentina, Brazil, Costa Rica, Ecuador, Honduras, and Panama have implemented, incentives such as Feed-in tariffs, which have allowed the growth of RE diffusion, ensuring the operation in the long term and allowing to solve the high investment costs for renewable technologies (Arias-Gaviria et al., 2019; Washburn & Pablo-Romero, 2019). Incentives such as net measurement have been used in Argentina, Brazil, Chile, Colombia, Costa Rica, Guatemala, Mexico, Nicaragua, Panama, Suriname, and Uruguay, mainly generating an effect on the diffusion of small-scale RE, such as the residential sector (Washburn & Pablo-Romero, 2019).

Other examples of the most recurrent mechanisms for the promotion of RE for electricity generation are energy auctions. In Latin America thirteen countries have implemented them, having increased effects on the installed capacity of RE. For example, Brazil has been achieved more than 15GW installed, with a total of 600 projects. The guarantee offered by the auctions consists of the purchase of the electricity generated at a fixed price promoting investment in renewable technologies and helping to promote their adoption in the market. Auctions have had better results than other incentives, such as FITs, since the support for RE no longer consists of a previously defined price but is based on competition, and the remuneration obtained is established based on the offers submitted.

Colombia is a country with an enormous potential for natural resources that can be used for electricity generation through renewable technologies. However, according to the Unidad de Planeación Minero Energética (2015) *"Colombia had not implemented mechanisms of explicit support to the FNCER" (pg. 96)* until the introduction of Law 1715 of 2014 (Congreso de la

República de Colombia, 2014), in which they defined important instruments to support and promote the diffusion of non-conventional renewable generation sources. Some of the instruments introduced by this law are bidirectional measurements for self-generators, the creation of the "Fondo de Energías No convencionales y Gestión Eficiente de la Energía" (FENOGE), which is intended to finance non-conventional generation programs and projects, the provision of four explicit tax incentives (Reduction of taxable income up to 50% of investment in non-conventional renewable projects, VAT exclusion, and accelerated depreciation) and general support in costs reduction for biomass, wind energy, geothermal, small hydroelectric power plants, the energy of the seas and solar energy. In 2018, Colombia introduced 40791 resolution (MinMinas, 2018a) in which they defined mechanisms to promote the long term contracts to generations projects through an auction. The first renewable energy auction was made in 2019, in which the marketer and the generators make a trade-off to establish a price for the energy in a long-term contract. This auction awarded 5 wind and 3 solar projects (UPME, 2019).

Next, we explain the evidence for use of microworlds as a learning and teaching tool, grounded on all of the advantages that this tool provides for their users, such as , allowing them to experiment with the system and their own making decisions.

1.2 Learning and teaching through Microworlds

From basic motor skills, such as catching a ball, to sophisticated cognitive skills, such as designing a programming code, learning is obtained by the feedback of the results of our actions (Sterman, 2014). Some authors argue that traditional teaching methods, based on lectures and debates, fail at improving the students' abilities to solve problems, promoting systemic thinking skills, and generating an experimentation environment. These three tools are necessary for students to internalize knowledge (Sterman, 2014). Thus, traditional methods as a single teaching technique may not be effective. For this reason, some alternatives to teaching have emerged in the last 40 years, such as constructionism, interactive learning, and student-led learning (Papert, 1980). With these alternatives, the professor no longer occupies the role of guide, but rather of a companion, and the students obtain feedback from their direct interaction with the problems. Traditional teaching methods may not provide adequate feedback, but they provide the theoretical aspects that are necessary for effective feedback at practicing time. That is why students must acquire learning with combined teaching methods.

Experimentation facilitates the learning experience because it has the advantage of running within the physical and temporal limitations of the classroom, it does not generate costs associated with the decisions and allow the making of prohibited or unethical decisions, and learning from their consequences. These advantages generate immediate feedback that would take months or years to occur in real life, facilitating learning in complex systems and allowing to identify leverage points of the systems. There are many systems, but it is hard to scale them to laboratory setups, such as economic systems, natural resources management, supply chains, managerial, and energy systems. One alternative, in this case, is the use of virtual tools, such as simulators and microworlds.

The difference between microworlds and traditional simulation lies in the control degree that the user has over the underlying model. With simulators, players perform a task to fulfill an objective, without making any decision that influences the underlying system model. With microworlds, the decision-making process affects the underlying model. The higher the degree of user control over the system, the higher the degree of experimentation. When a system more closely matches the individual needs of each user, it will generate a closer experience, and the learning process will become more productive. This experience affects the cognitive state and affective state, generating different learning for each specific user (L. Rieber, 2012).

Microworlds are based on Piaget's (Ackermann, 2001) pedagogical paradigm of constructivism, according to which knowledge does not come packaged in books or teacher brains. Instead, *"knowledge is a state of understanding and can only exist in the mind of each person"* (King, 1993, p.30), which means that each person acquires new knowledge with new experiences and based on the knowledge they already know. In conclusion, constructivism emphasizes generating interactions between students and problems through experience and experimentation. Given that constructivism presents the problem of the economic or time and space barriers to held the experimentation directly with many systems, Papert (1986) proposed constructionism, this new approach accepts the theory of constructivism and dictates the direct construction of learning, but integrating the possibility to students to use the computer as a support tool to provide the experimentation and built their knowledge. This approximation also includes virtual instructions making the students able to solve problems and challenges experimenting them by themselves, eliminating the consequences of experimentation in real life, such as high costs (Papert & Harel, 1991).

The specific advantages of microworlds as tools for learning and teaching are: (i) the easy access, which allows more people, from an early age to understand and explore concepts of complex systems; (ii) qualitative learning based on the construction and use of models suitable for complex systems and; (iii) the differentiation of learning about a concept and executing that concept in reality to obtain feedback (L. Rieber, 2012).

A well-known application of a microworld that uses combined traditional learning methods and virtual tools is FishBanks (MIT et al., 2020). This microworld is a free online game that exposes players to the tragedy of the commons (Hardin, 1968), in which players compete to maximize the economic value of their companies, while they exploit a shared resource. This tool has an introduction, an instructor's guide, a briefing, a debriefing, and a video to teach how to use the platform. This tool generates facilities to understand the theory needed to play and provides feedback after experiencing the situation so that players internalize the knowledge (MIT et al., 2020). A free online microworld also contributes to learning since it has all the teaching and learning support materials accessible and can be used as a part of a class or as a single player.

Based on the research on microworlds, renewable energy promotion and the learning and teaching process described in this section, we identified the research problem and objectives for this work.

1.3 Research problem

The electricity sector in Colombia is a complex system due to the interactions between market agents, the specific dynamics, the effects of the delays, and the speed of changes in the system. These elements constitute a barrier to quick learning of the system, specifically for renewable energy diffusion study which involves a strong learning curve effect. Different simulation models have been developed to explain the diffusion of renewable energy; however, the constant changes in the policies and regulations make the models' updating a complex task.

Additionally, these models usually fail at generating new knowledge in the users because they do not promote experimentation and do not involve the user in the electricity market system. In this work, instead of drawing attention to the development (or upgrading) of a model that attempts to capture the structure and the behavior of the system, we focused on the learning process by developing an interactive tool that allows people to speed up the process, introducing the users to an approximation of the real system, as the microworlds do, and work in an interactive learning environment.

The microworlds which were studied and have been applied to the Colombian electricity market seek to generate learning for market agents about the risk management involved in the decision-making process and the formation of the electricity spot price (Dyner et al., 2009; Franco et al., 2012). However, to our knowledge, no microworlds have been developed for learning about the diffusion of non-conventional renewable electricity generation technologies using incentives. Therefore, there is evidence of *the necessity of a learning-oriented microworld to understand the dynamics of renewable energy diffusion through incentives focusing on non-conventional renewable energy in Colombia.*

1.4 Research objectives

1.4.1 General objective

Develop a microworld for learning and understanding the diffusion dynamics of non-conventional renewable electricity generation technologies in Colombia.

1.4.2 Specific objectives

- Build an updated model based on the selection of existing models that represents the structure and explain the behavior of using incentives to promote different non-conventional renewable generation technologies in Colombia.
- Develop a virtual environment for the learning microworld, based on the selected diffusion model with the incorporation of incentives to non-conventional renewable generation technologies in Colombia.
- Evaluate the designed learning microworld through pilot testing.

2 Methodology

This work aims to develop a microworld to understand the driving forces of renewable energy diffusion in Colombia. We followed two phases for the development of the microworld, as shown in **Figure 2-1**.***Figure 2-1:*** Microworld's modeling and virtual environment methodology. In the first phase, we selected a simulation model based on system dynamics (Arias-Gaviria et al., 2019) and modified it to improve some mathematical formulations, and to include new incentives for renewable energy. We selected a System dynamics model because this methodology is a useful tool for understanding the system. The material developed during the construction of the simulation model, such as causal loop diagrams, can also be used to illustrate the complexity of the system to the users easily. However, the final users of the platform do not need any specific knowledge in system dynamics since the design of the microworld interface should simplify the understanding.

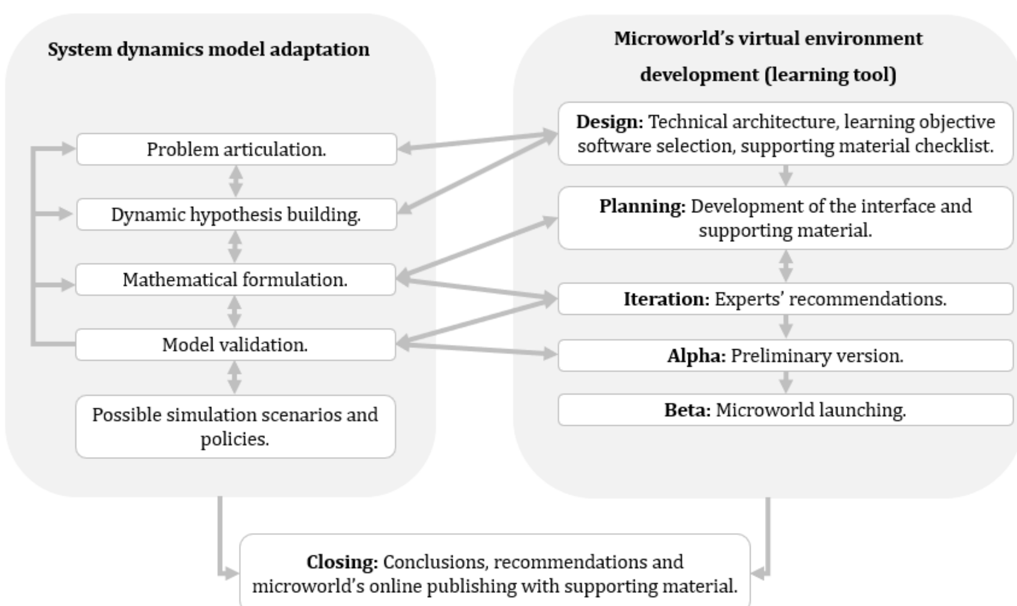


Figure 2-1: Microworld's modeling and virtual environment methodology.

Source: Own elaboration.

In the second phase, we developed a virtual environment for the microworld. The virtual environment included the design of the learning platform and its technical architecture, the definition of the learning objective, the game instructions, the briefing, and debriefing of the microworld, and pilot testing for the preliminary versions of the microworld. In this section, we explain each step of the methodology shown in **Figure 2-1**.

2.1 System dynamics approach

The system dynamics approach is based on stocks-and-flows modeling. The stocks are mass or information cumulative variables, and their formulation consists of a differential equation where the flows represent the inputs and outputs of the stocks over time. For the formulation of the model based on system dynamics, it is necessary to follow an iterative process that consists of five steps proposed by (Sterman, 2000):

- Problem articulation: In this step, we built a reference framework for the incentives for non-conventional renewable electricity generation technologies. This was done in the context of Latin America and Colombia and selected those incentives to include in the microworld. Also, we made a bibliographic review of the platforms and models that have described the diffusion of renewable energy and contributed to learning about the process of diffusion. In this step, the time horizon is defined for the simulation base case, which is useful as a reference to the actual situation of the country for the players in the microworld.

- Dynamic hypothesis: In this step, we defined the endogenous and exogenous variables that intervene in the problem, as well as the causal relationships between them. This step in the modeling process results in the construction of a causal loop diagram that allows us to observe the feedback loops formed from cause-effect relationships between model variables. The resulting causal loop diagram is based on Arias-Gaviria et al. (2019) model, with some additions and modifications made after a validation process.

- Mathematical formulation: The stocks-and-flows diagram is developed following the causal relations established in the last step. In this diagram, we proceed with the formulation of the equations that will generate the cause-effect relationships between variables and define the initial values for the model parameters. in this study, these values represent the base-case scenario for the microworld and a reference for the players' performance. We based the mathematical formulation on the F. Bass (1969) diffusion model, following the Arias-Gaviria et al. (2019) model, and then made modifications to its structure following additional considerations, such as improvement of the investment decision model. For the development of the stocks-and-flows diagram, as the underlying model for the microworld, we used "Stella Architect (2.0)" software (Isee Systems, 2020). We selected this tool because it brings the advantages of model building as well as the microworld's platform design and functionalities such as free online access for the final microworld users.

- Validation: For the model validation we made different structure and behavior tests:

  Structure validation: We made a consistency test of the structure with the real system, to verify the relationships between the model variables, such as the Bass diffusion model relations, by presentations and discussions with experts of "*Energética 2030*" (View Appendix A). Also, we made, dimensional consistency test, to prove that all variables in the model have the correct units, for this all the parameters in the model were verified with bibliographic references as regulations and laws in the electricity market in Colombia.

  Behavior validation: We made some extreme conditions testing, to evaluate if it reacts consistent with the expected results, the model has good results. Also, we made boundary testing, in which we determined additional needs variables and subsystems in the model, as the long-term contracts as an incentive, which was not in the Arias-Gaviria et al. (2019) model.

All the model was continuously verified through the tests mentioned and considering that the system dynamics process s iterative, some tests were made multiple times.

- Policies: In this step, we use the model developed in step two for the implementation and simulation of incentives for renewable generation technologies, we also use this model to simulate the diffusion using approximate values to reality, to provide players with a baseline scenario under the current behavior of the Colombian electricity market.

2.2 Tool selection for the development of the learning platform

The learning process in the microworld has been developed from different approaches and using different tools as a complement to the theoretical classes. To promote users learning about the diffusion of renewable energy in Colombia, we carried out an analysis of the ideal tool for developing the learning platform.

In this section, we selected a tool for the development of the learning platform. Considering that the simulation methodology of the underlying model is developed through system dynamics. To select the tool to use, we identified the differences between microworlds, the simulators, and the flight simulators; in this analysis, we considered the interface design characteristics, the results metrics, the advantages and limitations of its use, as summarized in **Table 2-1**. Additionally, we analyzed the required characteristics in the learning platform, as shown in **Table 2-2**.

Table 2-1: *Differences between microworlds, simulators, and flight simulators.*

Item	*Microworlds*	*Simulators*	*Flight simulators*
Interface	Simplified graphical users' interface.	Advanced programming view.	Digital mimics of analog instrumentation and controls.
Metrics	Variables behavior with automatic registration. Debriefing after playing.	Performance over repeated trials is often measured as success/failure.	Observed performance after playing and group debriefings.
Advantages	Ability to run a large number of experiments and facilities to be adaptable for each user's needs. Free online access.	True to reality model, and adaptable to new elements by programming.	True to reality model, commonly used for training.

Item	Microworlds	Simulators	Flight simulators
Limitations	Limited fidelity to reality, which means that the obtained experience is limited.	Its use is limited by each user's previous knowledge, it´s designed focused on an expert public.	Limitations on failure replication, which can only be learned with experience.

Source: Own elaboration from (Boring et al., 2012).

Table 2-2: *Required characteristics in the learning platform.*

Characteristic	*Microworlds*	*Simulators*	*Flight simulators*
Possibility of generating autonomous learning, without prior knowledge.	X		
Free online access	X	X	
Adaptability to different levels of knowledge.	X		X
Friendly interface	X		X
Possibility of making changes according to each user's needs or scenarios, in a simplified way.	X		

Source: Own elaboration.

The tool selected for the development of the learning-oriented platform were microworlds, considering that they have the characteristics presented in **Table 2-1**, such as the facilities in the integration of a underlying simulation model, the simplified graphical interface, and the possibility of making a briefing and debriefing in a guided session. These characteristics contribute to the fulfillment of this thesis's objective, that points to the development of the learning tool. We also evaluated the specific requirements for the learning tool in **Table 2-2** and we founded that microworlds accomplished these needs. This tool integrates the learning based on the experimentation and interactions of the users with a friendly platform, without the need for specific prior knowledge, additional to the ones generated in a class specifically designed to complement the learning platform or a users' guide. For this work, we considered that the microworld is not intended to explain the operation of the electricity market true to reality, but rather with simplifications to facilitate users' learning.

The following section describes the methodology for the development of the virtual environment of the microworld that includes complimentary tools for learning.

2.3 Virtual environment for the learning-oriented microworld

The virtual environment is described as all the tools and procedures that are necessary for the learning platform (Valencia O et al., 2011), these tools include the design of the microworld, and supporting learning material for a directed session (such as instructions for a facilitator in a class) or autonomous learning (such as individual users' guide). For the development of the virtual environment, we followed Valencia O, Víctor Riascos M, & Niño Z (2011) methodology proposed for immersive microworlds. This methodology considers that the systems have to change conditions and that decision making involves considerable risks in the system, which is an advantage when the users' needs to learn without the consequences or costs of their decisions.

i. The first step is called **Design**, the objective of this phase is to have a clear vision of the microworld approach. Valencia O et al. (2011) propose in this step the definition of the learning objective and the elaboration of the technical architecture included the selected development software: Stella Architect (2.0) (Isee Systems, 2020). This software was selected because of its advantages in making the underlying stocks-and-flows model and its mathematical formulation, as well as it provides an interface development tool. Also, Stella Architect (2.0) (Isee Systems, 2020) allows the microworld to be published online for free for the final users, which is a huge advantage to make it accessible for every interested person.

   Based on materials observed from another successful microworlds (MIT et al., 2020; J. Sterman, 1992), we proposed to add in this stage the selection of learning indicators, and the selection of the supporting learning material such material is included in a checklist of the material that the users will need, and in which moment of the learning experience will be provided to them to guarantee active learning. Such a checklist must include providing a teachers' guide (If the microworld is used as a part of a class), and a users' guide and key lessons (for self-learning), we present the checklist for the present study in Appendix B, which can also be used as a guide for other microworld development. All the checklist material development is part of the planning phase.

ii. During the **Planning** phase, we developed each one of the elements included in the checklist. In this step, we designed the microworld interface and developed the educational support elements. The educational support elements consist of a users' guide for the management of the virtual platform, additionally, we propose an instructor's guide for the teacher and learning indicators to evaluate the obtained knowledge by the users of the microworld and provide them feedback. The instructor's guide includes keynotes and lessons on the briefing and debriefing slides which were also developed in this step.

iii. The objective of the **Iteration** phase is to improve the microworld design with experts' recommendations in the field of study and teaching. To carry out this process iteratively until the final design is achieved. The final design will meet the expectations and will correct the errors of the planning phase model. This step is developed at the same time as the validation in the system dynamics process, it includes discussion and meetings with *"Energetica 2030"* experts on the design of the underlying model and interface of the microworld, and which of the proposed supporting learning material may be included in the platform.

iv. The **Alpha** phase consists of the launching of the preliminary version of the microworld for a target audience. The audience should be evaluators of the microworld with the ability to understand and recommend changes. This phase generates information on the experience generated by the microworld and the opinions of the evaluators on the new knowledge acquired. Also, the experts give feedback for the learning indicators defined in the planning phase telling if they are useful to evaluate whether the users acquire new knowledge or not and if playing the microworld is enough to acquire this knowledge. For this phase, we made a pilot testing session with some master and Ph.D. students and teachers on system dynamics, energy, and climate topics.

v. In the **Beta** phase, we launched the microworld for an audience with less knowledge about the microworld. This version did not contain known errors to developers. This Beta launch was made in a pilot testing session with undergraduate engineering students, giving important information on how to manage the session for the microworld and timing for the briefing, debriefing, and microworld guiding, as well as some key lessons that the users typically ignore. Those key lessons, such as the difference between power and energy were added to the supporting teaching tools as the instructor's guide.

vi. The **Closing** phase consists of evaluating the results observed in the beta phase and verifying if the learning indicators satisfactorily evaluate the lessons learned by the users in pilot testing. For this phase we analyzed the questionnaires that the beta phase users completed, the results show that the users get new knowledge in comparison with the one they had before playing.

3 Building the microworld's model

In this chapter we develop the first part of the proposed methodology: The system dynamics modeling for the underlying model for the microworld. In this segment, we undertake a review of different renewable energy and learning-related models. The microworld's underlying model includes the technology diffusion, based on Bass's (1969) model, and a modification of Arias-Gaviria, Carvajal-Quintero, & Arango-Aramburo (2019) model. Moreover, the model was further developed to include elements for learning as described later in this section. As a general view, the microworld's model includes renewable energy incentives, the involved costs and learning curve for the investment costs, and other improvements to Arias-Gaviria et al. (2019) model. Finally, we present the mathematical formulation and the base case used for the microworld.

3.1 Learning-related models and microworlds for renewable energy

Different microworlds have been increasingly used in recent years for teaching and training. Some examples for this are C-Roads (MIT et al., 2019) that teach people the effects of climate change by taking actions to reduce greenhouse gas emissions, and En-Roads (Climate Interactive et al., 2019) that is a free and online policy simulator that allows people to explore themselves the consequences of economic growth, land use, and other policies on energy growth. *World Energy: A Climate and Energy Policy Negotiation Game* (J. Sterman, Fiddaman, et al., 2019) is a game to understand the dynamics of climate change associated with the energy system, the players have to reach climate change goals such as the world temperature stabilization, the game promotes the experimentation and negotiation between participants. To know the effect of the participants' decisions on the world climate they use the En-Roads platform.

Particularly, in the Colombian electricity sector, the game Enerbiz (Dyner et al., 2009), was developed to train Colombian market agents to learn about the operation and the management of the risks associated with decision making. These platforms are considered learning environments of complex systems (Morecroft, 2007). There are also other platforms such as *Plataforma para la evaluación de políticas de mitigación de gases de efecto invernadero en el sector eléctrico* (Cárdenas Ardila, 2015), this model proposes policy evaluation on the supply and demand of energy for the mitigation of greenhouse gases. Users can interact with different incentives and micro-generation for the residential sector. The different simulations of this game contribute to the understanding of supply and demand of a particular user of the electricity system, but it does not include the 1715/2014 law (renewable energy law) incentives and does not have a free online platform (Congreso de la República de Colombia, 2014). Another relevant study in this regard is *Understanding Dynamics and Policy for Renewable Energy Diffusion in Colombia* (Arias-Gaviria et al., 2019) which considers Bass's (1969) classic product diffusion to model the installed capacity of the technologies in time. This model evaluates incentives of the renewable energy law such as tax reduction, feed-in-tariffs, tradable certificates, and other technical subsidies to promote the installation of renewable non-conventional energy technologies.

For the microworld's underlying model, we determined some required characteristics such as (i) adaptability of the model to different needs such as incentives modification/inclusion; (ii) an acceptable complexity of the model to adapt it for learning and teaching purposes; (iii) the accessibility to the detailed mathematical model; and (v) the adaptability of the model to different non-conventional renewable technologies. To evaluate which of the models or underlying models of the reviewed platforms were able to be adapted to the microworld we assigned a weight to each criterion and give a score for from 1 to 5 in each criterion for all the considered models (View **Table 3-1**), where 1 means that the model did not meet the criteria and 5 means the model fully met the criteria. Scores from 2 to 4 mean that the model partially met the criteria on a low level (2), medium level (3), and high level (4).

Table 3-1: *Weighted criteria for the underlying microworld's model selection.*

Criteria	Id.	Weight	Model*				
			M1	M2	M3	M4	M5
Adaptability to microworld needs	C1	20%	2	2	1	4	5
Model complexity	C2	20%	3	3	4	4	5
Adaptability to learning and teaching purposes	C3	20%	5	5	3	3	3
Accessibility	C4	20%	4	4	3	3	5
Adaptability to different generation technologies	C5	20%	2	2	1	5	5
		Total score	3,2	3,2	2,4	3,8	4,6
		Total weighted score	64%	64%	48%	76%	92%

*M1: C-Roads, M2: En-Roads, M3: Enerbiz, M4: *Plataforma para la evaluación de políticas de mitigación de gases de efecto invernadero en el sector eléctrico, M5: Understanding Dynamics and Policy for Renewable Energy Diffusion in Colombia.*

Source: Own elaboration.

Following the proposed criteria, the selected model to be adapted to the microworld is *Understanding Dynamics and Policy for Renewable Energy Diffusion in Colombia* (Arias-Gaviria et al., 2019). This model accomplishes most of the requirements to be the base for the underlying model to the microworld.

3.2 Dynamic hypothesis

The model used for this study was based on Arias-Gaviria, Carvajal-Quintero, & Arango-Aramburo (2019) model, in which they applied the classic Bass's (1969) diffusion model, where the technology diffusion occurs by an innovation rate and an imitation rate. In this thesis, we modified the modeling of the imitation effects and included a model for additional incentives for the generation of non-conventional renewable energies. The following sub-sections present the detailed modeling of such modifications and additions, as a starting point, we proposed the basic causal loops structure of **Figure 3-1**. This causal loop diagram consists of two reinforcement loops that drive the increase in installed capacity and three balance loops that represent limits to installed capacity growing. The interaction between the reinforcement and balancing loops generates the S-shaped expected behavior from a diffusion model.

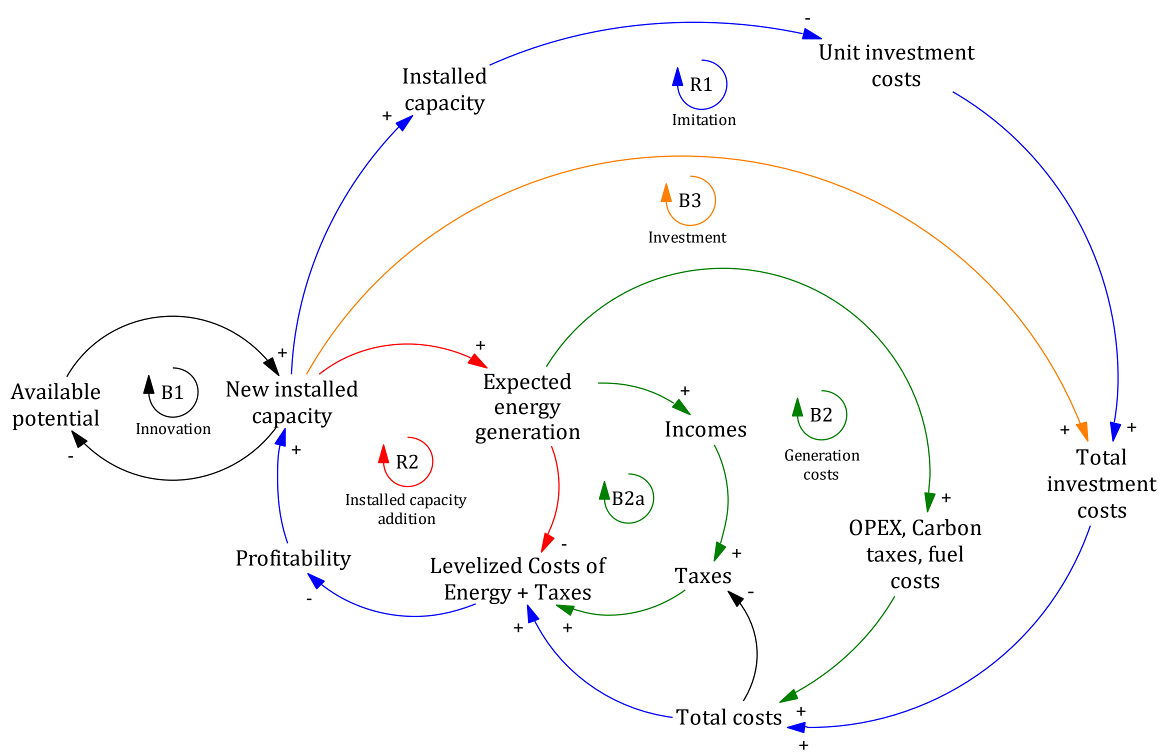


Figure 3-1: Microworld's causal loop diagram.

Source: Own elaboration based on (Arias-Gaviria et al., 2019).

In the innovation loop (B1), the starting point is the available energy potential that depends on the generation projects that can be built in Colombia. As this potential is exploited, the installation of new capacity will increase until the available potential is depleted. The imitation loop (R1) represents the learning effects (IRENA, 2000) observed for different renewable energy technologies: as the installation of new capacity increases, the total installed capacity also increases, which contributes to the decrease in the unit investment costs as a consequence of learning. In this regard, the total investment costs and LCOE also decrease, making the technology more profitable. As a consequence, the investors will be more attracted to invest, and the new installed capacity will be reinforced.

The R2 loop explains how the installation depends on the expected profitability. In this case, the profitability of the technology depends on the price of electricity and the Levelized Costs of Energy (LCOE), including taxes. As technology becomes more profitable, more capacity is installed and thus more expected electricity is generated, causing the expected LCOE to be reduced. Finally, the B2 loop represents the costs involved in generating electricity, which includes operational and maintenance costs, carbon tax costs (if the technology generates emissions), and fuel costs if necessary. B2aloop includes the incomes by electricity sales and the corresponding taxes if the income exceeds the total generation costs.

All the cycles described involve one of two components of innovation and imitation rates corresponding to Bass's (1969) diffusion model. However, in this microworld, we assumed that these loops may also be affected by exogenous variables such as the performance of the regulator (which affects the imitation factor), and incentives to renewable energy (which affects profitability). Some of these incentives are the reduction in aggregated taxes, long-term contracts auctions and feed-in tariffs use. These exogenous variables will depend on the player's decisions.

3.3 Model formulation

The causal structure described above is transformed into a stocks-and-flows diagram. In this diagram, we developed the equations and established the necessary parameters to structure a mathematical model. In this diagram, the stocks represent the state variables of the model, and they are modified by the flows that represent the changing rates of the states of the system.

We used Stella Architect (2.0) software (Isee Systems, 2020) to develop this structure of stocks-and-flows, as the underlying model of the microworld. The detailed formulation, which includes 148 equations and 246 variables, is presented in Appendix C. The equations that describe the system are based on the model proposed by Arias-Gaviria et al. (2019), which consists of four sub-models, one for each technology: Solar PV, Wind, Biomass, and Small Hydropower Plants (SHP), and each of these sub-models consists of two main state variables, available potential (AV) and installed capacity (IC), as shown in equations **(3-1)** and **(3-2)**. These stocks change based on the New Installed Capacity (NIC) rate formulated with Bass's (1969) model.

$$\frac{dIC}{dt} = +NIC \quad \textbf{(3-1)}$$

$$\frac{dAV}{dt} = -NIC \quad \textbf{(3-2)}$$

3.3.1 The diffusion model

New products or technology diffusion, in general, are modeled as an S-shape curve as shown in **Figure 3-2** where the diffusion is slow at the beginning and then it grows faster until it establishes at its maximum point (Rao & Kishore, 2010). This S-shaped curve is built following Bass's (1969) diffusion model, in this model, the amount of new adopted products depends on an innovation rate, an imitation rate, and the total available potential. This model evolves to include the costs and profitability as a decision variable over the investment in new products and is called Generalized Bass's Model (GBM) (Arias Gaviria, 2014).

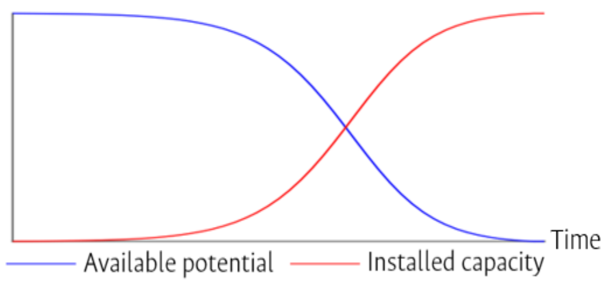


Figure 3-2: S-shaped expected Bass´s diffusion model behavior.

Source: Own elaboration based on (Bass, 1969)

There are three groups of diffusion models. The first one includes the fundamental diffusion models; these models assume that the total potential and the coefficients are constant over time. The second group is the flexible diffusion models that are similar to the first group, but they are flexible with the S-shaped curve symmetry. And the last group is the Refinements and extensions that include dynamic diffusion models with non-static parameters (Rao & Kishore, 2010). we used a model based on the third group because of the changing dynamics of electricity trading.

In this work, the new product is the installed capacity of specific renewable electricity technology. In this model, the innovation factor (p) includes, for example, the effectiveness of the advertising. The imitation parameter (q) includes how many of the installed capacity was installed based on the results of other previous installed capacity, in terms of profitability. For the microworld, we modified the Arias-Gaviria et al. (2019) model to include the effect of the regulator performance on the imitation rate, as shown in equation **(3-3)**. This modification makes the imitation parameter reduce while the regulator's performance decreases. The regulator's performance is a reduction percentage that depends on the player's decisions during the game, we explain it in the next section. We also included a variable called installation term (IT). This variable increases the installation due to imitation when the expected profitability of the technology is higher than 100%. When the profitability is lower than 100%, the installation due to imitation occurs naturally.

$$NIC = (p * AP) + \left(q' * IT * AP * \frac{IC}{AP + IC}\right) \tag{3-3}$$

$$q' = q * RPE \tag{3-4}$$

$$IT = \begin{cases} 1, & Expected\ profitability < 100\% \\ Expected\ profitability, & Expected\ profitability \geq 100\% \end{cases} \tag{3-5}$$

$Where$:

$$NIC: New\ installed\ capacity\ \left[\frac{MW}{Month}\right]$$

$$p: Innovation\ rate\ \left[\frac{1}{Month}\right]$$

$$q: Immitation\ rate\ \left[\frac{1}{Month}\right]$$

$$AP: Available\ potential\ [MW]$$

$$IC: Installed\ capacity\ [MW]$$

$$RPE: Regulator\ performance\ effect$$

The expected profitability is defined as the relation between the electricity price and the Levelized costs of energy (LCOE) plus aggregated taxes (AggTaxes):

$$Expected\ profitability = \frac{Electricity\ price}{LCOE + AggTaxes} \quad \textbf{(3-6)}$$

3.3.2 Regulator's performance

In this model, we include a conceptual variable, which represents the confidence that the investors have over the market stability, its regulations, and incentives. Since investments depend on the expected profitability of future projects, we assume that investors will perceive a more stable environment if the regulations do not change too much in a short time. As the role of the player in the microworld is the electricity market regulator, who decides what incentives to implement or eliminate, the game measures the number of changes that the player does during the game. The regulator's performance is a non-linear variable that depends on the player's decisions throughout the game, and it is a soft variable. Soft variables are important even though numerical data are unavailable because *"omitting concepts because they have no numerical data is a sure route to narrow model boundaries, biased results and policy resistance"* (J. D. Sterman, 2002, p. 523). Considering that the regulator's performance could have a huge impact on the system we decide to estimate it.

We model such non-linear variables depending on the number of changes made by the regulator (changes stock) as shown in **Figure 3-3** and equation **(3-7)**. When the changes made during the game reach a high value, the regulator's performance decreases. As a consequence of said decrease, if the regulator's performance is low, the investment in new capacity due to imitation will be reduced. Both of these effects follow an S-Shape curve because of the adaptability of the investors. This adaptability means that the investors can manage with some changes but when the changes start increasing, the effect increases exponentially. Finally, we included a rate to represent that the investors forget the changes made six years ago (Forgetting). We aim for a simple and direct function for learning purposes, such that users could get a feeling of the importance of the role of the regulator for renewable diffusion.

$$\frac{d\ Changes\ stock}{dt}\ [Changes] = +Changes\ during\ time - Forgetting \quad \textbf{(3-7)}$$

$$Forgetting\ \left[\frac{Changes}{month}\right] = \frac{Changes\ stock}{6 * 12\ [months]} \quad \textbf{(3-8)}$$

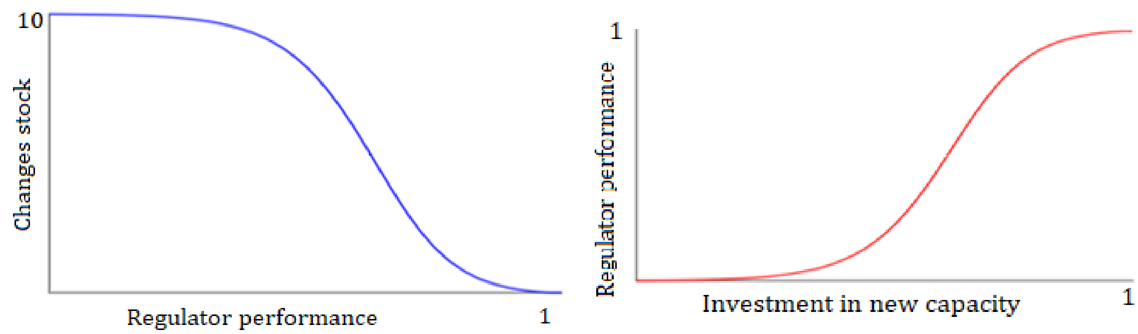


Figure 3-3: Regulator's performance non-linear modeling.

Source: Own elaboration.

3.3.3 Renewable energy incentives

One of the objectives of the microworld is to provide learning about the promotion of non-conventional renewable generation technologies through incentives such as the feed-in tariff, aggregated tax reduction, carbon taxes, long-term contracts auctions, and emissions trading. Here we present a brief description of the incentives and how were included in the microworld's model.

Feed-in-tariff

A feed-in-tariff (FIT) is a fixed electricity price paid to the non-conventional renewable energy generators. Currently, feed-in tariffs are not applied in Colombia, but in 2015 the "*Unidad de Planeación Minero Energética (UPME)"* (UPME & Ministerio de Minas y Energía, 2015) proposed its use as an incentive for the installation of new renewable capacity. FIT allows generators to have a stable energy price over time, to cover their capacity installation investment costs, and make the operation profitable during technology lifetime. In the microworld, the FIT works as an incentive that can be activated or deactivated by the player at any time during the game. When activated, this tariff replaces the market electricity price for renewable technologies; and the player establishes the initial tariff, which then will increase with an annual growth rate of 3%.

Tax incentives

In the microworld, the player can set up the following tax incentives:

- *Aggregated taxes:* Aggregated taxes are charged to generators when their net profits are positive, that is when their income is greater than their costs. The tax is paid on net profits, as shown in equation **(3-9)** (UPME & Ministerio de Minas y Energía, 2015). The player has the option of increasing or reducing the tax rate to pose different scenarios.

$$AggTaxesCosts(x) = \begin{cases} 0, & Net\ profits \leq 0 \\ AggTax * (Incomes - Total\ costs), & Net\ profits > 0 \end{cases} \quad \textbf{(3-9)}$$

  For the microworld, we assumed an initial tax value of 20%, with which the reduction of taxes is key so that non-conventional renewable generation technologies have a rapid diffusion in the Colombian market.

- *Carbon tax:* Is a charge for the emission of greenhouse gases (GHG), We assumed that the only non-conventional renewable technology with GHG emissions is biomass. The mathematical formulation of this incentive is developed in the Levelized Cost of Energy (LCOE) section, since this cost, unlike the aggregated taxes, is considered within the LCOE.

<u>Long-term contracts auctions</u>

The long-term contract auctions are a mechanism implemented in Colombia for increasing the total generation capacity. In the past, this mechanism led to the introduction of several large hydropower plants and fossil fuel plants. Recently, the country extended this mechanism to include non-conventional renewable technologies (MinMinas, 2018b). The first renewable energy auction was held in Colombia in October 2019, and it awarded 5 wind and 3 solar projects, which will increase the installed capacity of renewable energy in Colombia by 2022 (UPME, 2019).

For the microworld, we made several fundamental assumptions for the execution of the auctions. Since the game only considers the role of the regulator (not generator and marketer roles) then the only decisions are to make an auction and how much capacity will be auctioned. We established that the player can only auction every four years and the capacity that he auctioned will be installed with a delay of two years. Additionally, we established the final price of the long-term contract (final price of the auction) as the lowest LCOE value for the four non-conventional renewable generation technologies in the game, since it is the value that guarantees that the technology will be profitable and that can cover the investment costs during the lifetime of the technology.

We considered the auctioned capacity as a stock, which has an input pulse at the moment that the player decides to carry out an auction (with two years of delay), and the energy that is generated by that new auctioned installed capacity is not paid at the spot-price but rather at the final price of the auction (View Appendix C).

Emissions Trading Mechanism

This mechanism was established in the Kyoto Protocol (United Nations Framework Convention on Climate Change, 2008) and it dictates that certain countries can acquire surplus emissions rights from other countries. Colombia classifies as one of the countries from which surplus emissions can be purchased. In the microworld, the economic incomes from the sale of exceeding carbon credits are granted to the companies that generate the reduction of those emissions. For example, The energy matrix in Colombia is composed of 70% hydropower and 30% fossil fuel sources, if non-conventional renewable energy supplies 10% of the demand that is supplied by fossil fuels, then the emissions will be reduced due to those new installations. The corresponding value of these carbon credits sold is granted to non-conventional renewable generators that make the emissions reduction possible. In the microworld, the player can decide the price of the carbon bonds, this value corresponds to the price of each ton of CO_2 emitted in US dollars.

3.3.4 Levelized Costs of Energy

The Levelized Cost of Energy (LCOE) is the cost per energy generated unit, it includes all the associated lifetime costs of an energy plant. The LCOE is also the price at which all the lifetime generated energy must be sold to cover the investment costs, the carbon taxes, and the operational and maintenance costs, generating an internal rate of return over the investment of zero (Alejandro Castillo Ramírez et al., 2016). The LCOE is calculated as follows (IRENA et al., 2015):

$$LCOE\left[\frac{USD}{MWh}\right] = \frac{\sum_{t=1}^{T}(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t) * (1+r)^t}{\sum_{t=1}^{T} E_t * (1+r)^t} \quad \textbf{(3-10)}$$

$Where$:

$$Capital_t: Investment\ costs\ in\ time\ t\ \left[\frac{USD}{months}\right]$$

$$O\&M_t: Operational\ and\ maintenance\ costs\ in\ time\ t\ \left[\frac{USD}{Month}\right]$$

$$Fuel_t: Fuel\ costs\ in\ time\ t\ \left[\frac{USD}{Month}\right]$$

$$Carbon_t: Carbon\ emisions\ costs\ in\ time\ t\ \left[\frac{USD}{Month}\right]$$

$$D_t: Dismantling\ and\ waste\ management\ costs\ in\ time\ t\ \left[\frac{USD}{Month}\right]$$

$$E_t: Generated\ energy\ in\ time\ t\ \left[\frac{MWh}{Month}\right]$$

$$r: Discount\ rate\ (WACC)$$

$$T: Technology\ lifetime\ [Months]$$

For the microworld proposed to use the simplification in equation **(3-11)**, for the investment decision we consider the expected LCOE of the new installed capacity, assuming that O&M, fuel, and carbon costs will remain constant during the lifetime of the capacity to be installed. Also, the dismantling and waste management expenses are depreciated, assuming that the technologies that meet their lifetime are considered as new available potential.

$$LCOE\left[\frac{USD}{MWh}\right] = \frac{Capital + O\&M + Fuel + Carbon}{E} \quad \textbf{(3-11)}$$

$Where$:

$$Capital: Expected\ total\ investment\ costs\ \left[\frac{USD}{Month}\right]$$

$$O\&M: Total\ expected\ operational\ and\ maintenance\ costs\ during\ the\ lifetime\ \left[\frac{USD}{Month}\right]$$

$$Fuel: Total\ expected\ fuel\ costs\ during\ the\ lifetime\ \ [USD/Month]$$

$$Carbon: Total\ expected\ carbon\ costs\ during\ the\ lifetime\ \left[\frac{USD}{Month}\right]$$

$$E: Total\ expected\ energy\ generated\ during\ the\ lifetime\ \left[\frac{MWh}{Month}\right]$$

It is important to mention that, typically, the equations to estimate LCOE do not include aggregated taxes. Thus, in this model, we consider both the LCOE before and after paying the aggregated taxes. As shown in equation **(3-6)** we used the LCOE plus the aggregated taxes that the technology must pay throughout its lifetime to calculate the expected profitability of the technology.

Capital costs

The investment costs include all construction, contingency, and financing costs, such as (Alejandro Castillo Ramírez et al., 2016; IRENA et al., 2015):

i. Direct building costs plus pre-construction costs, such as site licensing, including environmental testing. Also, these costs include staff accommodation during construction.
ii. Indirect costs, such as engineering, overtime, and administrative costs that cannot be associated with a specific category of direct construction costs. These costs include plant start-up,
iii. Mechanical and electrical equipment, and their respective supply and installation.
iv. Property costs such as environmental, feasibility, and permitting studies, legal fees, insurance, and interconnection infrastructure.
v. Contingencies for changes in costs during construction.

Unit investment costs include a learning curve, which allows participants to study the change in technology costs as a result of the learning rate. Generally, increasing the installed capacity of production implies an increase in the repetition of the process, which generates knowledge about the production process. The economic implications of the learning process are the cost reduction by the learning rate. The learning rate works as follows (Schoots et al., 2008):

$$Unit\ capital\ costs\ [USD/MW] = Ref.\ capital\ costs * \frac{Installed\ capacity}{Ref.\ installed\ capacity}^{-Learning\ elasticity} \quad \textbf{(3-12)}$$

$$Learning\ elasticity = \frac{\ln(1 - Learning\ rate)}{\ln(2)} \quad \textbf{(3-13)}$$

$Where$:

$Ref.\ capital\ costs$: $Actual\ value\ of\ the\ investment\ per\ unit\ [USD/MW]$

$Installed\ capacity$: $Total\ technology\ installed\ capacity\ [MW]$

$Ref.\ installed\ capacity$: $Installed\ capacity\ at\ the\ beginning\ of\ the\ simulation\ [MW]$

$Learning\ rate$: $Percentage\ of\ cost\ reduction\ each\ time\ the\ installed\ capacity\ is\ doubled$.

This formulation implies, each time the installed capacity of a technology doubles, the unit investment costs will decrease according to the learning rate. When technology is mature and it had reached its diffusion stability, the learning rate is small and its costs do not vary much in time, when the technology is in evolution, its costs decrease considerably in time (Jamasb & Köhler, 2007). This learning favors the expected profitability of the technology since the LCOE decrease over time (Arias-Gaviria et al., 2019).

<u>Operational and maintenance costs</u>

These include variable and fixed costs. The variable costs depend on the generation technology and include all the necessary purchases to generate energy, such as chemicals, gases, lubricants, and consumables. Additionally, the general maintenance is carried out outside the normal budget for scheduled maintenance, including maintenance mechanical parts and unforeseen staff training. (Alejandro Castillo Ramírez et al., 2016). The monthly fixed costs are those that do not vary significantly, although the generation changes. These costs consist of administrative and operational staff salaries, equipment rents, preventive maintenance, and public services (Alejandro Castillo Ramírez et al., 2016).

Fuel costs

These are the monthly fuel costs, estimating the amount of MBTU used per month, that is necessary to produce the energy (IRENA et al., 2015)[1]. Fuel costs only apply to non-renewable generation technologies and biomass generation technology. In the microworld, we assumed that the fuel price (g) is constant during all the simulation.

$$Fuel\left[\frac{USD}{Month}\right] = E * g \qquad \textbf{(3-14)}$$

$$Where:$$
$$g: Fuel\ costs, including\ production\ costs\ and\ transport\ to$$
$$generation\ plant\ per\ generation\ unit\ \left[\frac{USD}{Month}\right]$$

Carbon costs

These costs represent the cost for the GHG emitting technologies, this cost is calculated as the amount that a plant must pay for each CO_2 emitted ton (IRENA et al., 2015)[2]: For the microworld, we consider that the carbon tax is simplified as:

$$Carbon\left[\frac{USD}{Month}\right] = E * \rho * \beta \qquad \textbf{(3-15)}$$

$$Where:$$

[1] Fuel costs are defined by the international Energy Agency (IRENA et al., 2015) as the following equation, but for the microworld purpose, we simplified it as equation **(3-14)**. $Fuel_t\left[\frac{USD}{Month}\right] = E * H\ \sum_{t=1}^{T} g_t$. $Where: g_t: Price\ of\ fuel, which\ includes\ the\ price\ of\ production\ and\ transportation\ to\ the\ generation\ plant\ in\ time\ t\ \left[\frac{USD}{MBTU}\right]$. $H: Average\ fuel\ consumption\ rate\ per\ MWh\ \left[\frac{MBTU}{MWh}\right]$.

[2] Carbon costs are defined by the international Energy Agency (IRENA et al., 2015) as the following equation, but for the microworld purpose, we simplified it as equation **(3-15)**. $Carbon_t\left[\frac{USD}{Month}\right] = E\rho H\ \sum_{t=1}^{T} \beta_t$. $Where: \rho: CO_2\ emissions\ factor\left[\frac{TonCO_2}{MBTU}\right]$. $\beta_t: CO_2\ emissions\ tax\ rate\left[\frac{USD}{TonCO_2}\right]$.

$$\rho: CO_2\ emissions\ rate\ per\ generation\ unit\ \left[\frac{TonCO_2}{MWh}\right]$$

$$\beta: CO_2\ emissions\ tax\ rate\ \left[\frac{USD}{TonCO_2}\right]$$

3.3.5 Energy generation

Energy generation depends on the installed capacity and the percentage of use of the plant in the year. In the microworld, it is calculated according to a plant factor and the number of operational hours per month, as shown in equation **(3-16)** (Arias-Gaviria et al., 2019). We used the capacity factors reported in **Table 3-2**.

$$E\left[\frac{MWh}{Month}\right] = IC * Plant\ capacity\ factor * Operational\ Hours \qquad \textbf{(3-16)}$$

Table 3-2: *Plan capacity factors.*

Technology	Plant capacity factor
Solar Photovoltaic	26%
Wind	57%
Biomass	70%
Small hydropower	54%

Source: (MinMinas & UPME, 2019)

3.4 Model validation

Validation is a fundamental stage in the modeling process, with the validation the model errors are minimized especially in the implementation of the computation model. For the microworld's underlying model we ensured that every equation was properly implemented in the model when all the components were finished and integrated. The validation process also seeks to build confidence in the model's outputs. The validation depends on the model's purpose since the purpose of this model is to make an approximation of the diffusion of non-conventional renewable energies in the Colombian electricity market, based on Arias-Gaviria et al. (2019) model and make that diffusion follows an S-shaped curve following Bass's (1969) diffusion model. Then validation should be focused first on structure, and then on proper behavior from such structure, rather than a replication of historical data. For the model validation and building confidence in the preliminary results for the base case, we validated the model using the different structure and behavior testing.

For the direct structure validation, we made the following tests:

i. *Structure consistency test with the real system: t*his test reaffirms the causal relationships between the established variables in the causal loop and stocks-and-flows diagrams by experts meeting verifications shown in Appendix A and comparing the relations with the base selected model.

ii. *Dimensional consistency test:* The dimensional consistency tests is an iterative process, and because of this, we verified the variable units and equations to make sure the state variables and flows, as well as all the components in the model, have consistency units with the reality and all the parameters are verified with regulations, laws and another literature review. Also, Stella Architect (2.0) (Isee Systems, 2020) offers dimensional consistency verification for physical units, we used it as a guide to this validation testing.

For the structure-oriented behavior validation, we made the following tests:

i. *Extreme-condition test:* To evaluate the model behavior using extreme conditions tests, we proved different variables, such as the available potential replacing its value for zero, which results in no new installed capacity, and verified the model functioning (View Appendix D). Other variables, such as the aggregated tax functioning, auctions, and feed-in tariffs were tested assuming their use in the model with high values and also assuming that those incentives were not considered in the model, both tests verified the model functioning.

ii. *Behavioral reproduction tests:* For this test, we verified that the S-shaped expected behavior for the installed capacity and available potential works for every technology, and also, that the diffusion speed works according to the expected results, for example, for Small Hydro Power technology, the installed capacity is near to the stabilization point than other technologies because of the amount of installed capacity and available potential nowadays, also for other technologies such as Solar Photovoltaic the expected behavior shows that because of the lower LCOE the stabilization will occur rapidly (View Appendix D). For all the technologies the results were valid.

To explain better the behavioral reproduction test, and the S-shaped behavior reproduction, we present **Figure 3-4**, which shows the historical behavior for the renewable installed capacity in Colombia, Chile, Argentina, Portugal, and Thailand. As it shows, some countries like Colombia have a strong S-shaped installation curve, while other countries, like Chile, have a smoothed curve. This behavior occurs because of the moment of the diffusion, which means that depending on the country the diffusion is faster:

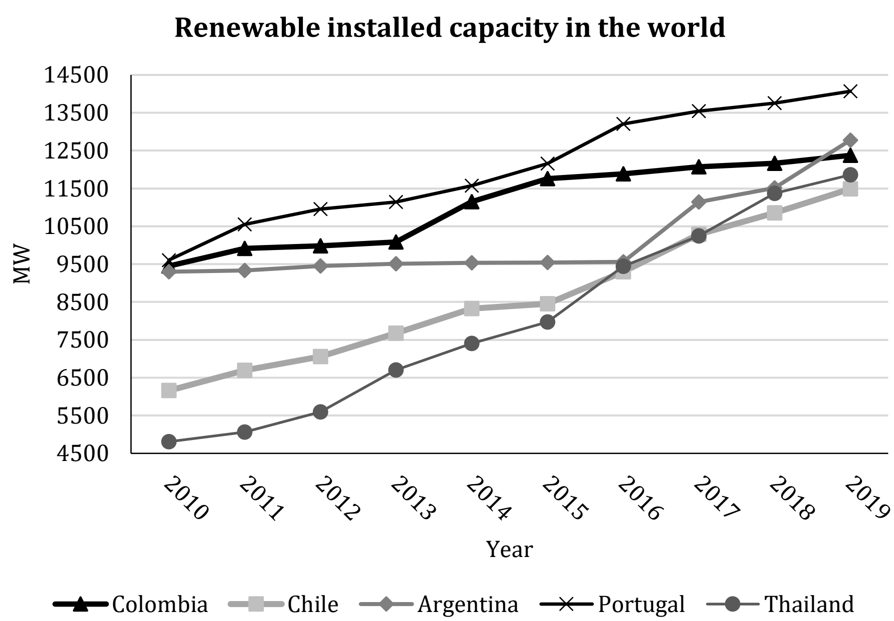


Figure 3-4: Renewable installed capacity behavior in the world.

Source: Own elaboration based on (IRENA, 2020).

iii. *Boundary adequacy test: f*or this test we verified which of the variables of Arias-Gaviria et al. (2019) were adequate to the microworld's modeling, also, which we verified which incentives to apply, to make the microworld understandable to the users, for this test we define the boundaries with the Alpha testing and with "*Energética 2030*" experts.

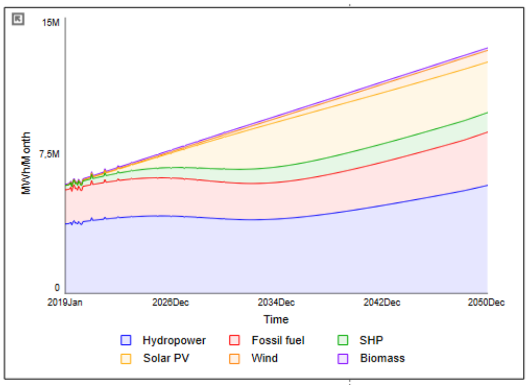
Following the validation tests, we can conclude that the microworld model structure and behavior are appropriate to represent the diffusion of non-conventional renewable energy technologies, to simulate the effect of incentives to promote its installation, and to be the base for a learning tool in which the users can modify and have feedback of their decisions.

3.5 Base case scenario

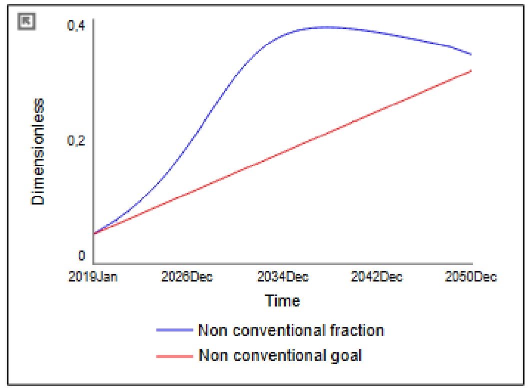
In the microworld, players have to deal with a decision-making process that includes the selection of different incentives during a time horizon of 31 years (from 2019 to 2050), and they also can set up their game scenario. Setting a game scenario requires inputs for electricity spot price, the initially available potential for each technology, the plant capacity factor, the unit costs, and the learning rates.

We used the parameters presented in Appendix C for simulating a base case scenario. The results for this scenario were verified in the validation section, the base case is used as the preset scenario for the microworld, the users can decide if they change those settings, also the base case is an approximation of the current electricity market scenario, we set the microworld's goals based on the base case values.

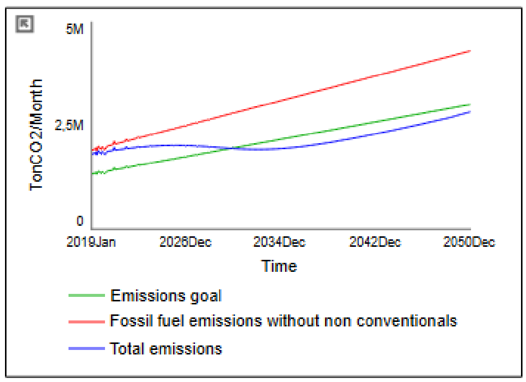
We present the results for the base case of microworld's model in **Figure 3-5**. Considering the goal for the shared non-conventional renewable energy, and considering the innovation and imitation rates (Arias-Gaviria et al., 2019), and the registered available potential (MinMinas & UPME, 2020) for each technology, **Figure 3-5** A & B present the current scenario for Colombia's shared generation and non-conventional generation fraction and goal respectively (UPME & Ministerio de Minas y Energía, 2015). The results show that Colombia has a good strategy to reach the non-conventional fraction goal, but the available potential needs to be updated to continue reaching that goal after 2050. Also, considering these parameters, Colombia can reach the emission reduction goal for 2030 (View **Figure 3-5** C) (MinMinas, 2018c).



A



B



C

Figure 3-5: Microworld's goals graphs.

Source: Own elaboration based on (Arias-Gaviria et al., 2019).

4 Microworld's virtual environment

This section presents the results of the second part of the proposed methodology: the development of the virtual environment of the learning microworld. As described in **Figure 2-1** these steps are iterative and developed in parallel with the construction of the simulation model proposed in the previous section.

For this part of the methodology, we present the design phase and first steps of the microworld's virtual environment, in which we defined the technical architecture, learning objectives, target users, and software for the microworld's development. Then, we present the planning phase, which includes the educational supporting elements for the microworld session. Next, we explain the feedback obtained in the iteration phase, with "*Energética 2030*" experts and the changes in the microworld after those sessions. Finally, we present the Alpha and Beta pilot testing, in this part, we explain the obtained results with an experienced target population, their recommendations to improve the microworld, and the obtained results with a less experienced target population, respectively. In the Beta testing phase, we included some of the conclusions for the closing phase of the proposed methodology, analyzing the obtained results statistically.

Though the steps developed in both, this, and the previous section we accomplished the final design for the microworld, which can be accessed here: https://exchange.iseesystems.com/public/santiagoarango/incentiver. Also, supporting material for the learning and teaching process can be found here: https://www.energetica2030.co/micromundo/ .

4.1 Microworld's design

We started by establishing the fundamental guidelines for the learning microworld, as the definition of the user´s learning objective, the target users, and the developing software. Also, we defined the technical architecture of the microworld interface and proposed the learning and teaching supporting material to complement the microworld session. Before start defining the technical architecture of the microworld we established the learning objectives for the users through multiple sessions (View Appendix A):

- To learn about the diffusion mechanisms of the installed capacity of non-conventional renewable energy and the effect of the installation on greenhouse gas emissions, using different renewable energy incentives in the system.
- To learn about the trade-offs that arise when trying to reach a renewable energy goal, emissions reduction goal, granting incentives, considering the involved costs, and maintaining the confidence in the regulator through the process.

To reach these learning goals we designed a complete class session, and a learning indicator consisting of a pre and post microworld session questionnaire to evaluate the participants' knowledge before and after the session, and identify if their knowledge improved with the interaction with the interface. The microworld session is directed to university students and upper academic levels, considering the mathematical formulation involved in the modeling process. Also, we considered the microworld session to be executed for training different energy market agents, for example in companies training. Nevertheless, this class plan can be used for a great variety of undergraduate and postgraduate courses with different learning approaches, such as:

- *System dynamic courses:* the microworld includes strong feedback effects and the underlying model is based on the system dynamics approach.
- *Energy-related courses:* the microworld includes energy technologies diffusion and renewable energy incentives.

- *Project management courses:* the microworld includes economic variables, as the costs and prices of the energy, and important investment decisions based on the expected profitability.

We considered different modeling software to develop the model and the interface for the learning-oriented microworld such as "Powersim Studio 10 Academic (10.14.5555.6)" (Powersim Software AS., 2020), "Vensim® PLE (8.1.0)" (Ventana Systems Inc, 2019), "Forio Simulate™" (MIT, 2020a) and "Stella Architect (2.0)" (Isee Systems, 2020). After evaluating different requirements for the model development, we concluded that all these software tools were appropriate for intuitive stocks-and-flows diagrams building. Nevertheless, we needed other specific characteristics for the learning platform, as the free-online access for the users and the possibility of creating a friendly user interface, in which we can include, for example, a scenario setting and different decisions for the users. In addition, the selected software needs to have intuitive functionalities, such as question marks and easy access buttons with key information. After evaluating and testing the mentioned software, we selected "Stella Architect (2.0)" (Isee Systems, 2020) because it accomplishes all the microworld's modeling and virtual environment needs.

4.1.1 Microworld's learning indicator

To identify if the microworld players had reached the learning objectives we studied different evaluating techniques, as self-evaluation, co-evaluation, or evaluation between equals and hetero-evaluation (Hamodi et al., 2015; Inda Caro et al., 2008). Self-evaluation refers to the student making his performance evaluation and can be carried out through self-reflection or documentary analysis. This type of evaluation can contribute to developing critical analysis capacities and creativity (Inda Caro et al., 2008). On the other hand, the co-evaluation is about the evaluation of the student by pairs, this favors the interaction between members of a group and allows the collection of information for the joint rating, being a collaborative method (Inda Caro et al., 2008). Finally, hetero-evaluation is the classic evaluation method in which the student's performance is evaluated by a person other than the student (Inda Caro et al., 2008). For the development of the learning indicator in the microworld, we used a hetero-evaluation, since the microworld session takes place in a short time and it can be developed individually. Thus, the hetero-evaluation is coupled with the microworld design needs, without the need for group interaction or documentary analysis.

Within the hetero-evaluation, there are different evaluation instruments, such as the following: (i) objective individual assessment test, which consists of a traditional assessment that each student performs on the content seen in a subject or class. (ii) Record of teamwork by the teacher, that assesses the exposure of information acquired and the debate of the research work carried out on a topic. (iii) Registration between a workgroup, which is carried out internally by each of the members of a work team based on criteria such as the development of the assigned role, intrapersonal interaction, and participation. These criteria focus on the presentation and debate of the investigative work. (iv) Intergroup registration consists of the evaluation of different workgroups that are part of the same class (Sáiz & Román, 2011).

For the design of the learning indicator, we selected the objective individual assessment type test, which was adapted to the microworld session. This adaptation consists of a questionnaire before the completion of the session to evaluate the participants' previous knowledge, and a post-session microworld test to assess the knowledge gained from playing microworld. The comparison between the results before and after the microworld session by each of the participants constitutes a paired sample of results that can be statistically evaluated. This questionnaire includes questions about the topics included in the microworld, such as energy and power, renewable energy and key variables expected behavior (View Appendix F).

We applied the pre and post questionnaire in the microworld pilot testing, and the results suggested that the players developed new knowledge in energy-related topics, as they increased their test scores. But it is important to mention that the post-test was carried out immediately after playing, so we did not evaluate the long-term knowledge of the players, as future work we proposed to implement the questionnaire in the long-term to verify that the knowledge acquired in the microworld session prevail in the participants.

4.1.2 Microworld’s technical architecture

Microworld’s technical architecture includes the definition of the microworld’s structure. For this part, we defined that the microworld will be available in English and Spanish languages, also we defined a voluntary register sheet to record some basic users information such as location and educational level (View Appendix E), then the users can select a preset scenario or input their parameters. After this, users start playing and making decisions. The microworld has a time horizon of 31 years (2019 -2050), and include four types of non-conventional renewable energy generation technologies: solar photovoltaic, wind, biomass, and small hydropower. Players can make initial decisions and run a complete scenario with no incentive decisions or run the microworld and change their decisions on timesteps of six months. When the users finish playing, they can see their results and analyze which were the effects of their own decisions.

In the technical architecture, we also selected the variables and parameters that the players can change for the scenario setup, the variables that the players will see during the game, and the incentives or mechanisms that they can use to incentivize the renewable energy capacity.

Scenario setup

In every game the users can set their scenario, this scenario will be defined for the following variables:

- *Electricity sport price:* The users can choose between three different spot price scenarios. The first one is the historical spot price projected until 2050 (XM, 2020b), the second and third scenario is a proportion of the historical spot price with an increment and a reduction of 20%. The players can also establish their price scenario:

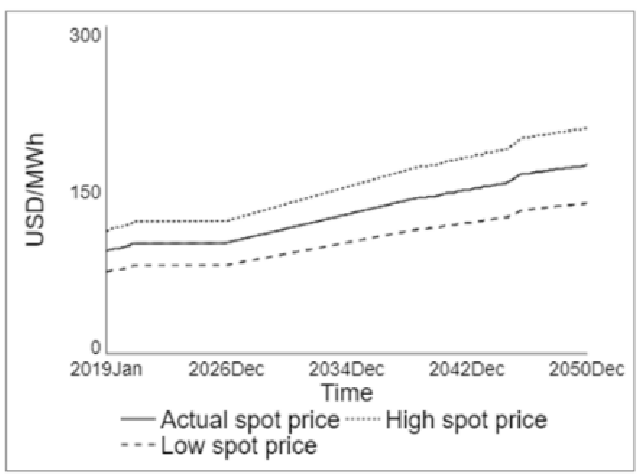


Figure 4-1: Electricity Price scenario setup.

Source: Own elaboration based on (XM, 2020b).

- *Available potential:* the users can set the available potential for each generation technology, the preset scenario include the registered available potential in Colombia, as the total registered generation projects (MinMinas & UPME, 2020), but we modified solar photovoltaic value, considering that the available potential for this technology includes a different kind of adequate surfaces, such as buildings roofs.
- *Plant capacity factor:* users can modify the plant capacity factor (MinMinas & UPME, 2019) to make the game approximate better to their scenarios.
- *Costs:* the game includes different costs, such as the fuel and carbon taxes costs for the LCOE calculation, but the fuel costs are an exogenous variable in the model, and the carbon taxes are established as a decision in the game, so for the setup scenario we consider the reference unit investment costs, and the unit operational and maintenance costs (A. Castillo Ramírez et al., 2017; Alejandro Castillo Ramírez et al., 2016; IRENA, 2018b), to adequate better the microworld to each users' needs as well as make the microworld easy to update in the future.
- *Learning rate:* as the learning rate value (Arias-Gaviria et al., 2019; IRENA, 2018b) is constantly changing, we let the users modify this parameter to allow the testing of different learning scenarios.

Specific goals

In the microworld the players have to deal with the decision-making process while trying to reach three different goals:

i. Reach a percentage of the total energy generation in Colombia with non-conventional technologies, starting with 5% in 2020, and increasing as follows: 10% of the demand in 2025, 15% of the demand in 2030, 24% of the demand in 2040, 32% of the demand in 2050.
ii. Reach a carbon emissions reduction of 30% by 2030, compared with the projected emissions.
iii. Maintain the investors' confidence in the country's regulator above 80%. If players change the decisions a lot, the perception of the market stability of investors will be

bad, so their confidence will be reduced, and will not invest. If players manage their decisions to be stable, the investors will be confident about the decisions and will invest.

Displayed variables

The players can see different variables' results while playing in every timestep, and also, they can see the final results at the end of the game. For each non-conventional technology, they can see the evolution of the following variables during all the time horizon: Available potential, installed capacity, total generation, new installed capacity, unit investment costs, total new installed capacity expected costs, and expected Levelized Cost of Energy. As the installation decision in the microworld depends on the expected profitability of the technology, the costs showed in the microworld correspond to the expected new installations.

The general variables that the users can observe during the game are Total non-conventional generation, incentives' costs of the applied incentives, price comparison between the historical spot price and the settled one, aggregated taxes comparison between the actual scenario and the game scenario, total shared generation, emissions reduction goal, monthly emissions reduction, carbon taxes comparison between the game paid carbon taxes and the paid carbon taxes without non-conventional technologies, savings or expenses due to the change in carbon taxes, carbon market incomes for the sold carbon credits, amount of changes made by the user in the game, and regulator's performance.

4.1.3 Learning and teaching support material checklist

In this phase, we defined all the supporting learning and teaching material in the checklist in Appendix B. This material includes:

- *Briefing slides:* contain the introduction and explanation of the microworld.
- *Debriefing slides:* contain the key lessons after playing, conclusions, and questions to promote conversation about the game and modeling debriefing for some specific users.

- *Users' guide*: It includes an introduction for the microworld in case the users are playing on their own and not as a part of a class, some key lessons, the interface guide, and the key lessons after play to give the players feedback.
- *Microworld's session instructor guide:* we followed *"Fishbanks"* (J. and A. K. Sterman, 2011) session instructor's guide, which includes the guide for a class session including lessons before playing, the game execution, and debriefing on the game.
- *Pre and post microworld's questionnaire:* in case the developing microworld is oriented to learning, we include questionnaire elaboration to evaluate users on pre-game knowledge and after-game knowledge.
- *Register sheet for recording purposes.*

4.2 Planning: interface and supporting material

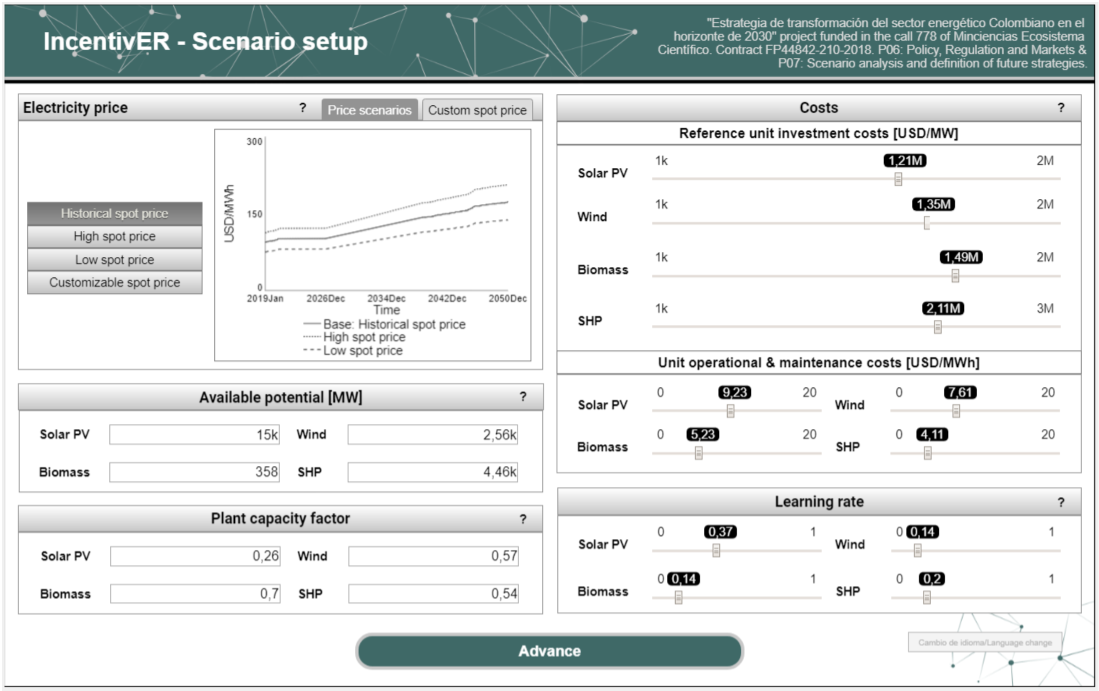
In the planning phase, we designed the microworld interface and developed the educational support elements. For the microworld interface design, we used the same software used for the underlying model, as it brings the necessary tools for a learning platform*: "Stella Architect (2.0)"* (Isee Systems, 2020)*.*

4.2.1 Microworld's interface design

Figure 4-2 shows the basic structure of the interface scenario setup, in the scenario setup the users can set the variables using different functionalities: for the *electricity price setting*, the users can choose between the historical spot price, a lower price scenario, or a higher prices scenario. Users can select preset scenarios by clicking on each button. For the customizable spot price, the users can draw their price graph by moving the mouse over the graph (View **Figure 4-2** B).

The second type of scenario setting is the fill-in variables, such as the *Available potential* and the *plant capacity factor,* for these variables' users can type the exact value that they want to use. Finally, the third type of variable is the slider bar ones, this group includes the costs, and the learning rate, for this type of variable, users can move the sliding bar to the value they want between the preset limits.

A



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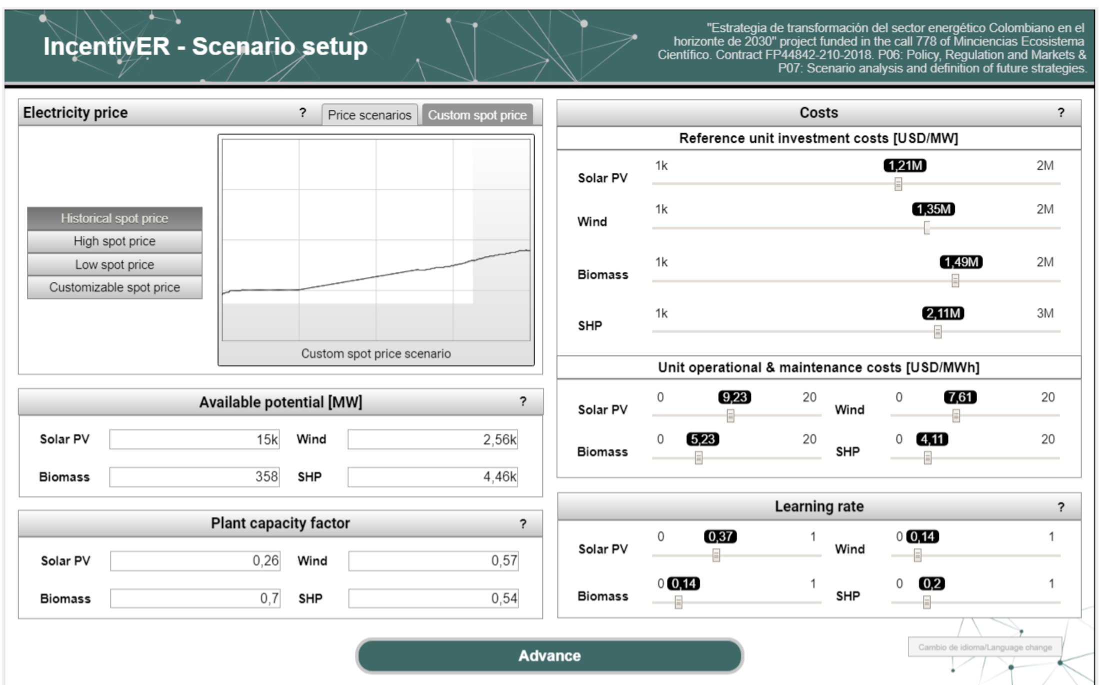

Figure 4-2: Microworld's scenario setting interface.

Source: Own elaboration.

When the players create their scenario, they can click on the advance button, this button will redirect them to the decision-making window (**Figure 4-3**). The decision-making window includes a decision panel, and a results panel, as well as the play button which directs the players directly to the final results, and the "6 months forward" button, which executes an advance in time of six months. If the players decide to advance six months, they will see their results step by step.

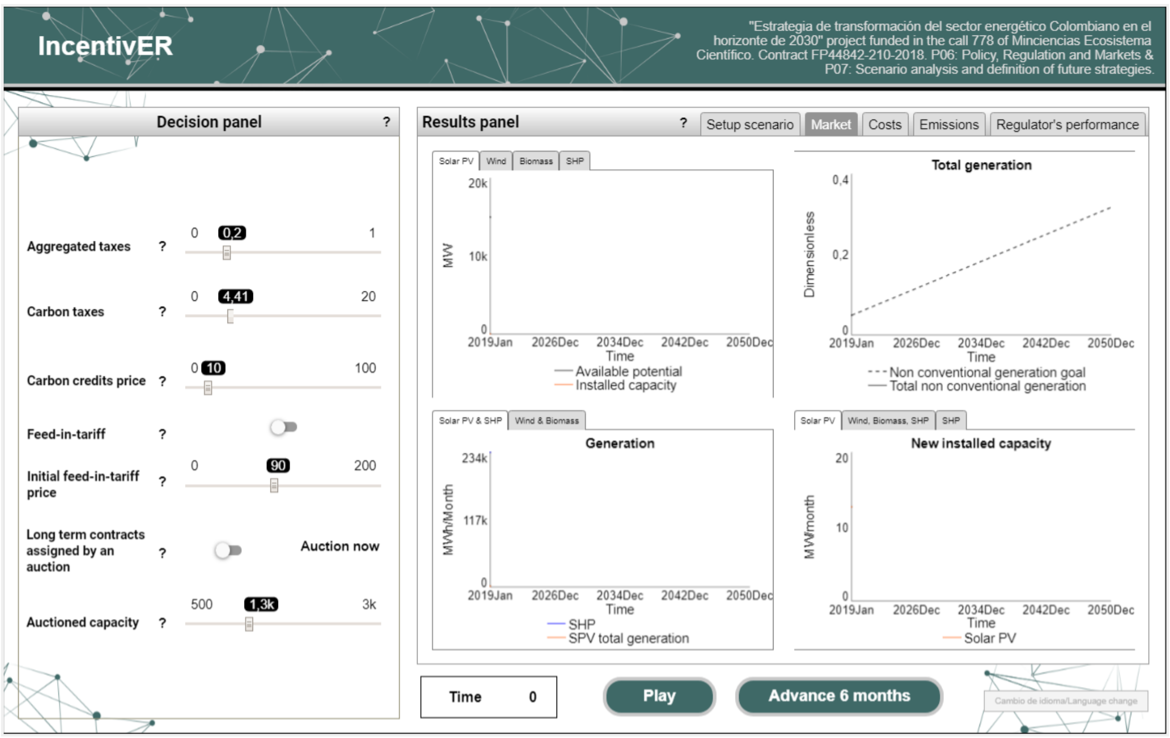

Figure 4-3: Microworld's decision-making window.

Source: Own elaboration.

In the decisions, panel players choose every timestep which incentives or mechanisms to activate to incentivize the installation of new capacity, reach the emissions goal, and maintain the regulator's performance over 80%. The decision panel contains two types of variables: sliding bar variables and hybrid switch-sliding variables. The first type are the aggregated taxes, the carbon taxes, and the carbon bonds or carbon credits price, these variables can be modified every timestep and their values can vary between the given boundaries. The second type of variable includes the feed-in tariff and the long-term contracts assigned by an auction. For the Feed-in tariff, the players can decide in every timestep if they apply a fixed tariff for all the non-conventional renewable technologies, and they must set the initial fixed price which will only increase according to a given growth rate. For the long-term contracts assigned by an auction, the players can decide when to make an auction and the amount of non-conventional renewable capacity that they are going to auction. This incentive can only be used every four years, and the auctioned capacity has a construction delay of two years. The players can decide if they want to play step by step or go forward to the final results.

The results panel contains five windows for the users to visualize different variable categories presented in **Table 4-1**. The first window contains the information for the settled scenario, then the market, costs, emissions, and performance windows display the variables that users need to track for their decision-making process (for a detailed microworld interface view Appendix G).

Table 4-1: *Microworld's windows variables.*

Window	Displayed variables
Market window	• Available potential for each non-conventional generation technology. • Installed capacity for each non-conventional generation technology. • Total generation for each non-conventional generation technology. • New installed capacity for each non-conventional generation technology. • Total non-conventional generation.
Costs window	• Unit investment costs. • Total new installed capacity expected costs. • Expected Levelized Cost of Energy. • Incentives' costs of the applied incentives. • Price comparison between the historical spot price and the settled one. • Aggregated taxes comparison between the actual scenario and the game scenario.

Emissions window	• Total shared generation • Emissions reduction goal • Monthly emissions reduction • Carbon taxes comparison between the game paid carbon taxes and the paid carbon taxes without non-conventional technologies. • Savings or expenses due to the change in carbon taxes. • Carbon market incomes for the sold carbon credits.
Regulator's performance window	• Number of changes made by the user in the game. • Regulator's performance.

Source: Own elaboration.

Finally, the results window displays all the results for players to analyze:

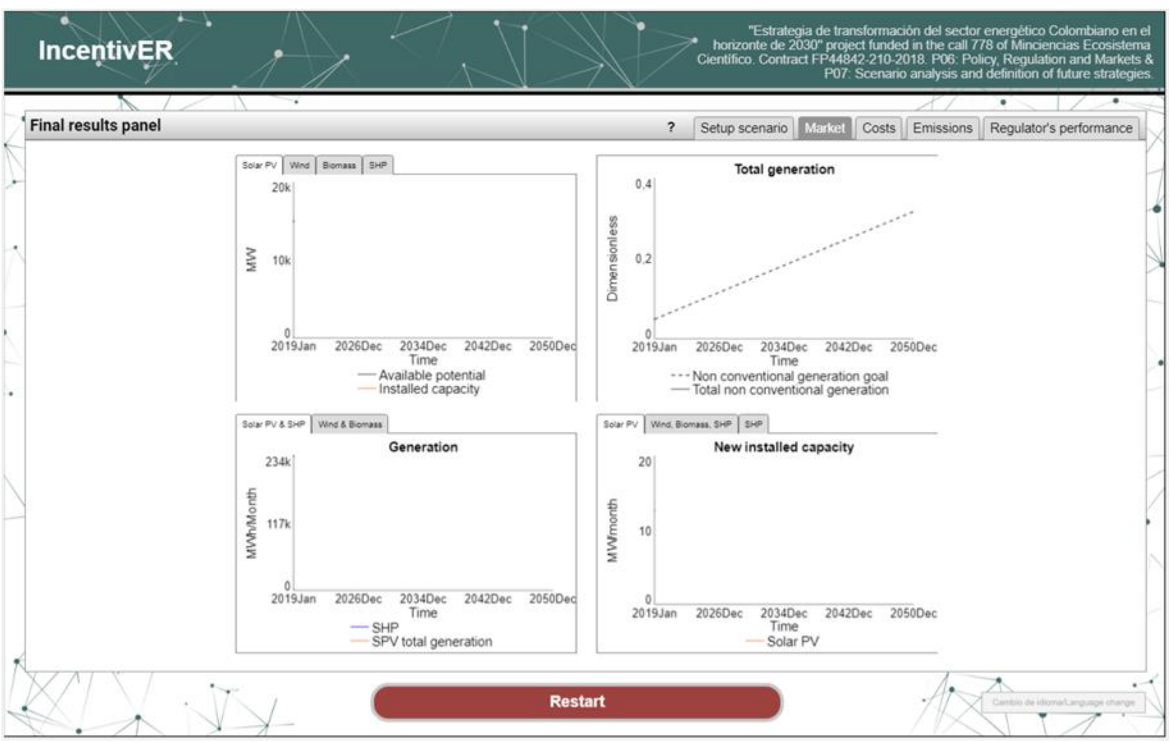

Figure 4-4: Microworld's results window.

Source: Own elaboration.

Finally, the microworld contains language selection at the beginning of the game and a link to a register sheet, also it has the question mark through all the windows, this functionality displays a definition for all the microworld variables, to serve as a game guide. Players can also change the language anytime during the game, and they can restart the game when they finish playing. For a detailed microworld, interface see Appendix G.

4.2.2 Microworld learning and teaching supporting material design

As the microworld is a compliment tool for learning, in addition to a class session or a guided learning supporting material, to let the users acquire new knowledge, we developed the supporting material for different types of users, based on FishBanks teaching instructions (MIT, 2020b): a self-guidance microworld game, and a complete class session directed by an instructor. This material follows the checklist for the learning and teaching supporting material (View Appendix B).

For a self-guided microworld session, we developed the users' guide presented in Appendix H, which include:

- *Microworld game introduction:* short explanation on how the game works, including the decisions that the player have to deal with, the variables that they can change to create their scenarios, the time horizon, and the objectives to achieve while playing,
- *Definitions:* This section includes the definition of all the variables in the microworld, as we assume that many players may not have previous knowledge of energy-related topics.
- *Microworld interface:* this section presents the microworld interface functionalities and how to use them, such as switch buttons, slider bars, and fill-in variables, as well as explain how to visualize the preliminary and final results.
- *Game assumptions:* After playing, the users will be redirected to the users' guide to check this section as well as the key lessons that they should learn. In this section, we provide the users with the game assumptions, in terms of the price-setting, simplifications on incentives, and generation.
- *Key lessons after play:* After playing, the users can access again the users' guide to read the key lessons, in which we include feedback about the diffusion model, allowing the

users to understand better their results as a consequence of causal relationships in the underlying model of the microworld. We assume that users may not know system dynamics, so we added a basic explanation of causal loop diagrams and stocks-and-flows diagrams.

For a class session guided by an instructor, we proposed several materials, including a briefing, a debriefing, and also the users' guide. All the class composition and guides are developed in the instructors' guide. This document serves as a base for a complete session, or different sessions depending on the time available for each class. A complete session for the microworld is designed to be developed in 3 hours, but this time is flexible depending on each course's needs, and on the conversation generated at the end of the game. The instructor's guide in Appendix I includes the following information:

- *Abstract:* a short review of the game and the objectives of the instructors' guide, as well as the target users for the microworld and the access to the microworld platform.
- *Setup and player briefing:* in this part, we provide instructors with the necessary tools for executing the microworld session, including the key lessons before playing, the necessities to run a game, and the class plan with timing and briefing keynotes and comments:

    i. *Key lessons:* We provide an introduction on three important topics for the microworld and recommend explaining it before star playing using the proposed briefing slides. The key lessons include technology diffusion in the electricity market, feedback effects in the system, and energy and power.

    ii. *Before running a game:* we prepare the instructor to inform or provide the users with a computer and a good internet connection, as the microworld is played online.

    iii. *Class plan for a session:* In the class plan we include the timing as a class of three hours, two of them dedicated to the introduction and playing the game, and one of them to debriefing. We also provide the briefing slides (View Appendix J) and keynotes and comments on the briefing, this information will help the instructors to teach the microworld session. Before start playing, we recommend the instructors to conduct a simulation orientation, and we propose some practice runs in which the users will manage with different scenario settings and decisions making as training for playing. In the class plan, we include some common questions identified in the microworld pilot testing, and expected players results, to give instructors a clear vision and anticipate them to what they can explain in the class.

- *Debriefing and teaching notes:* As a learning-oriented tool, the instructors have to discuss the microworld results with the users to provide feedback. We provide some debriefing slides that are oriented to have a conversational analysis of what happened during the game. In the debriefing, we include keynotes and comments on debriefing slides, as well as some key messages that should be discussed in the microworld debriefing:

    i. *Key messages:* the key messages for the microworld include the functioning of the renewable energies diffusion, the applied incentives, how the installation occurs due to the profitability and the regulator's performance, how to reach the emissions and energy demand goals, and finally how does the learning rate for investment costs works.

    ii. *Keynotes and comments on debriefing slides:* The debriefing slides (View Appendix K) are aimed to enable discussion in the class, and include the explanation of the key variables of the model such as installed capacity, available potential, emissions, costs, and regulator's performance results. We also provide a debriefing on the underlying model for specific classes, such as system dynamics courses.

    iii. *Outline for a short debriefing:* for limited time classes we included a short debriefing guide with key questions for the user, such as: "*How can the non-conventional renewables installation of new capacity be sped up?", "What if there were no non-conventional renewable technologies on the market?", "What strategies did you use?", and "What could be a responsible strategy?".*

iv. *Five minutes debriefing summary:* to conclude the session we propose a five-minute conclusion, including a quick review on diffusion, system dynamics, and the stability of the electricity market.

Additional learning-oriented microworld's material

In the microworld's supporting material checklist (View Appendix B), we included a pre and post microworld questionnaire (View Appendix F) as a learning indicator for the users in the microworld. This questionnaire evaluates previous and post microworld users' knowledge in terms of renewable energy, the renewable energy context in Colombia, the objectives in emissions reduction, and energy matrix diversification.

Finally, we predefined a results' register sheet (View Appendix L) for the users to save the results for the game, these results are useful for debriefing purposes, because it gives the players a base to talk about what happened with their decisions during the game.

4.3 Iteration: experts' feedback

This phase includes all the review sessions for the microworld, presented in Appendix A, in those sessions we refined the microworld modeling as well as the microworld complexity for the users. We made this phase parallel with the model validation process, to ensure the model structure consistent with the real system.

Specific improvements and changes made during this phase include modeling variables like the long-term contracts' auctions, which were initially modeled assuming that all the non-conventional installed capacity wins a long-term contract. Instead, we modify it to be a portion of the capacity established by the users. Other modifications include the LCOE calculation, excluding the aggregated taxes, which results in the expected decreasing results and building confidence in the model.

For the interface and microworld structure, we made several improvements, the first microworld design in **Figure 4-5** did not include the scenario setup window, the long-term contracts auction as described, and the carbon bonds. Other crucial elements added during the iteration process was the regulator's performance and the clear vision of the game goals. With the iteration process, we achieve the final design in Appendix G, which includes new functionalities such as the language selection, the register sheet link, the setup scenario window, carbon bonds mechanism, correct implementation of the auctions, and excludes the reliability charge to maintain the microworld's complexity manageable during the time of the designed session.

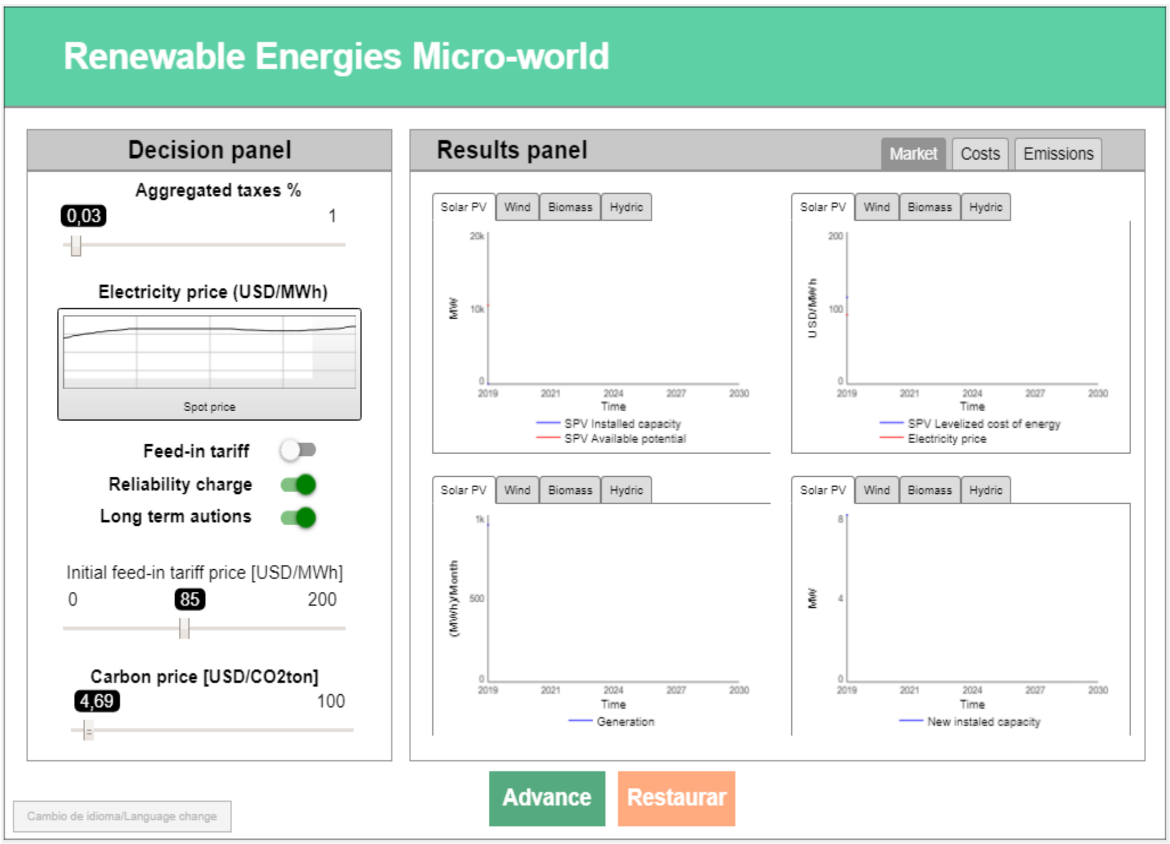

Figure 4-5: Initial microworld's interface design, before the iteration phase.

Source: Own elaboration.

4.4 Microworld's Pilot testing and closing

Microworld's pilot testing includes the Alpha and Beta phases, in the Alpha phase, we tested the microworld with a specific audience which included experts on energy, climate, and economics, as well as professors to reinforce the learning-oriented platform. The audience included "Energética 2030" experts, and members of the Decision Sciences research group

(View Appendix A). All of them, had specific knowledge to give feedback to the microworld interface and modeling as well as the functionalities that must be included.

In the alpha test we made a demo of the class plan for the microworld, including the briefing, gaming, and debriefing part, with this pilot testing we identified the required time to develop the microworld session in a specific course, divided into sections for the briefing, the game, and debriefing. The participants also gave feedback and recommendations on the briefing and debriefing slides, and in the microworld's interface, such recommendations included:

- Inclusion of energy vs. power explanation for the users without previous knowledge in energy concepts.
- The suggestion of adding a log-in and sim orientation in the briefing, so the users can learn how to use the microworld interface before actually dealing with decisions.
- Addition of a results record sheet to incentivize the discussion at the end of the game, using that record, users can remember what they did and discuss their results effectively.
- Explicitly show the goals in the interface.
- Add question marks for all variables in the model, so users can click on them and read a definition of each variable while playing.
- Provide the players with the users' guide during the game. At the time of the Alpha testing, we had not completed the users' guide, but it was included in the final version.
- The suggestion of eliminating the reliability charge incentive because it already includes the feed-in tariff and the long-term contracts which were high complexity incentives.

The main contribution of the alpha testing was related to the microworld's session upgrade, adding a better briefing and debriefing, and preparing the timing for the Beta pilot testing. As we expected, we did not identify modeling errors during this phase, given that the model was previously validated. We implemented all the proposed changes and proceeded to the beta phase.

To choose the sample size to carry out the pilot test in the Beta phase, we considered a target population (N) of 9986 people, who correspond to engineering, architecture, urban planning, and related studies from the National University of Colombia in Medellín headquarters (UNAL, 2019). With a confidence level of 90% and an estimation error (e) of 10%, and a sample proportion (p) of 0,5, the minimum sample size (n) accepted to conclude on the target population is 67 people (Krejcie & Morgan, 1970) (View Appendix M).

Considering the estimated sample size, in the Beta phase, we tested the microworld with an audience with less knowledge in energy and climate than the audience in the Alpha phase, we included 72 undergraduate engineering students. This session included the application of the learning indicator: pre and post microworld's session knowledge questionnaire for participants in Appendix F. This learning indicator includes 15 questions related to renewable energy, Colombian electricity market, energy vs power, capacity installation, and participant's criteria. After a short presentation and introduction, we asked the participants to solve the pre-session knowledge questionnaire, also we requested them to answer "I do not know" in the questions they were not sure, to have clear results. The results for the pre microworld session in **Figure 4-6** show that the general score for the questionnaire was low, with a mean score of 5,6 points.

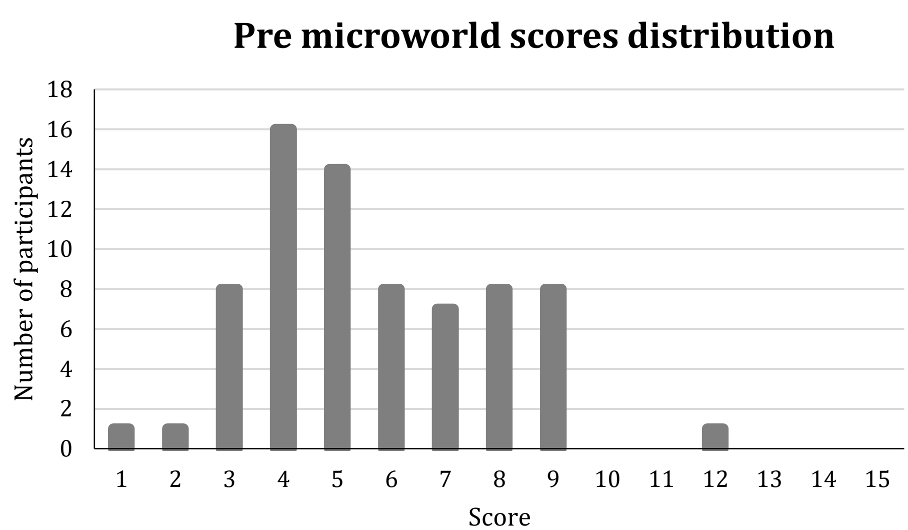

Figure 4-6: Pre microworld questionnaire scores distribution.

Source: Own elaboration.

After letting participants answer the questionnaire, we performed the briefing session. In this part, we had questions about energy and power and on different incentives, those questions were included in the "common questions" in the instructors' guide in Appendix I. Then we ask the participants to start playing in the microworld as they wanted. Finally, we concluded the session with a debriefing on the microworld results. In this session, we considered the recommendations of the alpha phase for the briefing, game, and debriefing part, and we had a very active discussion session.

Finally, we asked the participants to answer the same questionnaire they did at the beginning of the microworld pilot testing session. For our pilot testing purposes, we gave the participants a period of two days to solve de post-questionnaire. **Figure 4-7** shows the results for the post microworld session, in which participants had an average score of 10,2 points, twice as in the pre-questionnaire. This score is an indicator of short-term learning. In future steps, the same questionnaire could be used for testing long term learning.

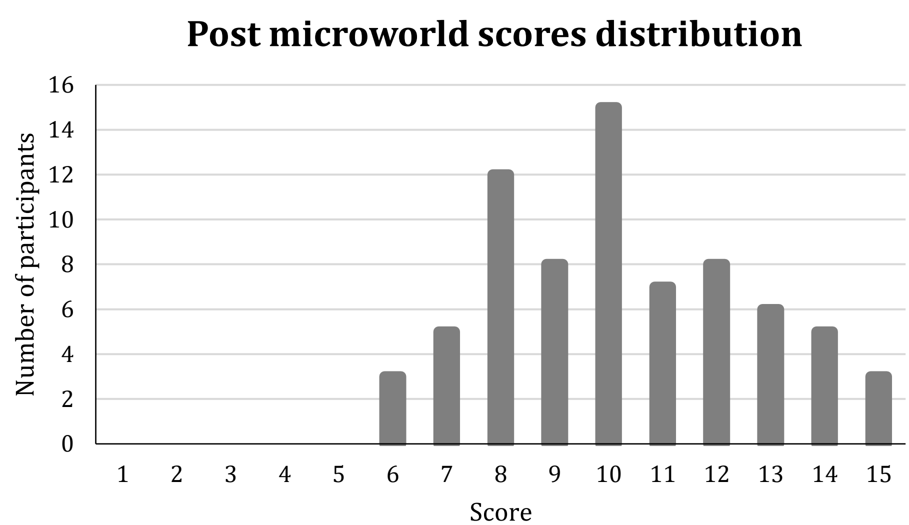

Figure 4-7: Post microworld questionnaire scores distribution.

Source: Own elaboration.

To confirm that the difference between the obtained results in both samples are statistically different, we made a means comparison considering that the samples were paired. We used the software RStudio (1.1.456) (Rstudio Inc, 2018) for all statistical testing.

First, we analyzed the normality of the data of both simples with a Kolmogorov-Smirnov test since the sample is greater than 30 (Mohd Razali & Bee Wah, 2011) (View Appendix M)., In this case, we used a confidence level of 95%. For the pre-microworld questionnaire scores, given that the p-value of the Kolmogorov-Smirnov test was 0.02781, which was less than the alpha value of 0,05, we could conclude with a 95% confidence level that the null hypothesis (H_0: The scores for the pre-microworld test follows a normal distribution) was rejected, and therefore there was insufficient evidence to conclude that the scores for the pre-microworld questionnaire were normally distributed. For the post-microworld questionnaire scores, given that the p-value of the Kolmogorov-Smirnov test was 0.133, which was higher than the alpha value of 0,05, we could conclude with a 95% confidence level that the null hypothesis (H_0: The scores for the post-microworld test follows a normal distribution) was not rejected, and therefore there was enough evidence to conclude that the scores for the pre-microworld questionnaire were normally distributed.

We tested the differences between the pre- and post-scores (View Appendix M). Considering that only one of the samples is normally distributed, it could have been possible to use the Wilcoxon Mann Whitney test for the comparison of sample means. However, the results of this test are only robust for independent samples and size less than 30 samples, with which we carried out the t-student test for paired samples, since with samples of size greater than 30 the t-student distribution tends to a normal distribution (Bernardo Calderón, 2008).

After making the T-Student test for the comparison of paired simples means (View Appendix M), and given that the p-value of the test was less than 2,2e-16, which was less than the alpha value of 0,05, we could conclude with a 95% confidence level that the null hypothesis (H_0: The scores mean is the same before and after the microworld) was rejected and therefore there was enough evidence to conclude that the post microworld questionnaire score mean was higher than the mean score from the pre microworld questionnaire.

Finally, the learning indicator (questionnaire) used in the pilot testing suggests that the microworld increases the understanding of the participants, at least based on the statistical tests. Also, some of the questions that had a greater number of incorrect answers in the pre-microworld questionnaire were about what the non-conventional renewable generation technologies in Colombia are, why is it important for Colombia to diversify its energy matrix, what is the LCOE and the questions on the behavior of key variables such as the available potential and the installed capacity of the technologies over time. However, in the post-microworld questionnaire's results, this scenario changed, as the number of incorrect answers to the critical questions was drastically reduced, showing that immediately after the session, the participants had more clarity on the subjects. In general, the number of incorrect answers in the post-microworld questionnaire was much lower than in the pre-microworld questionnaire. For these reasons we conclude that the microworld session generated knowledge in the short term and accomplished the proposed learning objectives for the participants, and that it's a successful learning-oriented tool.

5 Conclusions

Colombia has committed to reducing 20% of the projected emissions by 2030 (Barrera et al., 2015) and the goal of covering 15% of the demand by 2030 by renewable energy (XM, 2020c). Therefore, the country has implemented different renewable energy incentives in the framework of energy transition toward a cleaner, secure, and more sustainable system. This energy transition is a complex process that includes delays, interactions between agents, feedback mechanisms, and -with major relevance- fast changes. Although it is important to have highly complex simulation models to support the decision-making process in the energy sector, it is also necessary to have tools designed for learning and teaching concepts of energy transition and renewable energy. The learning tools are necessary for capacity building for the new challenges that the energy sector is facing. Particularly in Colombia, it is necessary to implement learning tools for training the different publics on the electricity sector, including the private sector, policymakers, and consumers; but also, to positively influence the public knowledge of renewable energy.

One of these practical learning tools are microworlds, which use both traditional and constructionist teaching methods and promote experimentation-based learning, with the premise of learning by doing. This is why this thesis aims to develop a microworld for learning and understanding the diffusion dynamics of non-conventional renewable electricity generation in Colombia, following three specific objectives: (i) selecting and adapting an existing simulation model for the adoption of renewable energy in Colombia, considering different incentives; (ii) developing a virtual environment for the microworld; and (iii) evaluating the microworld through pilot testing. We used an iterative methodology, combining system dynamics for the development of the simulation model and microworld's virtual environment developing a methodology to build the virtual environment which includes the microworld's interface and all learning and teaching supporting material.

After reviewing several models and platforms, we selected Arias-Gaviria et al. (2019) model to be modified and adapted as the underlying model for the microworld due to its complexity level, its adaptability for learning and teaching purposes, the accessibility to its information, and its adaptability to different generation technologies. We added incentives such as long-term contracts auctions and carbon credits, also we added the incentive costs and non-linear variables such as the regulator's performance which affects the installation of new capacity. We adapted the model to represent the technology diffusion in the electricity market and used Bass's (1969) diffusion model to simulate the available potential and the installed capacity of renewable energy. Also, we modified the expected profitability as the price-LCOE ratio. We performed several validation tests and concluded that that the model is a good approximation for diffusion of renewable energy technologies. We also concluded that learning curves may have a high impact on renewable technology diffusion in Colombia. This impact is caused because of the reduction on the unit investment costs for the technologies that make technologies become attractive to investors since the total costs for the technologies decrease, making it more profitable in time.

For the design of the microworld and the entire virtual environment, we followed the methodology proposed by Valencia O, Víctor Riascos M, & Niño Z (2011), for immersive microworlds, and we modified it to include the design of the learning and teaching support material. The development of the virtual environment for the microworld included six fundamental steps: Design, Planning, Iteration, Alpha and Beta pilot testing, and the Closing phase. Through this methodology, we defined the player role as the regulator of the electricity market and the learning objectives for the microworld as (i) learn about the diffusion mechanisms for the renewable installed capacity and its effect on GHG, and (ii) learn about the trade-offs that arise while trying to reach the game goals. We also defined the microworld's technical architecture, we proposed a checklist for the elaboration of microworlds as a scientific contribution and we designed the microworld's interface. For the learning and teaching supporting material, we developed an instructor's guide, a user's guide, a briefing, and debriefing. We carried an iterative reviewing process with experts and performed the alpha pilot test for the microworld (with an experienced public) to verify the correct functioning of the microworld and obtain feedback. Finally, we proceeded with the Beta pilot testing (with the inexperienced public) to make conclusions about the learning process using the microworld.

In the Beta pilot testing phase, we used the supporting material for the teaching process, following the instructor's guide, the briefing, and the debriefing proposed, carrying out complete sessions in system dynamics classes and amongst undergraduate engineering students. In these sessions, we implemented the evaluating tool (pre and post microworld questionnaire) for the new knowledge of the players after the game. We made the questionnaire at the beginning and the end of the session, and we obtained evidence to conclude that the microworld for learning about the diffusion of non-conventional renewables generation technologies in Colombia is a useful tool to support the learning process. However, further analysis should be developed to evaluate if the gained knowledge is maintained in the long term (e.g. after several months of playing with the microworld).

This thesis has three main contributions. First, we have contributed to the literature of simulation models for the adoption of renewable energy, by improving the existing Arias-Gaviria et al. (2019) model. We reformulated the investment function to consider the price-LCOE ratio and the regulator's performance effect and included a formulation for auctions, which was not considered in the previous literature. This function add reality to the underlying simulation model, on the one hand the price- LCOE ratio incorporates elements such as the investment, operational and maintenance costs, as well as, the generated energy and the electricity spot price; on the other hand, the regulator's performance is a way to incorporate the consistency of issuing regulation that actually affects investments.

Second, we developed forward the methodology proposed by Valencia O, Víctor Riascos M, & Niño Z (2011) for immersive microworlds and adapted it to learning microworlds, including a checklist to future learning-oriented microworlds and the development of the learning and teaching supporting material. This adjusted methodology depicts a series of clear steps for the development of a microworld. In fact, there are many already built microworlds, but there were no documented methodologies for such development, i.e. the microworlds have been built based on experience as far as we know.

Finally, to our knowledge, the microworld is a novel tool with free online access for learning about the diffusion of non-conventional renewable generation technologies in Colombia. This tool includes self-learning material and instructor's material to be used in different classes, for example, university courses, such as system dynamics, electricity market-related courses, or workshops with professionals and practitioners in the area. Likewise, the user interface allows an alternative parametrization to be applied in other countries.

Several research opportunities arose from this work. First, the formulation of the underlying model can be complemented with a more accurate demand forecasting methodology. Colombia's goal is to cover a percentage of the demand with non-conventional renewable energy, so the microworld focuses on learning about the drivers of the diffusion of those technologies, but it is important to analyze the energy demand. Additionally, it would allow for integrating demand scenarios. Future work should consider the modeling of the energy price as a daily trade-off as it occurs in the electricity market, in addition to the possibility of pre-establishing price scenarios as it is already formulated in the microworld.

Other options for future work include the incorporation of different pre-established game scenarios such as the prospective scenarios of the energy sector prosed in project 7 of "Energética 2030" (Ortega, Ángel Sanint, & Jaramillo Vélez, 2020), or according to different scenarios of climate change and dependence on water resources, in the case of Colombia. Regarding the underlying model, future work includes the incorporation of radiation and wind variability for solar photovoltaic and wind technologies, as well as the water cycles for SHP, as the current model makes use of plant factors established by MinMinas & UPME (2019). These modifications will allow the microworld to be a more versatile tool in terms of the geographical location of the users, allowing them to create game scenarios adapting to each of their specific climatic contexts. Additionally, future work should also consider the pertinence of including other technologies such as energy storage (batteries), geothermal energy, and different forms of ocean energy.

Finally, we propose to extend the pilot testing sample to have a greater scope, increase the confidence level, and reduce the error margin on the samples. To extend these samples it is proposed to incorporate the tool in a variety of courses to generate a greater contribution to the knowledge of users about the diffusion of non-conventional renewable energies in Colombia and obtain a wide variety of data to verify the microworld's learning contribution to the participants. This variety of data will make it possible to make different conclusions on the results, for example, which type of users have a greater score depending on the educational context. Additionally, it is necessary to implement long-term learning tests for the new samples, as a complement to the pre and post microworld questionnaire. This type of testing would allow us to study if the knowledge acquired during the microworld remains in the long term, or if it is temporary. Additional testing should also evaluate learning through the use of the microworld compared with a 100% traditional teaching method.

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Appendix

A. Meetings schedule

Introduction

The microworld development was made in multiple stages. The first steps included a lot of bibliographic reviewing and model development. In the next steps, we developed the microworld's virtual environment with *"Energética 2030"* experts and through pilot testing.

Meetings and sessions

Table A-1: *Meetings and sessions schedule.*

Date	Topic	Participants
August 5th, 2019	Microworld brainstorming.	Decision sciences research group Erik Reimer Larsen
November 15th, 2019	Thesis ideas presentation.	Energética 2030: P06 & P07 participants: • Santiago Arango Aramburo • Jessica Arias Gaviria • Alexándra Valencia Zapata • Yris Olaya Morales

		• Juan Felipe Parra Rodas • Verónica Valencia Hernandez
February 3rd, 2020	Thesis ideas presentation.	• Decision sciences research group
March 27th, 2020	Thesis proposal review and microworld's virtual environment introduction.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
March 30th, 2020	Microworld's structure review: • Which technologies include? • What are the goals for the players? • Learning objective. • Regulator's performance.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
April 6th, 2020	Model parameters review.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
April 14th, 2020	Base generation model review. Briefing, debriefing, and instructions introduction.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
April 23rd, 2020	Regulator's performance modeling review.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
May 5th, 2020	Briefing, debriefing, and instructions review.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen

May 19th, 2020	Auctions, feed-in-tariff, and investment costs modeling review.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
May 26th, 2020	Plant capacity factors and final generation review.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
March 27th, 2020	Planning for the testing of the Alpha phase: • Slides and session review.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
June 12th, 2020	Alpha testing session.	• Alexandra Valencia Zapata (Master Student) • Clara Inés Villegas Palacio (Ph.D.) • Jessica Arias Gaviria (Ph.D.) • Juan Felipe Parra Rodas (Ph.D. Student) • Santiago Arango Aramburo (Ph.D.) • Sebastián Bernal García (Master) • Simón García Orrego (Master student) • Syndi Martínez (Ph.D. Student) • Sandra Ximena Carvajal Quintero (Ph.D.) • Verónica Valencia Hernández (Engineer)

		• Jhon Jairo García Rendón (Ph.D.)
June 16th, 2020	Review the Alpha phase testing session.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
June 30th, 2020	Planning for the pilot testing of the beta phase: • Session planning and slides.	• Santiago Arango Aramburo • Jessica Arias Gaviria • Erik Reimer Larsen
July 1st, 2020	Planning for the pilot testing of the beta phase: • Virtual session strategies.	• Santiago Arango Aramburo • Jessica Arias Gaviria
July 3rd, 2020	Pilot testing Beta phase, session 1.	• Santiago Arango Aramburo • Jessica Arias Gaviria • 17 System dynamics students
July 3rd, 2020	Review the Beta phase pilot testing session.	• Santiago Arango Aramburo • Jessica Arias Gaviria
July 9th, 2020	Microworld's design and interactive platform planning.	• Eliana Barrientos • Santiago Arango Aramburo • Jessica Arias Gaviria
August 31st, 2020	Pilot testing Beta phase, session 2.	• Santiago Arango Aramburo • 55 Engineering students

Source: Own elaboration.

B. Microworlds’ teaching and supporting material checklist

Introduction

This checklist includes all the material that the users will need to guarantee active learning. This material can be adequate to use in the development of other microworlds’ virtual environments. The checklist had a task recommended in order, to make the elaboration of the microworld teaching and learning support material efficient.

Checklist

Table B-1: *Microworld’s learning and teaching supporting material checklist.*

1. Briefing slides	☐
• Key lessons.	☐
• Short game explanation.	☐
• Role in the game.	☐
• Purpose of the game.	☐
• Goals.	☐
• Game assumptions.	☐

2. Debriefing slides	☐

- Key questions to the players. ☐
- Strategies to reach their goals. ☐
- Key variables explanation ☐
- Proposed scenario explanation. ☐
- What is next? Slide: to promote debating to the players. ☐

3. Users' guide ☐

- Introduction: ☐
  - ✓ Decisions to make. ☐
  - ✓ Particular considerations for the microworld. ☐
  - ✓ Objectives. ☐
  - ✓ Microworld horizon time. ☐
- Variables definitions. ☐
- Microworld interface guide. ☐
- Game assumptions. ☐
- Key lessons after play. ☐

4. Microworld session instructors' guide ☐

- Setup and player briefing: ☐
  - ✓ Key lessons. ☐
  - ✓ Considerations before running a game. ☐
  - ✓ Class plan for a session: ☐
    - Required time. ☐
    - Keynotes and comments in briefing slides. ☐
    - How to log in and simulation orientation. ☐
    - Common questions. ☐
    - Expected players' results. ☐
    - Briefing conclusion. ☐

• Debriefing and teaching notes:	☐
✓ Overview.	☐
✓ Key messages.	☐
✓ Keynotes and comments on debriefing slides.	☐
✓ Keynotes and comments on modeling debriefing slides.	☐
✓ Outline for a short debriefing.	☐
✓ Five minutes debriefing summary.	☐

The next two steps may be included for development and testing purposes, the 6th step includes the evaluations for the pilot testing users, to test their learning. The 7th step includes a register sheet to know the users in the microworld.

5. Pre and post microworld tests	☐

6. Results register sheet	☐

Source: Own elaboration.

C. Microworld's underlying model

Introduction

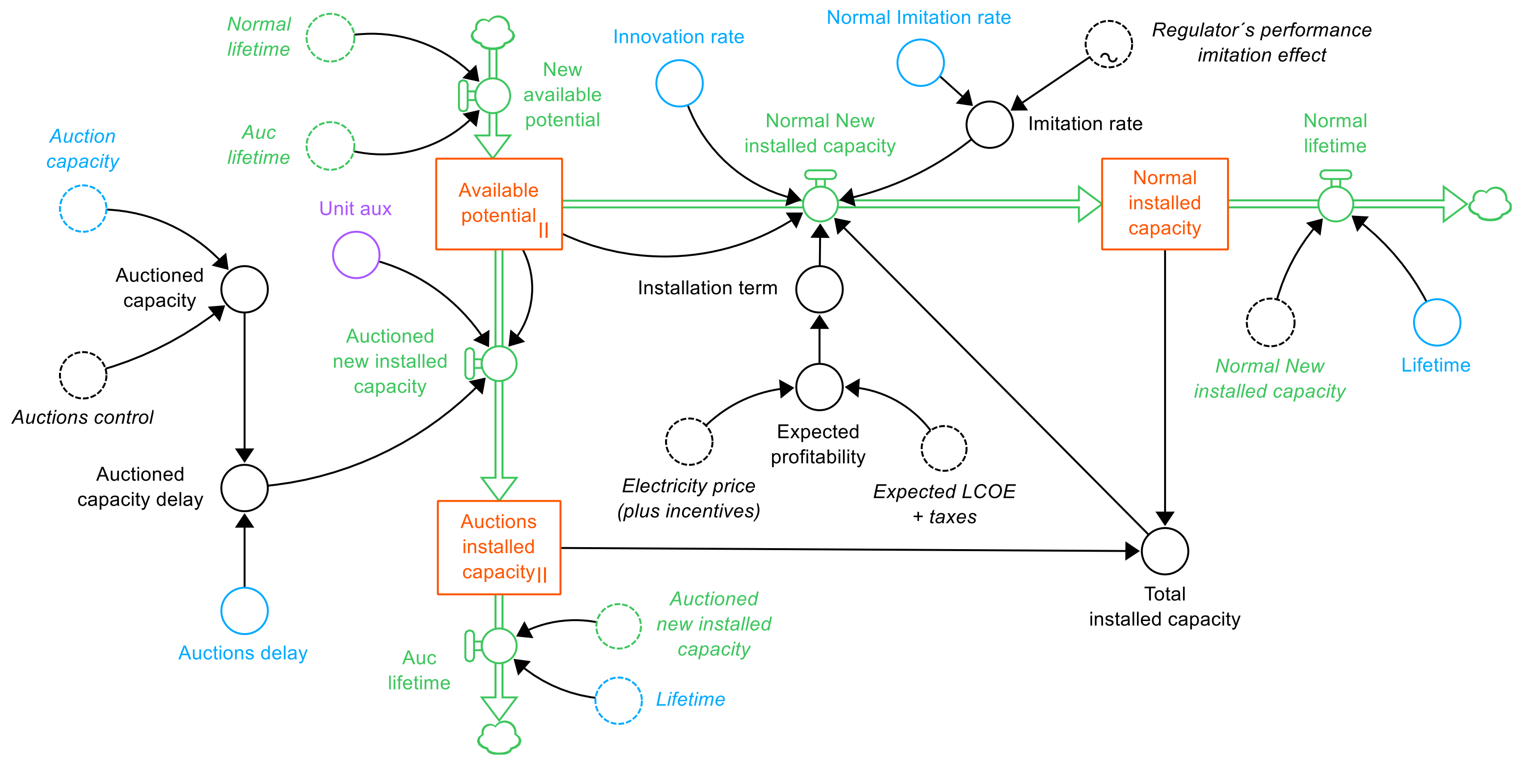
We present the mathematical formulation used in the stocks-and-flows diagrams. We present the microworld model divided into three sections, the first one includes the stocks-and-flows diagram for the technology diffusion, this model is replicated for all of the non-conventional generation technologies: solar photovoltaic, wind, biomass, and small hydropower.

The second part includes the stocks-and-flows diagram used for all the generation technologies, as the incentives, the setup scenario calculations, the emissions, and the shared generation and energy demand. All stocks-and-flows diagrams are based on Arias-Gaviria, Carvajal-Quintero, & Arango-Aramburo (2019); and Bass's (1969) models.

In the final part, we present the mathematical formulation of the model and the parameters for all the technologies to model replication.

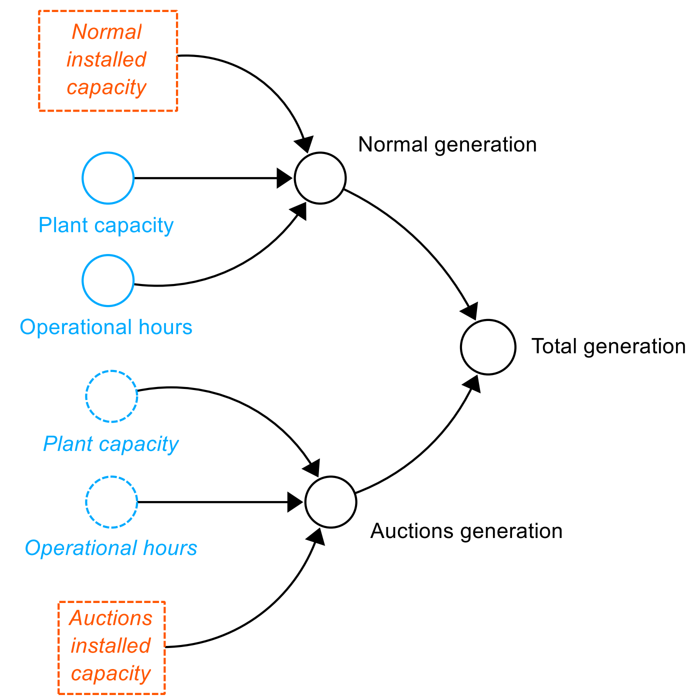
Technology diffusion modeling[3]

i. Diffusion model

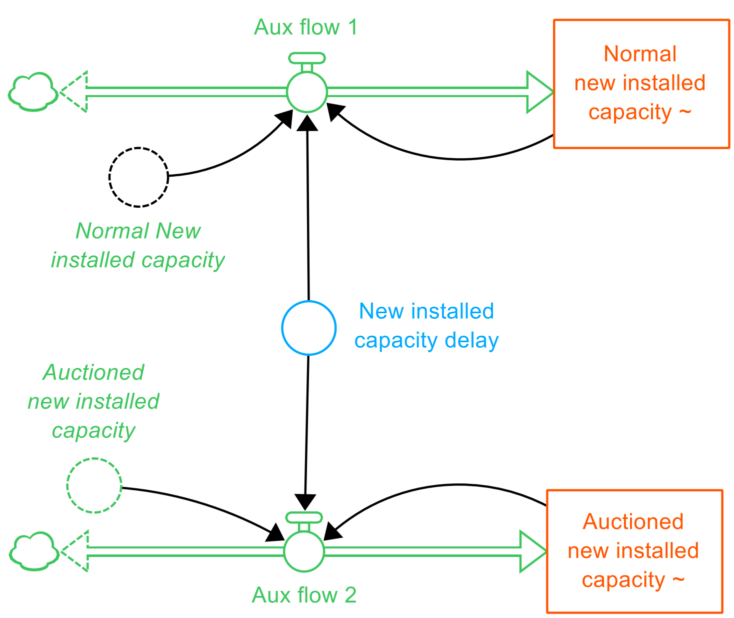


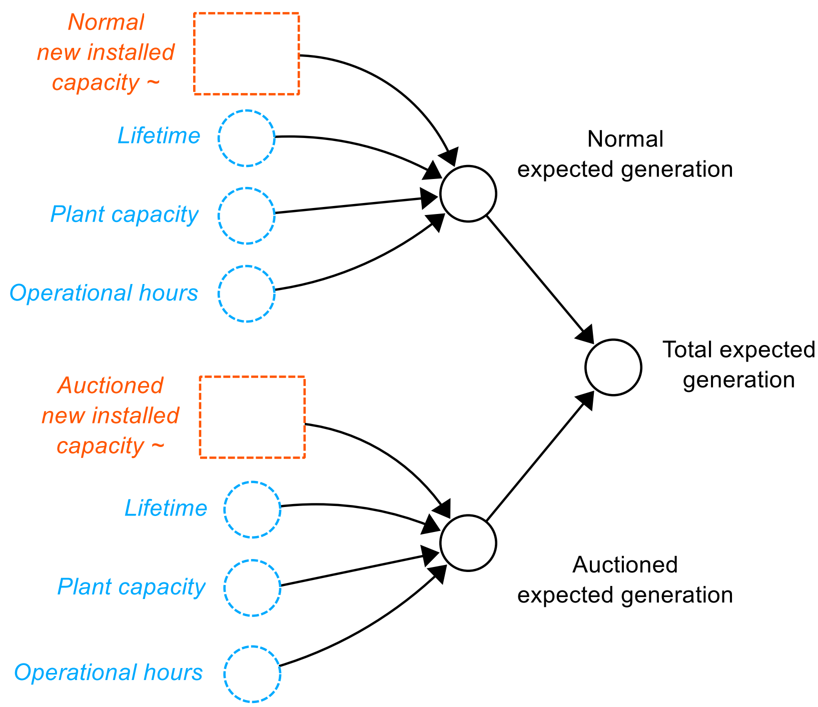
[3] Note that in all diagrams we defined solid line variables, dash dotted variables are copies and are defined in other part of the model. Also, we represented the model parameters with color blue.

i. Total generation

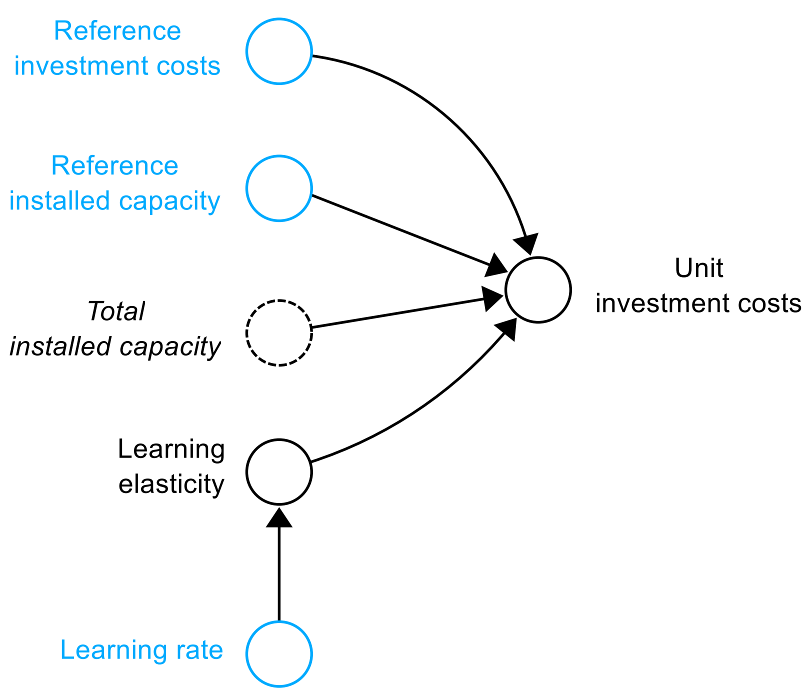


ii. New installed capacity expected generation

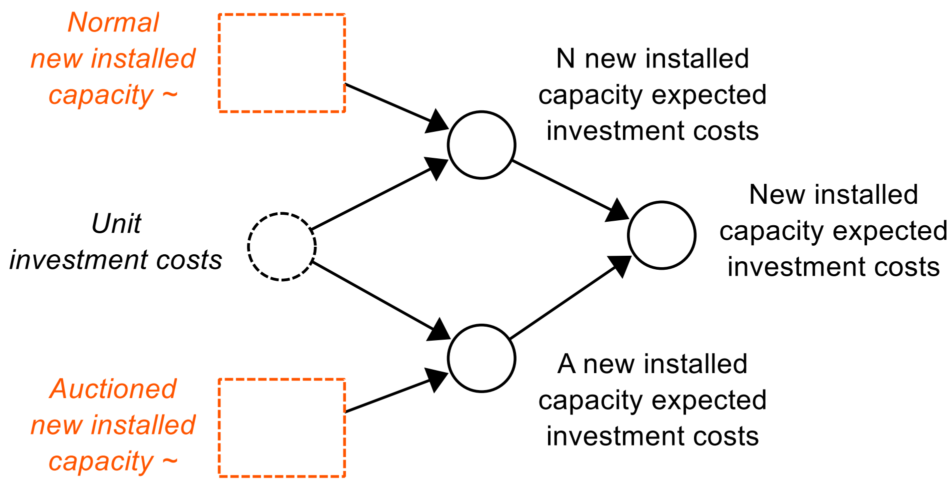




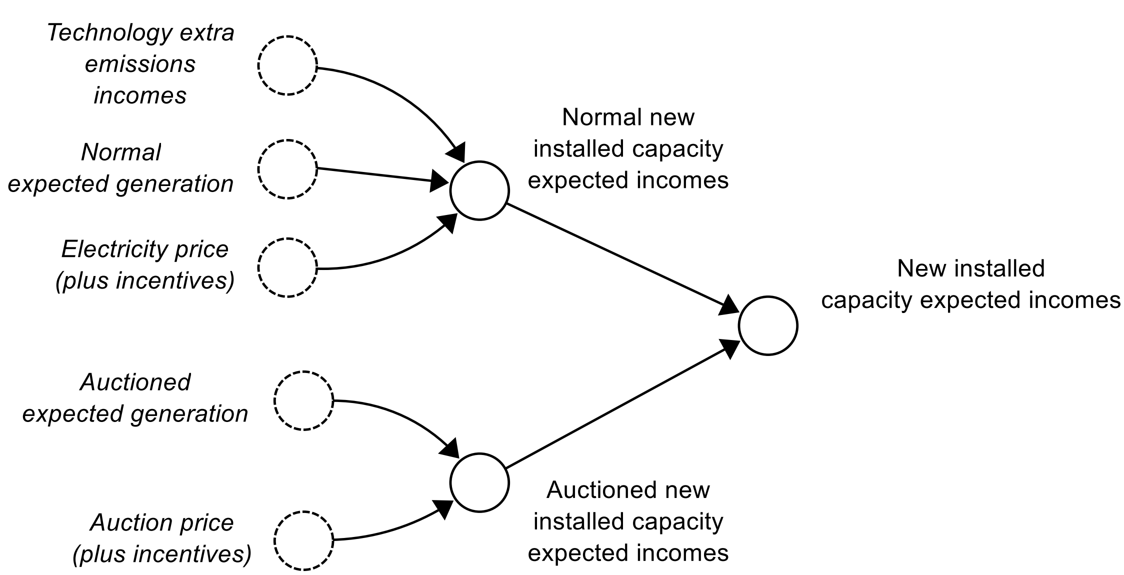
iii. New installed capacity expected unit investment costs



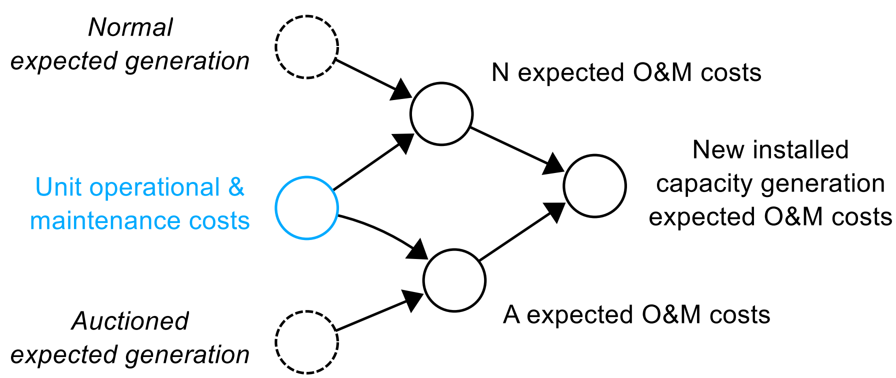
iv. New installed capacity expected total investment costs



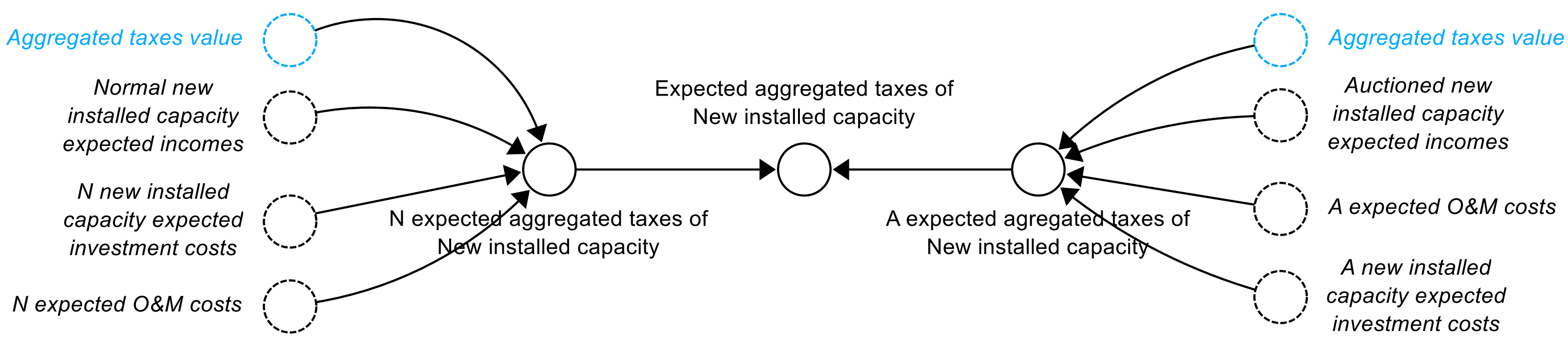
v. New installed capacity expected incomes



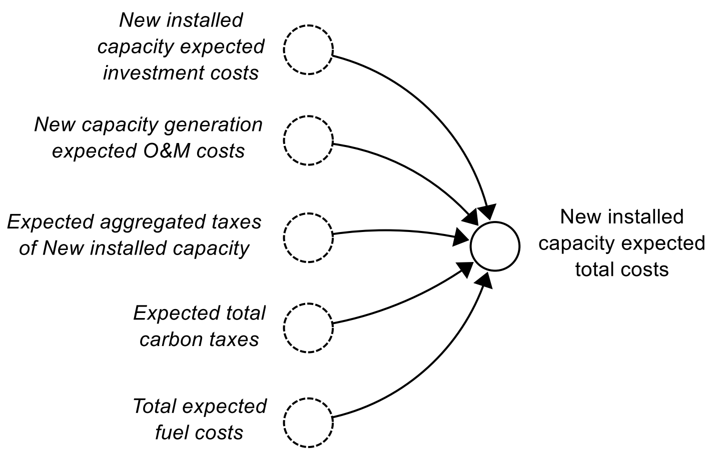
vi. New installed capacity expected total operational and maintenance costs



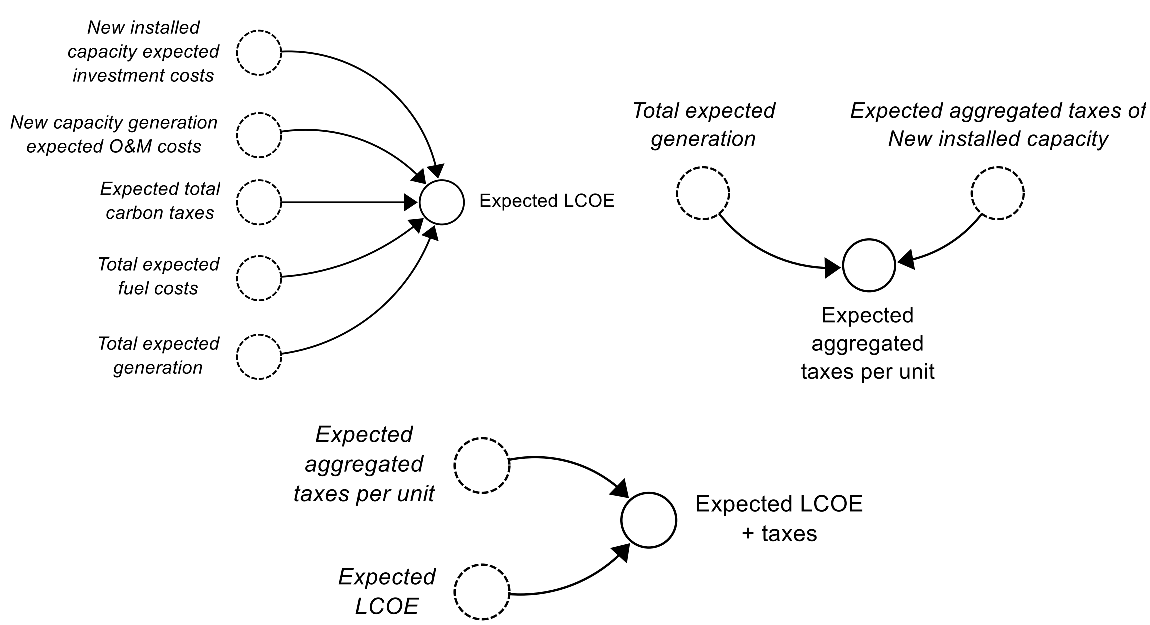
vii. New installed capacity expected aggregated taxes



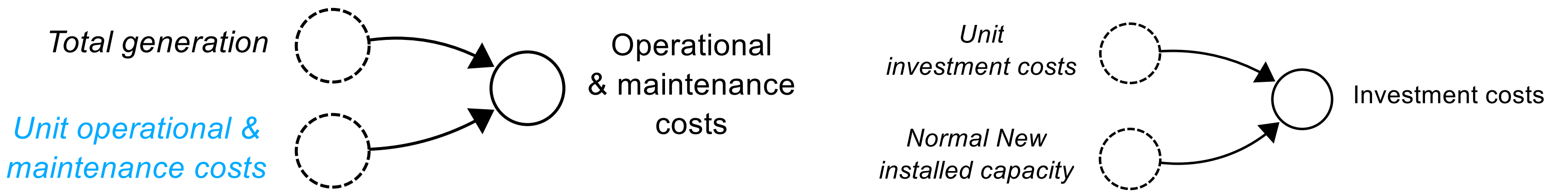
viii. New installed capacity expected total costs

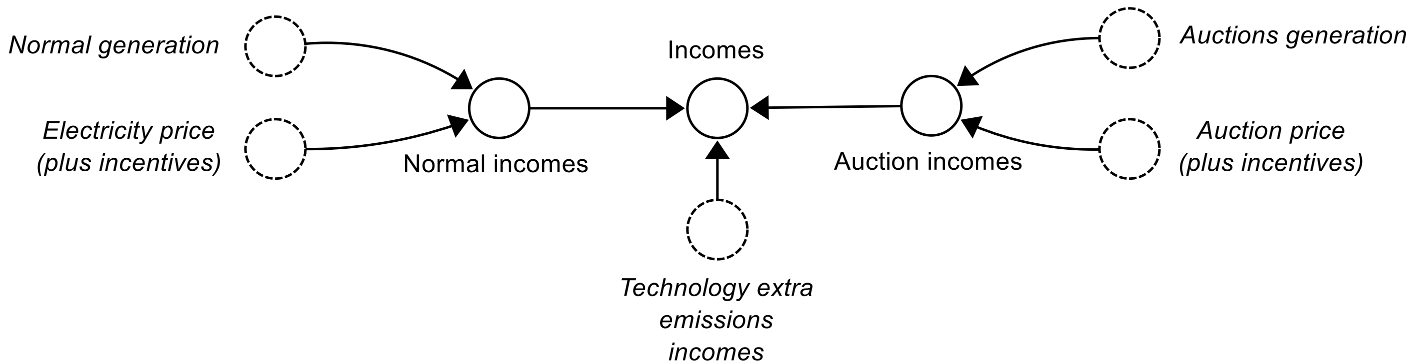


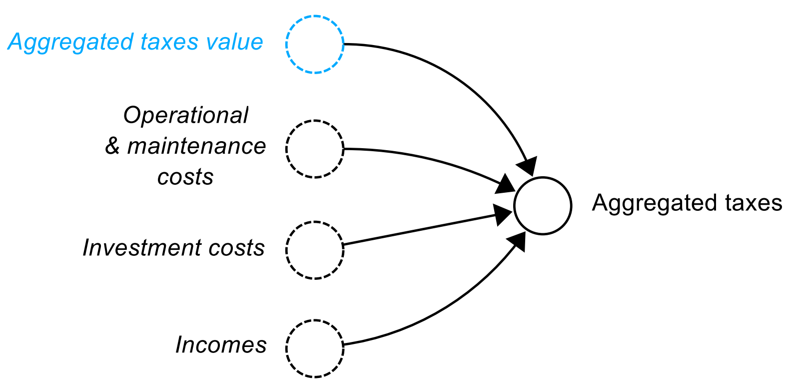
ix. New installed capacity expected LCOE plus aggregates taxes



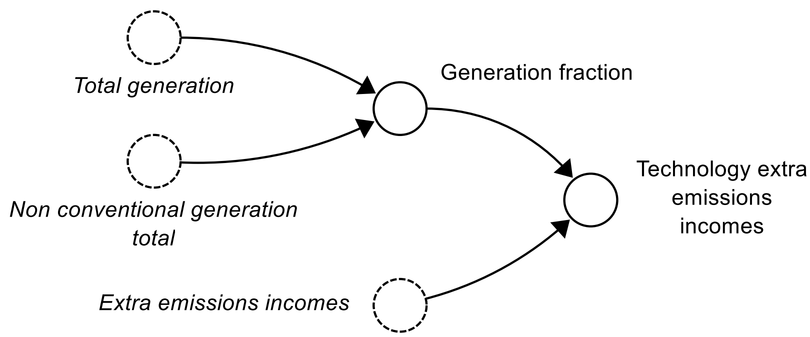
x. Economic calculations for all the installed capacity



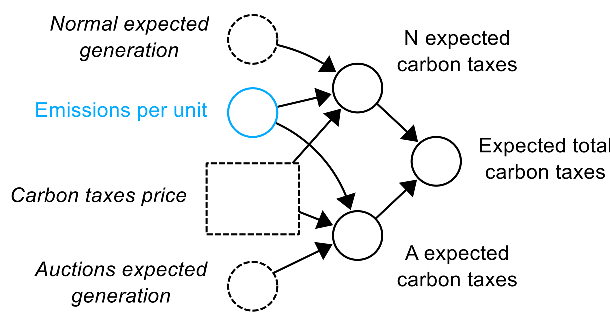




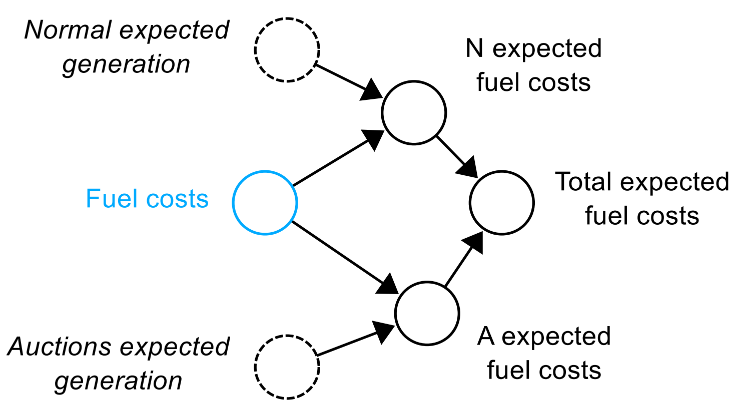
xi. New installed capacity carbon market incomes



xii. Biomass new installed capacity expected carbon taxes

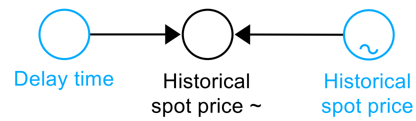


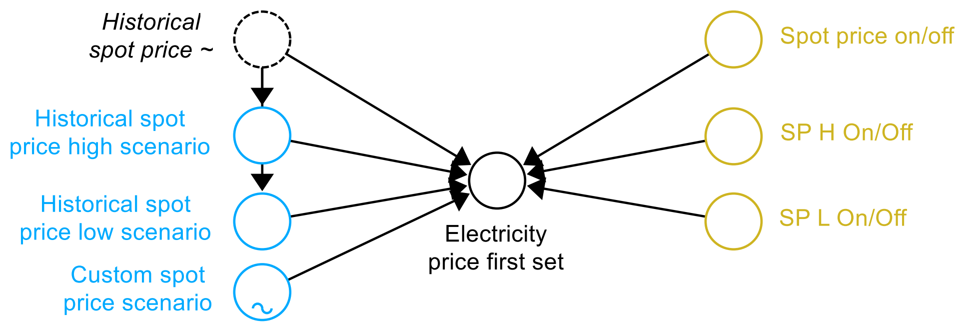
xiii. Biomass new installed capacity expected fuel costs

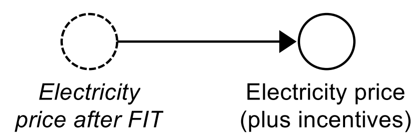


General modeling

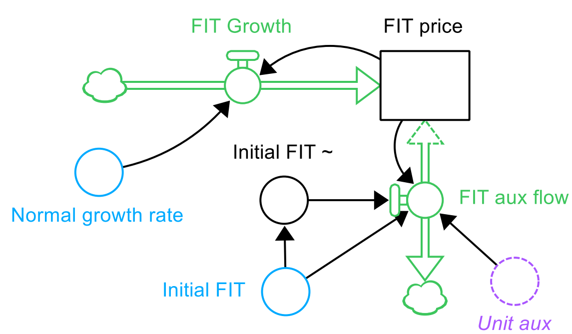
i. Electricity Price

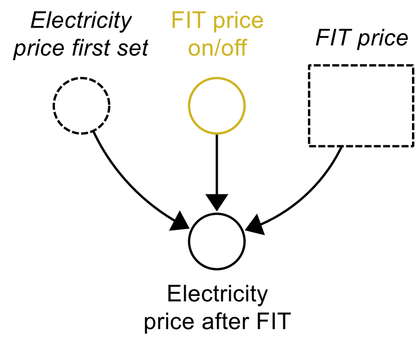




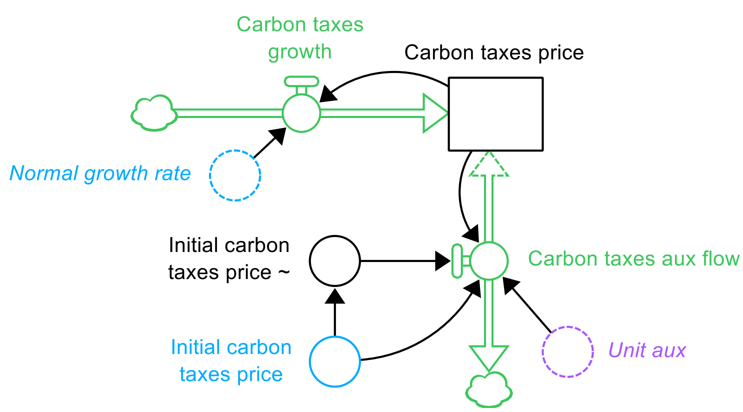


ii. Feed-in tariff



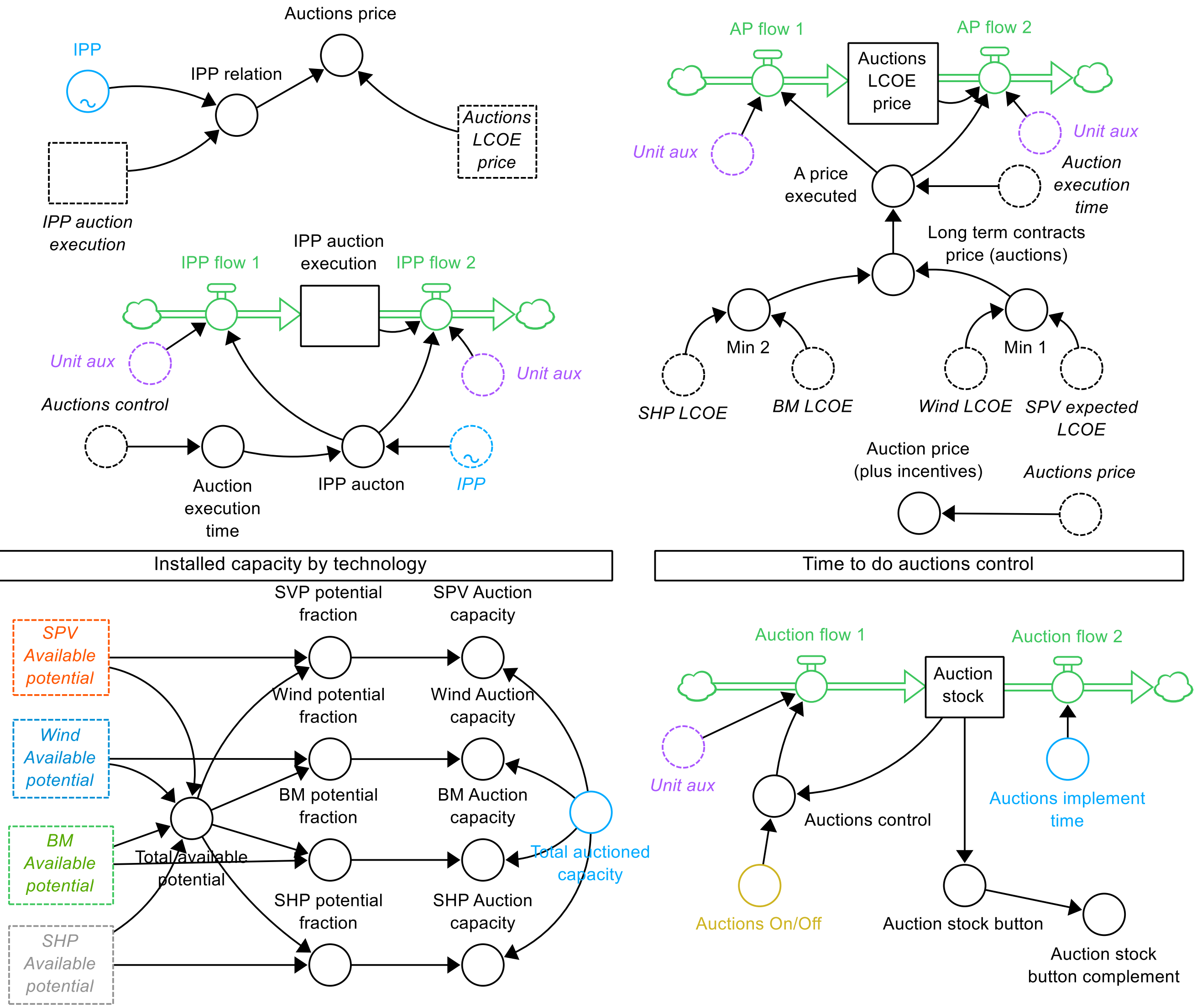


iii. Carbon taxes

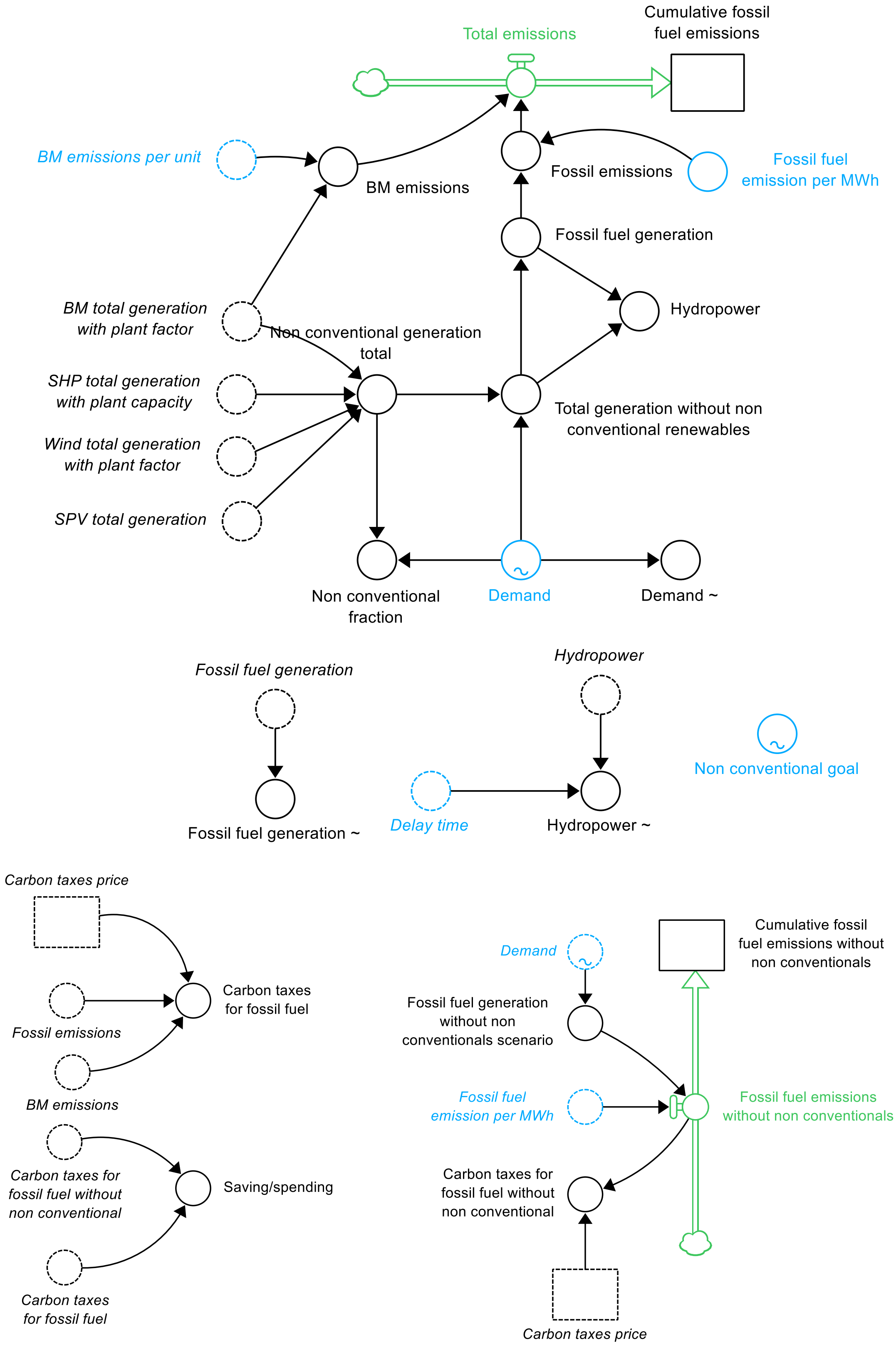


iv. Aggregated taxes

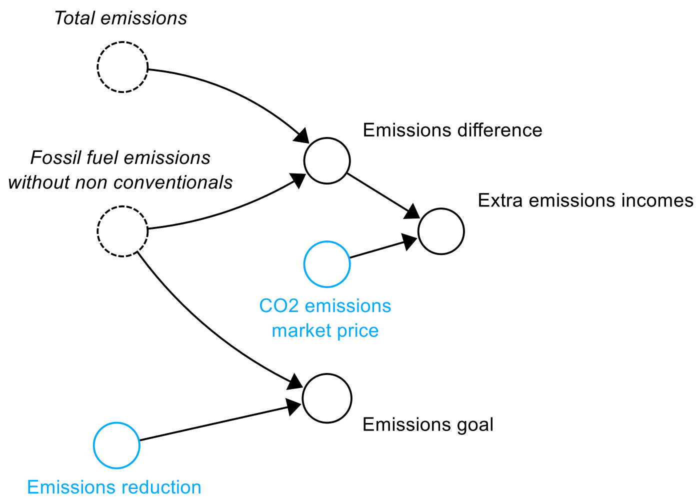
v. Long term contracts auctions



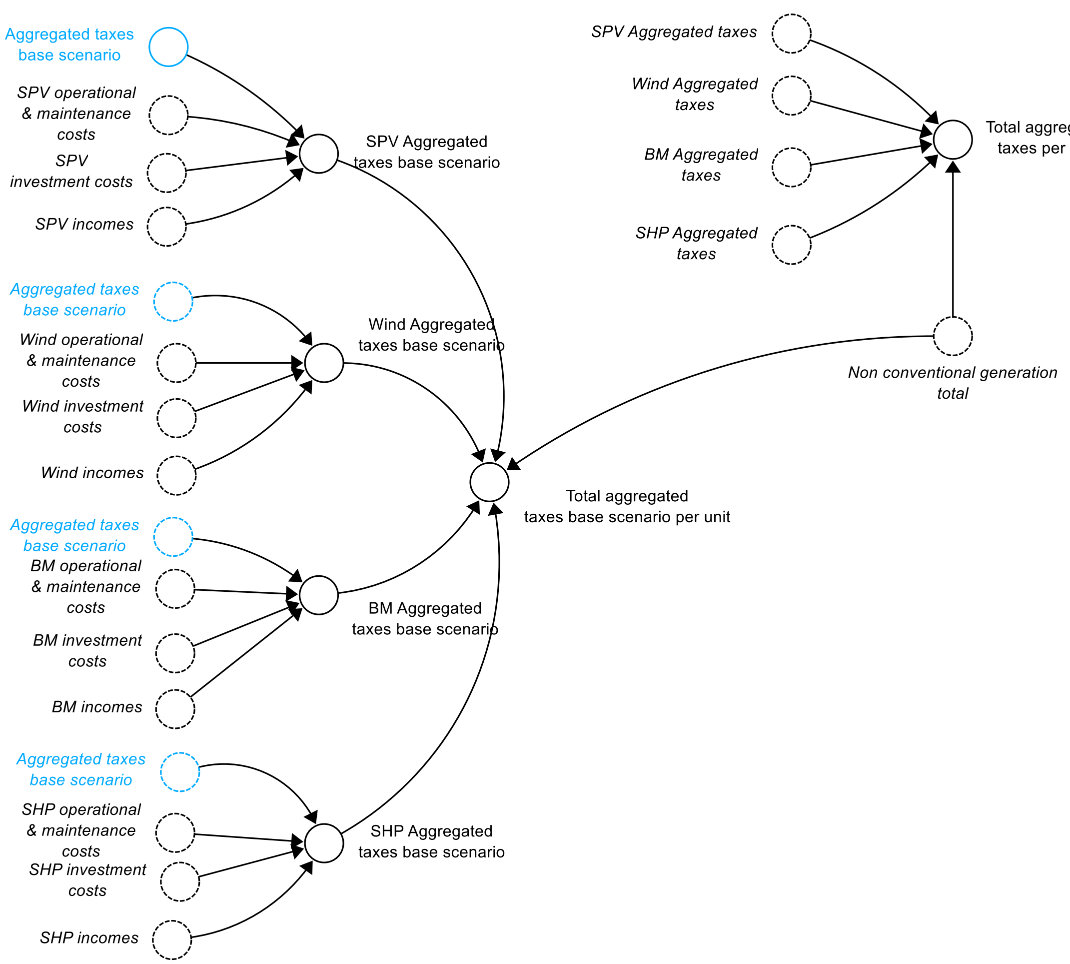
vi. Demand and emissions

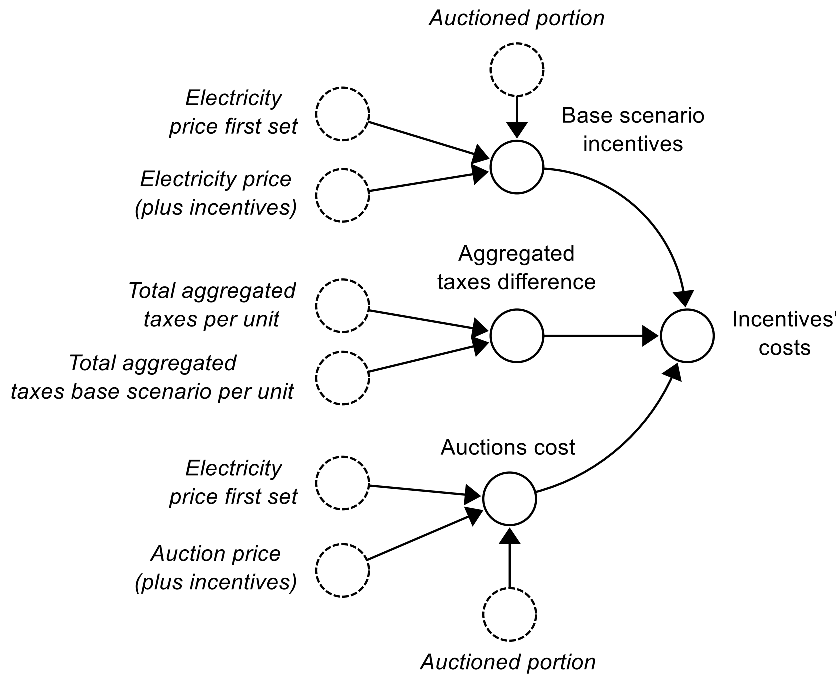


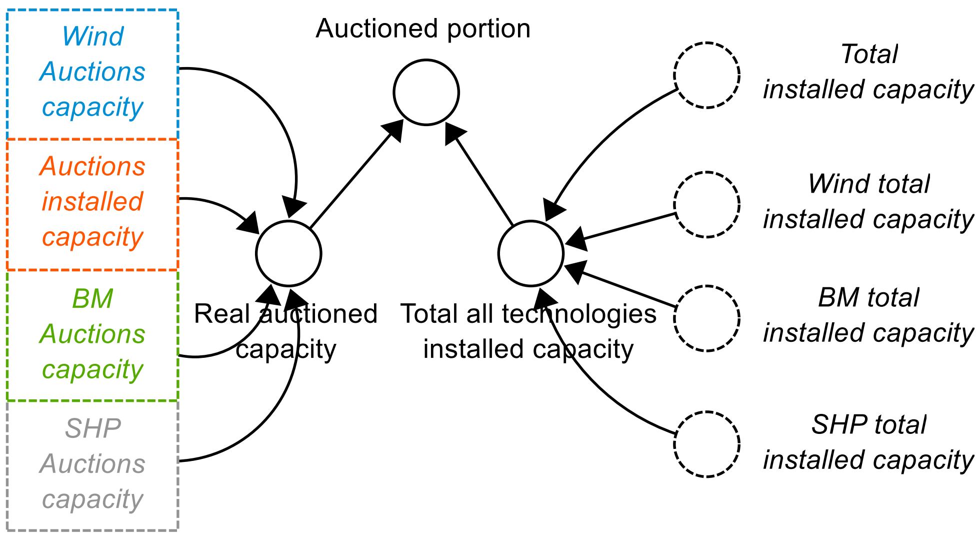
vii. Emissions market



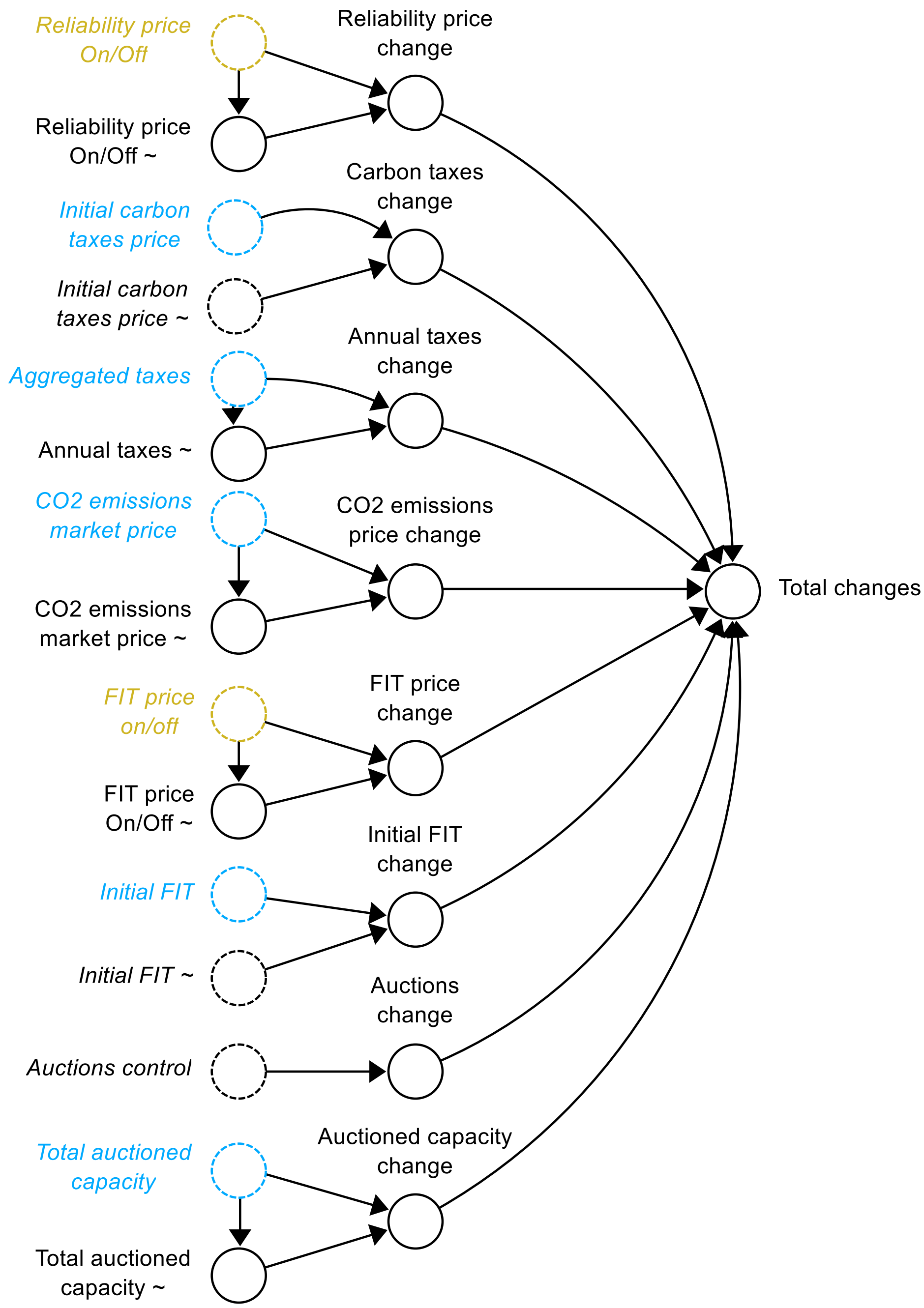
viii. Incentives' costs

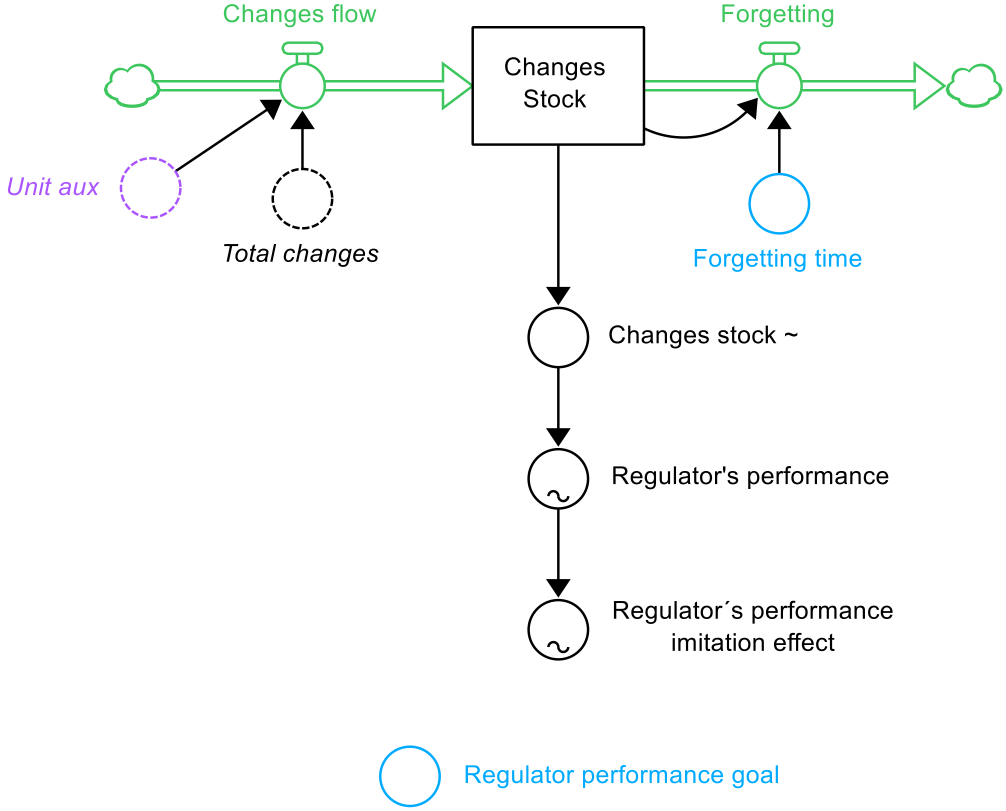



Auctioned portion
Electricity price first set
Base scenario incentives
Electricity price (plus incentives)
Aggregated taxes difference
Total aggregated taxes per unit
Incentives' costs
Total aggregated taxes base scenario per unit
Auctions cost
Electricity price first set
Auction price (plus incentives)
Auctioned portion


Wind Auctions capacity
Auctioned portion
Total installed capacity
Auctions installed capacity
Wind total installed capacity
BM Auctions capacity
Real auctioned capacity
Total all technologies installed capacity
BM total installed capacity
SHP Auctions capacity
SHP total installed capacity

ix. Regulator's confidence





Model variables

For each technology: solar photovoltaic (SPV), wind, biomass, and small hydropower (SHP) we used the same base model, and all the variable has the identification prefix, for example, the available potential for solar photovoltaic technology is "SPV available potential". Next, we present the diffusion model variables used for all the technologies and the general modeling variables. Finally, we present all the parameters in the model.

Note: We identified the delayed variables with the next symbol: ~.

i. General diffusion model variables

Table C-1: *Stock variables of the general diffusion model.*

Stocks			
Variable	**Units**	**Equation**	**Comment**
Available potential	MW	$\frac{\text{d Available potential}}{dt} = +\, New\ available\ potential - Normal\ new\ installed\ capacity - Auctioned\ new\ installed\ capacity$	
Auctions installed capacity	MW	$\frac{\text{d Auctions installed capacity}}{dt} = +\, Auctioned\ new\ installed\ capacity - Auc\ lifetime$	
Normal installed capacity	MW	$\frac{\text{d Normal installed capacity}}{dt} = +\, Normal\ new\ installed\ capacity - Normal\ lifetime$	
Normal new installed capacity ~	$\frac{MW}{Month}$	$\frac{\text{d Normal new installed capacity} \sim}{dt} = +\, Aux\ flow\ 1$	Information delay for the normal new installed capacity.
Auctioned new installed capacity ~	$\frac{MW}{Month}$	$\frac{\text{d Auctioned new installed capacity} \sim}{dt} = +\, Aux\ flow\ 2$	Information delay for the auctioned new installed capacity.

Source: Own elaboration based on (Arias-Gaviria et al., 2019; Bass, 1969).

Table C-2: *Flow variables of the general diffusion model.*

Variable	Units	Equation	Comment
		Flows	
New available potential	$\frac{MW}{Month}$	$Normal\ lifetime + Auc\ lifetime$	
Normal new installed capacity	$\frac{MW}{Month}$	$(Innovation\ rate * Available\ potential) + (Imitation\ rate * Installation\ term * Available\ potential) * \left(\frac{Total\ installed\ capacity}{Available\ potential + Total\ installed\ capacity}\right)$	Bass´s (1969) diffusion model was modified with the installation term.
Auctioned new installed capacity	$\frac{MW}{Month}$	$\begin{cases} Auctioned\ capacity\ delay, & x \geq Auctioned\ capacity\ delay \\ x, & x < Auctioned\ capacity\ delay \end{cases}$ $x = \frac{Available\ potential}{Unit\ aux}$	The players can auction capacity if the available potential is enough.
Normal lifetime	$\frac{MW}{Month}$	$\begin{cases} x, & TIME \geq Lifetime \\ 0, & TIME < Lifetime \end{cases}$ $x = HISTORY(Normal\ new\ installed\ capacity; TIME - Lifetime)$	When the technology reaches its lifetime, it becomes available potential again.
Auc lifetime	$\frac{MW}{Month}$	$\begin{cases} x, & TIME \geq Lifetime \\ 0, & TIME < Lifetime \end{cases}$ $x = HISTORY(Auctioned\ new\ installed\ capacity; TIME - Lifetime)$	When the technology reaches its lifetime, it becomes available potential again.
Aux flow 1	$\frac{MW}{Month^2}$	$\frac{Normal\ new\ installed\ capacity - \text{Normal new installed capacity} \sim}{New\ installed\ capacity\ delay}$	Auxiliar flow to make the information delay, for the expected normal new installed capacity.

Flows			
Variable	**Units**	**Equation**	**Comment**
Aux flow 2	$\frac{MW}{Month^2}$	$\frac{Auctioned\ new\ installed\ capacity - \text{Auctioned new installed capacity} \sim}{New\ installed\ capacity\ delay}$	Auxiliar flow to make the information delay, for the expected auctioned new installed capacity.

Source: Own elaboration based on (Arias-Gaviria et al., 2019; Bass, 1969).

Table C-3: *Auxiliar variables of the general diffusion model.*

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Auctioned capacity	$\frac{MW}{Month}$	$Auction\ capacity * Auctions\ control$	
Auctioned capacity delay	$\frac{MW}{Month}$	$DELAY(Auctioned\ capacity; Auctions\ delay; 0)$	
Imitation rate	$\frac{1}{Month}$	$Normal\ imitation\ rate * Regulator's\ performance\ imitation\ effect$	Modification of the imitation rate due to the regulator's performance
Installation term	$Dimensionles$	$\begin{cases} Expected\ profitability, & Expected\ profitability \geq 1 \\ 1, & Expected\ profitability < 1 \end{cases}$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Expected profitability	$Dimensionles$	$\frac{Electricity\ price\ (plus\ incentives)}{Expected\ LCOE + taxes}$	
Total installed capacity	MW	$Normal\ installed\ capacity + Auctions\ istalled\ capacity$	
Normal generation	$\frac{MWh}{Month}$	$Normal\ installed\ capacity * Plant\ capacity * Operational\ hours$	
Auctions generation	$\frac{MWh}{Month}$	$Auctions\ installed\ capacity * Plant\ capacity * Operational\ hours$	
Total generation	$\frac{MWh}{Month}$	$Normal\ generation + Auctions\ generation$	
Normal incomes	$\frac{USD}{Month}$	$Normal\ generation * \ Electricity\ price\ (plus\ incentives)$	
Auctions incomes	$\frac{USD}{Month}$	$Auctions\ generation * \ Electricity\ price\ (plus\ incentives)$	
Incomes	$\frac{USD}{Month}$	$Normal\ incomes + Auctions\ incomes + Technology\ extra\ emissions\ incomes$	
Operational & maintenance costs	$\frac{USD}{Month}$	$Total\ generation + Unit\ operational\ \&\ maintenance\ costs$	
Learning elasticity	$Dimensionles$	$\frac{-\ln(1 - Learning\ rate)}{\ln 2}$	
Unit investment costs	$\frac{USD}{MW}$	$Reference\ investment\ costs * \frac{Total\ installed\ capacity}{Reference\ installed\ capacity^{-Learning\ elasticity}}$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Investment costs	$\frac{USD}{Month}$	$Unit\ investment\ costs * Normal\ new\ installed\ capacity$	
Aggregated taxes	$\frac{USD}{Month}$	$\begin{cases} Aggregated\ taxes\ value * Net\ profits, & Net\ profits\ > 0 \\ 0, & Net\ profits\ \leq 0 \end{cases}$ $Net\ profits = Incomes - Investment\ cost - Operational\ \&\ maintenance\ costs$	
Normal expected generation	$\frac{MWh}{Month}$	$Normal\ new\ installed\ capacity \sim * Plant\ capacity * Operational\ hours * Lifetime$	
Auctioned expected generation	$\frac{MWh}{Month}$	$Auctioned\ new\ installed\ capacity \sim * Plant\ capacity * Operational\ hours * Lifetime$	
Total expected generation	$\frac{MWh}{Month}$	$Normal\ expected\ generation\ +\ Auctioned\ expected\ generation$	
Normal new installed capacity expected incomes	$\frac{USD}{Month}$	$(Normal\ expected\ generation * Electricity\ price\ (plus\ incentives)) + Technolgy\ extra\ emissions\ incomes)$	
Auctioned new installed capacity expected incomes	$\frac{USD}{Month}$	$(Auctioned\ expected\ generation * Electricity\ price\ (plus\ incentives)) + Technolgy\ extra\ emissions\ incomes)$	
New installed capacity expected incomes	$\frac{USD}{Month}$	$Normal\ new\ installed\ capacity\ expected\ incomes +\ New\ installed\ capacity\ expected\ incomes$	
N expected aggregated taxes of	$\frac{USD}{Month}$	$\begin{cases} Aggregated\ taxes\ value * Expected\ net\ profits, & Expected\ net\ profi \\ 0, & Expected\ net\ profi \end{cases}$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
new installed capacity		$Expected\ net\ profits = Normal\ new\ installed\ capacity\ expected\ incomes - N\ new\ installed\ capacity\ expected\ investment\ costs - N\ expected\ O\&M\ costs$	
A expected aggregated taxes of new installed capacity	$\frac{USD}{Month}$	$\begin{cases} Aggregated\ taxes\ value * Expected\ net\ profits, & Expected\ net\ profi \\ 0, & Expected\ net\ profi \end{cases}$ $Expected\ net\ profits = Auctioned\ new\ installed\ capacity\ expected\ incomes - A\ new\ installed\ capacity\ expected\ investment\ costs - A\ expected\ O\&M\ costs$	
Expected aggregated taxes of new installed capacity	$\frac{USD}{Month}$	$N\ expected\ aggregated\ taxes\ of\ new\ installed\ capacity + A\ expected\ aggregated\ taxes\ of\ new\ installed\ capacity$	
N expected carbon taxes	$\frac{USD}{Month}$	$Carbon\ taxes\ price * Emissions\ per\ unit * Normal\ expected\ generation$	
A expected carbon taxes	$\frac{USD}{Month}$	$Carbon\ taxes\ price * Emissions\ per\ unit * Auctioned\ expected\ generation$	
Expected total carbon taxes	$\frac{USD}{Month}$	$N\ expected\ carbon\ taxes + A\ expected\ carbon\ taxes$	
N expected fuel costs	$\frac{USD}{Month}$	$Fuel\ costs * Normal\ expected\ generation$	
A expected fuel costs	$\frac{USD}{Month}$	$Fuel\ costs * Auctioned\ expected\ generation$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Total expected fuel costs	$\frac{USD}{Month}$	$N\ expected\ fuel\ costs + Total\ expected\ fuel\ costs$	
Generation fraction	$Dimensionles$	$\frac{Total\ generation}{Non\ conventional\ generation\ goal}$	
Technology extra emissions incomes	$\frac{USD}{Month}$	$Generation\ fraction * Extra\ emissions\ incomes$	
N new installed capacity expected investment costs	$\frac{USD}{Month}$	$Normal\ new\ installed\ capacity \sim * Unit\ investment\ costs$	
A new installed capacity expected investment cost	$\frac{USD}{Month}$	$Auctioned\ new\ installed\ capacity \sim * Unit\ investment\ costs$	
New installed capacity expected investment costs	$\frac{USD}{Month}$	$N\ new\ installed\ capacity\ expected\ investment\ costs + A\ new\ installed\ capacity\ expected\ investment\ cost$	
N expected O&M costs	$\frac{USD}{Month}$	$Normal\ new\ installed\ capacity \sim * Unit\ operational\ \&\ maintenance\ costs$	
A expected O&M costs	$\frac{USD}{Month}$	$Auctioned\ new\ installed\ capacity \sim * Unit\ operational\ \&\ maintenance\ costs$	
New installed capacity generation expected O&M costs	$\frac{USD}{Month}$	$N\ expected\ O\&M\ costs + A\ expected\ O\&M\ costs$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
New installed capacity expected total costs	$\frac{USD}{Month}$	$New\ installed\ capacity\ expected\ investment\ costs + New\ installed\ capacity\ generation\ expected\ O\&M\ costs + Expected\ aggregated\ taxes\ of\ new\ installed\ capacity + Expected\ total\ carbon\ taxes + Total\ expected\ fuel\ costs$	
Expected aggregated taxes per unit	$\frac{USD}{MWh}$	$\frac{Expected\ aggregated\ taxes\ of\ new\ installed\ capacity}{Total\ expected\ generation}$	
Expected LCOE	$\frac{USD}{MWh}$	$\frac{New\ installed\ capacity\ expected\ investment\ costs + New\ installed\ capacity\ generation\ expected\ OM\ costs + Expected\ total\ carbon\ taxes + Total\ expected\ fuel\ costs}{Total\ expected\ generation}$	
Expected LCOE + taxes	$\frac{USD}{MWh}$	$Expected\ aggregated\ taxes\ per\ unit + Expected\ LCOE$	

Source: Own elaboration based on (Arias-Gaviria et al., 2019; Bass, 1969).

ii. General model variables

In this section, we present the variables used for all the generation technologies, as the incentives, the setup scenario calculations, the emissions, and the shared generation and energy demand.

Table C-4: *Stock variables of the general model.*

Stocks			
Variable	**Units**	**Equation**	**Comment**
Carbon taxes price	$\frac{USD}{Ton\ CO_2}$	$\frac{d\ Carbon\ taxes\ price}{dt} = +\ Carbon\ taxes\ growth - Carbon\ taxes\ aux\ flow$	Considering the carbon tax price as an incentive that users can activate or not, it has to be a stock to change over time.
FIT price	$\frac{USD}{MWh}$	$\frac{d\ FIT\ price}{dt} = +FIT\ growth - FITaux\ flow$	Considering the FIT price as an incentive that users can activate or not, it has to be a stock to change over time.
Auctions LCOE price	$\frac{USD}{MWh}$	$\frac{d\ Auctions\ LCOE\ price}{dt} = +AP\ flow\ 1 - AP\ flow\ 2$	The auctions price is the minimum LCOE in the game, and it is considered only in the auction time.
Auction stock	*Dimensionless*	$\frac{d\ Auction\ stock}{dt} = +Aucction\ flow\ 1 - Auction\ flow\ 2$	Time to do auctions.
IPP auction execution	*Dimensionless*	$\frac{d\ IPP\ auction\ execution}{dt} = +IPP\ flow\ 1 - IPP\ flow\ 2$	Identification of the IPP at the auction time.
Cumulative fossil fuel emission	$Ton\ CO_2$	$\frac{d\ Cumulative\ fossil\ fuel\ emission}{dt} = +\ Total\ emissions$	
Cumulative fossil fuel emissions	$Ton\ CO_2$	$\frac{d\ Cumulative\ fossil\ fuel\ emissions\ without\ non\ convent}{dt} = +\ Fossil\ fuel\ emissions\ without\ non\ conventionals$	

Stocks			
Variable	**Units**	**Equation**	**Comment**
without non-conventional			
Changes stock	$Changes$	$\frac{d\ Changes\ stock}{dt} = +\ Changes\ flow - Forgetting$	Amount of changes for the regulator's performance.

Source: Own elaboration based on (Arias-Gaviria et al., 2019).

Table C-5: *Flow variables of the general model.*

Flows			
Variable	**Units**	**Equation**	**Comment**
Carbon taxes growth	$\frac{USD}{Ton\ CO_2 * Month}$	$Carbon\ taxes\ price\ *\ Normal\ growth\ rate$	Change in the carbon tax price.
Carbon taxes aux flow	$\frac{USD}{Ton\ CO_2 * Month}$	$\begin{cases} 0, & Initial\ carbon\ taxes\ price = Initial\ carbon\ taxes\ price \sim \\ x, & Initial\ carbon\ taxes\ price \neq Initial\ carbon\ taxes\ price \sim \end{cases}$ $x = \frac{Carbon\ taxes\ price - Initial\ carbon\ taxes\ price}{Unit\ aux}$	Change in the carbon tax price.
FIT growth	$\frac{USD}{MWh * Month}$	$FIT\ price\ *\ Normal\ growth\ rate$	Change in the FIT price.
FIT aux flow	$\frac{USD}{MWh * Month}$	$\begin{cases} 0, & Initial\ \ FIT = Initial\ \ FIT \sim \\ \frac{FIT\ price - Initial\ FIT}{Unit\ aux}, & Initial\ \ FIT \neq Initial\ \ FIT \sim \end{cases}$	Change in the FIT price.

Flows			
Variable	**Units**	**Equation**	**Comment**
IPP flow 1	$\frac{1}{Month}$	$\frac{IPP\ auction}{Unit\ aux}$	
IPP flow 2	$\frac{1}{Month}$	$\begin{cases} \frac{IPP\ auction\ execution}{Unit\ aux}, & IPP\ auction > 0 \\ 0, & IPP\ auction \leq 0 \end{cases}$	
AP flow 1	$\frac{USD}{MWh * Month}$	$\frac{A\ proce\ executed}{Unit\ aux}$	Change in the auctions price.
AP flow 2	$\frac{USD}{MWh * Month}$	$\begin{cases} \frac{Auctions\ LCOE\ price}{Unit\ aux}, & A\ price\ executed > 0 \\ 0, & A\ price\ executed \leq 0 \end{cases}$	Change in the auctions price.
Auction flow1	$\frac{1}{Month}$	$\frac{Auctions\ control}{Unit\ aux}$	
Auction flow 2	$\frac{1}{Month}$	$\frac{1}{Auctions\ implement\ time}$	
Total emissions	$\frac{TonCO_2}{Month}$	$Fossil\ emissions + BM\ emissions$	
Fossil fuel emissions without non-conventional	$\frac{TonCO_2}{Month}$	$Fossil\ \ fuel\ generation\ without\ non\ conventionals * Fossil\ fuel\ emissions\ per\ MWh$	
Changes flow	$\frac{Changes}{Month}$	$\begin{cases} \frac{Total\ changes}{Unit\ aux}, & TIME\%6 = 0 \\ 0, & TIME\%6 \neq 0 \end{cases}$	In the model, the time step is six months, so the changes count only in those months. We used the residue

Flows			
Variable	**Units**	**Equation**	**Comment**
			to identity the simulation time to add changes.
Forgetting	$\frac{Changes}{Month}$	$\frac{Changes\ stock}{Forgetting\ time}$	

Source: Own elaboration based on (Arias-Gaviria et al., 2019).

Table C-6: *Auxiliar variables of the general model.*

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Historical spot price ~	$\frac{USD}{MWh}$	$SMTH1(Historical\ spot\ price;\ 6;\ Historical\ spot\ price)$	Information delay to smooth the spot price.
Historical spot price high scenario	$\frac{USD}{MWh}$	$Historical\ spot\ price \sim * 1{,}2$	
Historical spot price low scenario	$\frac{USD}{MWh}$	$Historical\ spot\ price \sim * 0{,}8$	
Electricity price first set	$\frac{USD}{MWh}$	$\begin{cases} Historical\ spot\ price \sim, & Spot\ price\ On/Off = 1 \\ Historical\ spot\ price\ high\ scenario, & SP\ H\ On/Off = 1 \\ Historical\ spot\ price\ low\ scenario, & SP\ L\ On/Off = 1 \\ Custom\ spot\ price\ scenario, & In\ other\ case \end{cases}$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Electricity price after FIT	$\frac{USD}{MWh}$	$\begin{cases} FIT\ price, & FIT\ price\ On/Off = 1 \\ Electricity\ price\ first\ set, & In\ other\ case \end{cases}$	
Electricity price (plus incentives)	$\frac{USD}{MWh}$	$Electricity\ price\ after\ FIT$	We use this variable for model updating, with new incentives.
Initial carbon taxes price ~	$\frac{USD}{TonCO_2}$	$DELAY(Initial\ carbon\ taxes\ price;\ 6; 17211/3900)$	
Initial FIT ~	$\frac{USD}{MWh}$	$DELAY(Initial\ FIT; 6; 90)$	
Auctions price	$\frac{USD}{MWh}$	$Auctions\ LCOE\ price * IPP\ relation$	
IPP relation	*Dimensionless*	$\begin{cases} 0, & IPP\ auction\ execution = 0 \\ IPP\ auction\ execution, & In\ other\ case \end{cases}$	
Auction execution time	Months	$\begin{cases} 1, & TIME = 0\ AND\ Auctions\ control = 1 \\ TIME * Auctions\ control, & In\ other\ case \end{cases}$	
IPP auction	*Dimensionless*	$\begin{cases} IPP, & TIME = 0\ AND\ Auctions\ execution\ time = 1 \\ 0, & Auctions\ execution\ time = 0 \\ x, & In\ other\ case \end{cases}$ $x = HISTORY(IPP; Auction\ execution\ time)$	Selection of the IPP for the auction execution time.
A price executed	$\frac{USD}{MWh}$	$\begin{cases} AUC, & TIME = 0\ AND\ Auctions\ execution\ time = 1 \\ 0, & Auctions\ execution\ time = 0 \\ x, & In\ other\ case \end{cases}$	Selection of the price for the

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
		$x = HISTORY(AUC; Auction\ execution\ time)$	auction execution time.
Long term contracts price (auctions) [AUC]	$\frac{USD}{MWh}$	$MIN(SPV\ expected\ LCOE; Wind\ expected\ LCOE; BM\ expected\ LCOE; SHP\ Expected\ LCOE)$	
Auction price (plus incentives)	$\frac{USD}{MWh}$	$Auctions\ price$	We use this variable for model updating, with new incentives.
Total available potential	MW	$SPV\ available\ potential; Wind\ available\ potential; BM\ avaiable\ potential; SHP\ available\ potential$	
SPV potential fraction	$Dimensionless$	$\frac{SPV\ available\ potential}{Total\ available\ potential}$	
Wind potential fraction	$Dimensionless$	$\frac{Wind\ available\ potential}{Total\ available\ potential}$	
BM potential fraction	$Dimensionless$	$\frac{BM\ avaiable\ potential}{Total\ available\ potential}$	
SHP potential fraction	$Dimensionless$	$\frac{SHP\ available\ potential}{Total\ available\ potential}$	
SPV auction capacity	$\frac{MW}{Month}$	$Total\ auctioned\ capacity * SPV\ potential\ fraction$	

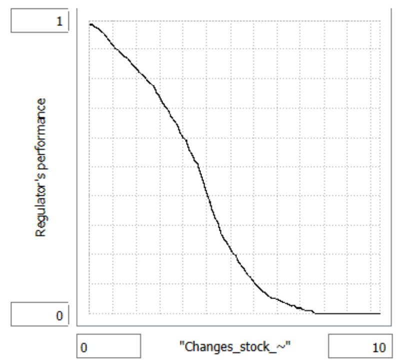
Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Wind Auction capacity	$\frac{MW}{Mont}$	$Total\ auctioned\ capacity * Wind\ potential\ fraction$	
BM Auction capacity	$\frac{MW}{Month}$	$Total\ auctioned\ capacity * BM\ potential\ fraction$	
SHP auction capacity	$\frac{MW}{Month}$	$Total\ auctioned\ capacity * SHP\ potential\ fraction$	
Auctions control	$Dimensionless$	$\begin{cases} 0, & Auctions\ stock > 0 \\ Auctions\ On/Off, & In\ other\ case \end{cases}$	
Auction stock button	$Dimensionless$	$\begin{cases} 1, & Auctions\ stock > 0 \\ 0, & In\ other\ case \end{cases}$	
Fossil emissions	$\frac{TonCO_2}{Month}$	$Fossil\ fuel\ generation * Fossil\ fuel\ emissions\ per\ MWh$	
BM emissions	$\frac{TonCO_2}{Month}$	$BM\ emissions\ per\ unit * BM\ total\ generation$	
Non-conventional generation fraction	$\frac{MWh}{Month}$	$SPV\ total\ generation + Wind\ total\ generation + BM\ total\ generation + SHP\ total\ generation$	
Fossil fuel generation	$\frac{MWh}{Month}$	$Total\ generation\ without\ non\ con\ conventional\ renewables * 0{,}33$	
Hydropower	$\frac{MWh}{Month}$	$Total\ generation\ without\ non\ con\ conventional\ renewables - Fossil\ fuel\ generation$	
Total generation without non-	$\frac{MWh}{Month}$	$\begin{cases} Demand - Non\ conventional\ generation\ total, & x > 0 \\ 0, & In\ other\ case \end{cases}$	

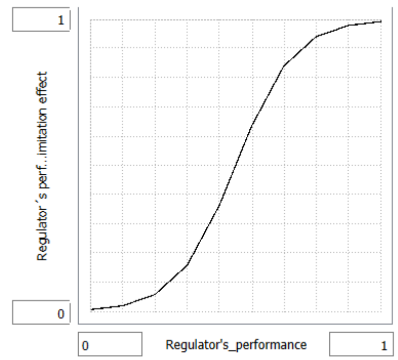
Auxiliar			
Variable	**Units**	**Equation**	**Comment**
conventional renewables		$x = Demand - Non\ conventional\ generation\ total$	
Non-conventional fraction	$Dimensionless$	$\frac{Non\ conventional\ generation\ total}{Demand}$	
Carbon taxes for fossil fuel	$\frac{USD}{Month}$	$Carbon\ taxes\ price * (Fossil\ emissions + BM\ emissions)$	
Saving/spending	$\frac{USD}{Month}$	$Carbon\ taxes\ for\ fossil\ fuel\ without\ non\ conventional - Carbon\ taxes\ for\ fossil\ fuel$	
Fossil fuel generation without non-conventionals scenario	$\frac{MWh}{Month}$	$Demand * 0{,}33$	
Carbon taxes for fossil fuel without non-conventionals	$\frac{USD}{Month}$	$Carbon\ taxes\ price * Carbon\ taxes\ for\ fossil\ fuel\ without\ non\ conventional$	
Emissions difference	$\frac{TonCO_2}{Month}$	$\begin{cases} x, & Total\ emissions > 0 \\ y, & In\ other\ case \end{cases}$ $x = Fossil\ fuel\ emissions\ without\ non\ conventionals$ $y = Fossil\ fuel\ emissions\ without\ non\ conventionals - Total\ emissions$	
Extra emissions incomes	$\frac{USD}{Month}$	$Emissions\ difference * CO_2\ emissions\ market\ price$	
Emissions goal	$\frac{TonCO_2}{Month}$	$Fossil\ fuel\ emissions\ without\ non\ conventionals * (1 - Emissions\ reduction)$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
SPV aggregated taxes base scenario	$\frac{USD}{Month}$	$\begin{cases} y, & x > 0 \\ 0, & In\ other\ case \end{cases}$ $x = SPV\ incomes - SPV\ investment\ costs - SPV\ operational\ \&\ maintenance\ costs$ $y = Aggregated\ taxes\ base\ scenario * (SPV\ incomes - SPV\ investment\ costs - SPV\ operational\ \&\ maintenance\ costs)$	
Wind aggregated taxes base scenario	$\frac{USD}{Month}$	$\begin{cases} y, & x > 0 \\ 0, & In\ other\ case \end{cases}$ $x = Wind\ incomes - Wind\ investment\ costs - Wind\ operational\ \&\ maintenance\ costs$ $y = Aggregated\ taxes\ base\ scenario * (Wind\ incomes - Wind\ investment\ costs - Wind\ operational\ \&\ maintenance\ costs)$	
BM aggregated taxes base scenario	$\frac{USD}{Month}$	$\begin{cases} y, & x > 0 \\ 0, & In\ other\ case \end{cases}$ $x = BM\ incomes - BM\ investment\ costs - BM\ operational\ \&\ maintenance\ costs$ $y = Aggregated\ taxes\ base\ scenario * (BM\ incomes - BM\ investment\ costs - BM\ operational\ \&\ maintenance\ costs)$	
SHP aggregated taxes base scenario	$\frac{USD}{Month}$	$\begin{cases} y, & x > 0 \\ 0, & In\ other\ case \end{cases}$ $x = SHP\ incomes - SHP\ investment\ costs - SHP\ operational\ \&\ maintenance\ costs$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
		$y = Aggregated\ taxes\ base\ scenario * (SHP\ incomes - SHP\ investment\ costs - SHP\ operational\ \&\ maintenance\ costs)$	
Total aggregated taxes base scenario per unit	$\frac{USD}{MWh}$	$(SPV\ aggregated\ taxes\ base\ scenario + Wind\ aggregated\ taxes\ base\ scenario + BM\ aggregated\ taxes\ base\ scenario + SHP\ aggregated\ taxes\ base\ scenario) / Non\ conventional\ generation\ total$	
Total aggregated taxes per unit	$\frac{USD}{MWh}$	$(SPV\ Aggregated\ taxes + Wind\ Aggregated\ taxes + BM\ Aggregated\ taxes + SHP\ Aggregated\ taxes) / Non\ conventional\ generation\ total$	
Base scenario incentives	$\frac{USD}{MWh}$	$(Electricity\ price(plus\ incentives) - Electricity\ price\ first\ set) * (1 - Auctioned\ portion)$	
Aggregated taxes difference	$\frac{USD}{MWh}$	$Total\ aggregated\ taxes\ base\ scenario\ per\ unit - Total\ aggregated\ taxes\ per\ unit$	
Auctions cost	$\frac{USD}{MWh}$	$(Auctions\ price\ (plus\ incentives) - Electricity\ price\ first\ set) * Auctioned\ portion$	
Incentives' costs	$\frac{USD}{MWh}$	$Base\ scenario\ incentives + Aggregated\ taxes\ difference + Auctions\ cost$	
Real auctioned capacity	MW	$SPV\ auctions\ capacity + Wind\ auctions\ capacity + BM\ auctions\ capacity + SHP\ auctions\ capacity$	
Total installed capacity	MW	$SPV\ total\ installed\ capacity + Wind\ total\ installed\ capacity + BM\ total\ installed\ capacity + SHP\ total\ installed\ capacity$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Auctioned portion	*Dimensionless*	$\frac{Real\ auctioned\ capacity}{Total\ installed\ capacity}$	
Reliability price on/Off ~	*Dimensionless*	$DELAY(Reliability\ price\ On/Off; 6; 0)$	
Reliability price change	*Changes*	$\begin{cases} 0, & Reliability\ price\ On/Off = Reliability\ price\ On/Off\sim \\ 1, & In\ other\ case \end{cases}$	
Carbon taxes change	*Changes*	$\begin{cases} 0, & Initial\ carbon\ taxes\ price = Initial\ carbon\ taxes\ price\sim \\ 1, & In\ other\ case \end{cases}$	
Annual taxes ~	*Dimensionless*	$DELAY(Aggregated\ taxes; 6; 0{,}2)$	
Annual taxes change	*Changes*	$\begin{matrix} 0, & IAggregated\ taxes = \text{Annual taxes} \sim \\ 1, & In\ other\ case \end{matrix}$	
CO_2 emissions market price ~	$\frac{USD}{TonCO_2}$	$DELAY(CO_2\ emissions\ market\ price; 6; 10)$	
CO_2 emissions price change	*Changes*	$\begin{cases} 0, & CO_2\ emissions\ market\ price = \text{CO}_2 \text{ emissions market price} \sim \\ 1, & In\ other\ case \end{cases}$	
FIT price on/Off ~	*Dimensionless*	$DELAY(\text{FIT price on/Off}; 6; 0)$	
FIT price change	*Changes*	$\begin{cases} 0, & FIT\ price\ on/Off = FIT\ price\ on/Off \sim \\ 1, & In\ other\ case \end{cases}$	
Initial FIT change	*Changes*	$\begin{cases} 0, & Initial\ FIT = Initial\ FIT \sim \\ 1, & In\ other\ case \end{cases}$	
Auctions change	*Changes*	$\begin{cases} 1, & Auctions\ control = 1 \\ 0, & In\ other\ case \end{cases}$	

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Total auctioned capacity ~	$\frac{MW}{Month}$	$DELAY(Total\ auctioned\ capacity;\ 6;\ 1300)$	
Auctioned capacity change	$Changes$	$\begin{cases} 1, & Total\ auctioned\ capacity\ = Total\ auctioned\ capacity \sim \\ 0, & In\ other\ case \end{cases}$	
Total changes	$Changes$	$Auctioned\ capacity\ change + CO_2\ emissions\ price\ change + Annual\ taxes\ change + Carbon\ taxes\ change + Reliability\ price\ change + FIT\ price\ change + Initial\ FIT\ change + Auctions\ change$	
Changes stock ~	$Changes$	$SMTH1(Changes\ stock;\ 6;\ Changes\ stock)$	
Regulator's confidence	$Dimensionless$		

Auxiliar			
Variable	**Units**	**Equation**	**Comment**
Regulator's confidence imitation effect	*Dimensionless*		

Source: Own elaboration based on (Arias-Gaviria et al., 2019).

Next, we present the control variables in the model, they are represented by the yellow color in the stocks-and-flows diagram and are used in the microworld as a binary variable to activate and deactivate variables while playing:

Table 5-7: *Control variables for microworld interface using.*

Variable	Comment
FIT price On/Off	Control variable for the FIT.
Spot price On/Off	Control variable to activate the historical spot price.
SP H On/Off	Control variable to activate the high historical spot price scenario.
SP L On/Off	Control variable to activate the low historical spot price scenario.

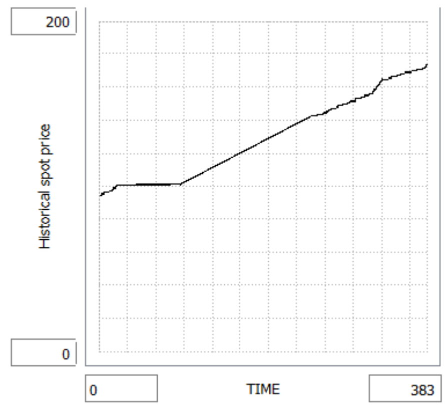
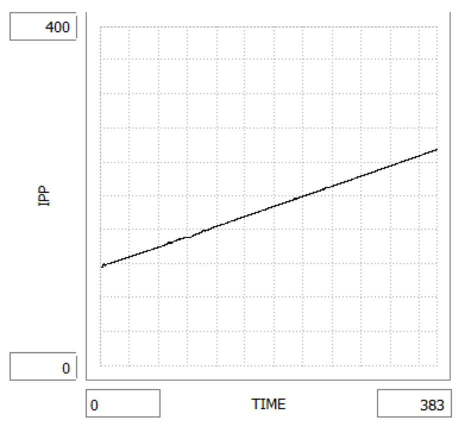
Variable	Comment
SP C On/Off	Control variable to activate the custom historical spot price scenario.
Auctions On/Off	Control variable to activate the auctions of long-term price contracts.

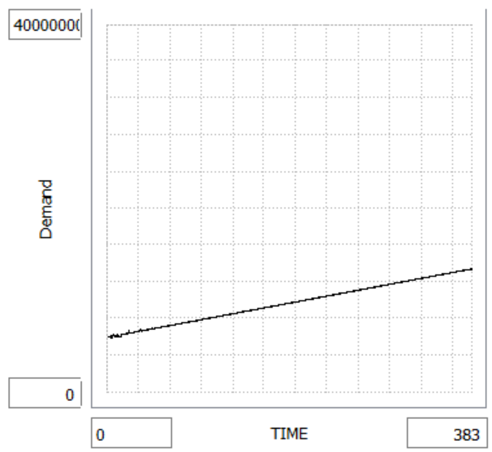
Source: Own elaboration.

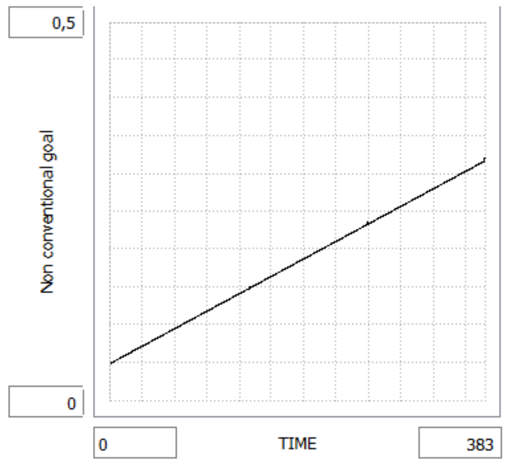
iii. Model parameters

Table C-8: *Parameter variables for microworld modeling.*

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
Custom spot price	$\frac{USD}{MWh}$	–	The player can set its scenario.	
Initial carbon taxes price	$\frac{USD}{TonCO_2}$	4,41		(Dirección de Impuestos y Aduanas Nacionales - DIAN, 2020)
Normal growth rate	$\frac{1}{Month}$	0,03/12		(Departamento Administrativo Nacional de Estadística - DANE, 2020)
Initial FIT	$\frac{USD}{MWh}$	90	The player can set its scenario.	(XM, 2020b).

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
Historical spot price	$\frac{USD}{MWh}$		Projected spot price from 2019 to 2050.	(XM, 2020b).
Aggregated taxes	*Dimensionless*	0,2	The player can set its scenario.	(Arias-Gaviria et al., 2019)
IPP	*Dimensionless*		Projected IPP from 2019 to 2050.	(Departamento Administrativo Nacional de Estadística - DANE, 2020)

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
Total auctioned capacity	$\frac{MW}{Month}$	1300	The player can set its scenario.	
Auctions implement time	$Months$	$12 * 4$	The player can only auction every four years.	
Fossil fuel emissions per MWh	$\frac{TonCO_2}{MWh}$	$975{,}30 * 1000/1000000$		(Varun et al., 2009)
Demand	$\frac{MWh}{Month}$		Projected demand from 2019 to 2050.	(XM, 2020c)

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
Non-conventional goal	*Dimensionless*			(UPME & Ministerio de Minas y Energía, 2015)
Emissions reduction	*Dimensionless*	0,3		(UPME & Ministerio de Minas y Energía, 2015)
CO_2 emissions market price	$\frac{USD}{TonCO_2}$	10	The player can set its scenario.	
Aggregated taxes base scenario	*Dimensionless*	0,2		(Arias-Gaviria et al., 2019)
Forgetting time	*Months*	$6 * 12$	The changes made by the regulator are forgotten in six years.	

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
Regulator's performance goal	$Dimensionless$	0,8	Own scenario.	
Unit aux	$Months$	1	Own scenario.	
Auctions delay	$Months$	24	The auctions have an entry delay of two years.	
New installed capacity delay	$Months$	6	Own scenario.	
Carbon taxes price	$\frac{USD}{TonCO_2}$	$Carbon\ taxes\ price\ (2019) = 4{,}41$	The player can set its scenario.	(Dirección de Impuestos y Aduanas Nacionales - DIAN, 2020)
FIT price	$\frac{USD}{MWh}$	$FIT\ price\ (2019) = 90$	The player can set its scenario.	(XM, 2020b).
IPP auction execution	$Dimensionless$	$IPP\ auction\ execution\ (2019) = 0$	The player can set its scenario.	
Auctions LCOE price	$\frac{USD}{MWh}$	$Auctions\ LCOE\ price\ (2019) = 0$	The player can set its scenario.	
Auctions stock	$Dimensionless$	$Auctions\ stock\ (2019) = 0$	The player can set its scenario.	
Cumulative fossil fuel emissions	$TonCO_2$	$Cumulative\ fossil\ fuel\ emissions\ (2019) = 100000000$	Own scenario.	

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
Cumulative fossil fuel emissions without non conventionals	$TonCO_2$	$Cumulative\ fossil\ fuel\ emissions\ withou$ $non\ conventionals\ (2019) =$ 100000000	Own scenario.	
Changes stock	$Changes$	$Changes\ stock\ (2019) = 0$	The player decisions modify this variable.	
SPV available potential	MW	$SPV\ available\ potential\ (2019)$ $=\ 15000$	The real available potential is 9480 MW, but participants cannot achieve the game goals with that scenario.	(MinMinas & UPME, 2020)
Wind available potential	MW	$Wind\ available\ potential\ (2019)$ $= 2555$		(MinMinas & UPME, 2020)
BM available potential	MW	$BM\ available\ potential\ (2019) = 358$		(MinMinas & UPME, 2020)
SHP available potential	MW	$SHP\ available\ potential\ (2019) = 4456$		(MinMinas & UPME, 2020)
SPV Normal capacity	MW	$SPV\ Normal\ capacity\ (2019) = 8{,}16$		(XM, 2020a)
Wind Normal capacity	MW	$Wind\ Normal\ capacity\ (2019) = 18{,}42$		(XM, 2020a)

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
BM Normal capacity	MW	$BM\ Normal\ capacity\ (2019) = 139$		(XM, 2020a)
SHP Normal capacity	MW	$SHP\ Normal\ capacity\ (2019) = 860{,}11$		(XM, 2020a)
SPV Auctions capacity	MW	$SPV\ Auctions\ capacity\ (2019) = 0$	The player decisions modify this variable.	
Wind Auctions capacity	MW	$Wind\ Auctions\ capacity\ (2019) = 0$	The player decisions modify this variable.	
BM Auctions capacity	MW	$BM\ Auctions\ capacity\ (2019) = 0$	The player decisions modify this variable.	
SHP Auctions capacity	MW	$SHP\ Auctions\ capacity\ (2019) = 0$	The player decisions modify this variable.	
SPV normal new installed capacity ~	$\frac{MW}{Month}$	$SPV\ normal\ new\ installed\ capacity \sim (2019) = 8{,}16$		(XM, 2020a)
Wind normal new installed capacity ~	$\frac{MW}{Month}$	$Wind\ normal\ new\ installed\ capacity \sim (2019) = 18{,}42$		(XM, 2020a)
BM normal new installed capacity ~	$\frac{MW}{Month}$	$BM\ normal\ new\ installed\ capacity \sim (2019) = 139$		(XM, 2020a)

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
SHP normal new installed capacity ~	$\frac{MW}{Month}$	$SHP\ normal\ new\ installed\ capacity \sim (2019) = 860{,}11$		(XM, 2020a)
SPV auctioned new installed capacity ~	$\frac{MW}{Month}$	$SPV\ auctioned\ new\ installed\ capacity \sim (2019) = 0$	The player decisions modify this variable.	
Wind auctioned new installed capacity ~	$\frac{MW}{Month}$	$Wind\ auctioned\ new\ installed\ capacity \sim (2019) = 0$	The player decisions modify this variable.	
BM auctioned new installed capacity ~	$\frac{MW}{Month}$	$BM\ auctioned\ new\ installed\ capacity \sim (2019) = 0$	The player decisions modify this variable.	
SHP auctioned new installed capacity ~	$\frac{MW}{Month}$	$SHP\ auctioned\ new\ installed\ capacity \sim (2019) = 0$	The player decisions modify this variable.	
SPV innovation rate	$\frac{1}{Month}$	0,01/12		(Arias-Gaviria et al., 2019)
Wind innovation rate	$\frac{1}{Month}$	0,005/12		(Arias-Gaviria et al., 2019)

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
BM innovation rate	$\frac{1}{Month}$	0,03/12		(Arias-Gaviria et al., 2019)
SHP innovation rate	$\frac{1}{Month}$	0,025/12		(Arias-Gaviria et al., 2019)
SPV normal imitation rate	$\frac{1}{Month}$	0,1/12		(Arias-Gaviria et al., 2019)
Wind normal imitation rate	$\frac{1}{Month}$	0,05/12		(Arias-Gaviria et al., 2019)
BM normal imitation rate	$\frac{1}{Month}$	0,06/12		(Arias-Gaviria et al., 2019)
SHP normal imitation rate	$\frac{1}{Month}$	0,06/12		(Arias-Gaviria et al., 2019)
SPV lifetime	$Months$	$30 * 12$		(Arias-Gaviria et al., 2019)
Wind lifetime	$Months$	$30 * 12$		(Arias-Gaviria et al., 2019)
BM lifetime	$Months$	$20 * 12$		(Arias-Gaviria et al., 2019)
SHP lifetime	$Months$	$20 * 12$		(Arias-Gaviria et al., 2019)

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
Wind plant capacity	$Dimensionless$	0,26		(MinMinas & UPME, 2019)
SPV plant capacity	$Dimensionless$	0,57		(MinMinas & UPME, 2019)
BM plant capacity	$Dimensionless$	0,7		(MinMinas & UPME, 2019)
SHP plant capacity	$Dimensionless$	0,54		(MinMinas & UPME, 2019)
SPV operational hours	$\frac{Hours}{Month}$	$24 * 30$	Own scenario.	
Wind operational hours	$\frac{Hours}{Month}$	$24 * 30 * 0{,}7$	Own scenario.	
BM operational hours	$\frac{Hours}{Month}$	$24 * 30 * 0{,}7$	Own scenario.	
SHP operational hours	$\frac{Hours}{Month}$	$24 * 30 * 0{,}7$	Own scenario.	
SPV Reference investment costs	$\frac{USD}{MW}$	$1210 * 1000$		(IRENA, 2018b)

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
Wind Reference investment costs	$\frac{USD}{MW}$	$1353 * 1000$		(IRENA, 2018b)
BM Reference investment costs	$\frac{USD}{MW}$	$1492 * 1000$		(IRENA, 2018b)
SHP Reference investment costs	$\frac{USD}{MW}$	$2105 * 1000$		(IRENA, 2018b)
SPV Reference installed capacity	MW	8,16		(XM, 2020a)
Wind Reference installed capacity	MW	18,42		(XM, 2020a)
BM Reference installed capacity	MW	139		(XM, 2020a)
SHP Reference	MW	860,11		(XM, 2020a)

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
installed capacity				
SPV learning rate	$Dimensionless$	0,37		(IRENA, 2018b)
Wind learning rate	$Dimensionless$	0,14		(Arias-Gaviria et al., 2019)
BM learning rate	$Dimensionless$	0,14		(Arias-Gaviria et al., 2019)
SHP learning rate	$Dimensionless$	0,2		(Arias-Gaviria et al., 2019)
SPV emissions per unit	$\frac{TonCO_2}{MWh}$	0		
Wind emissions per unit	$\frac{TonCO_2}{MWh}$	0		
BM emissions per unit	$\frac{TonCO_2}{MWh}$	$35 * 1000/1000000$		(Varun et al., 2009)
SHP emissions per unit	$\frac{TonCO_2}{MWh}$	0		
SVP fuel costs	$\frac{USD}{MWh}$	0		

Parameters				
Variable	**Units**	**Value**	**Comment**	**Reference**
Wind fuel costs	$\frac{USD}{MWh}$	0		
BM fuel costs	$\frac{USD}{MWh}$	0		
SHP fuel costs	$\frac{USD}{MWh}$	0		
SPV unit operational & maintenance costs	$\frac{USD}{MWh}$	9,22716895		(Alejandro Castillo Ramírez et al., 2016)
Wind unit operational & maintenance costs	$\frac{USD}{MWh}$	7,608447489		(Alejandro Castillo Ramírez et al., 2016)
BM unit operational & maintenance costs	$\frac{USD}{MWh}$	5,227283105		(Alejandro Castillo Ramírez et al., 2016)
SHP unit operational & maintenance costs	$\frac{USD}{MWh}$	4,114155251		(Alejandro Castillo Ramírez et al., 2016)

D. Structure oriented behavior tests for microworld's model validation

We present the results for the extreme conditions test and the behavioral reproduction test.

Behavioral reproduction test

S-shaped verification for the installed capacity and the available potential:

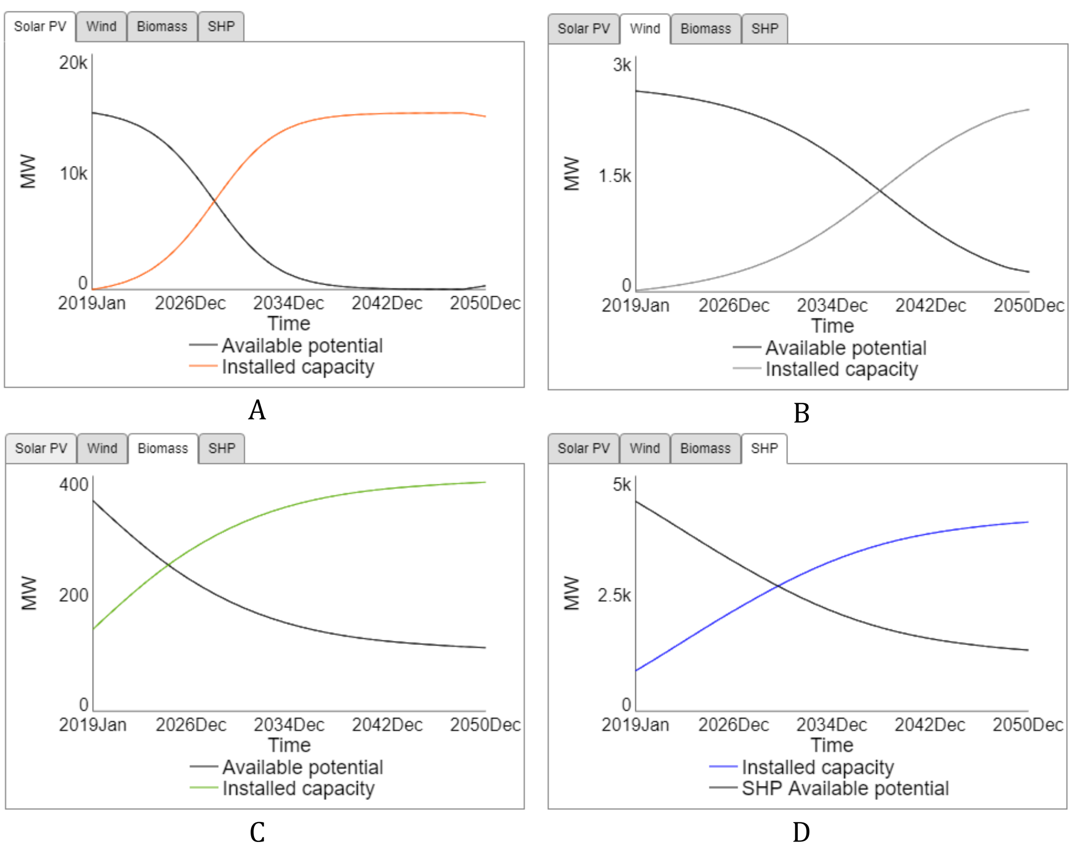


Figure D-1: Available potential and installed capacity for microworld's technologies for behavioral reproduction test.

Source: Own elaboration.

Extreme conditions test

The extreme conditions test result as expected for all the technologies, considering the actual installed capacity, and considering the lifetime of that installed capacity. When the lifetime finishes it becomes available potential.

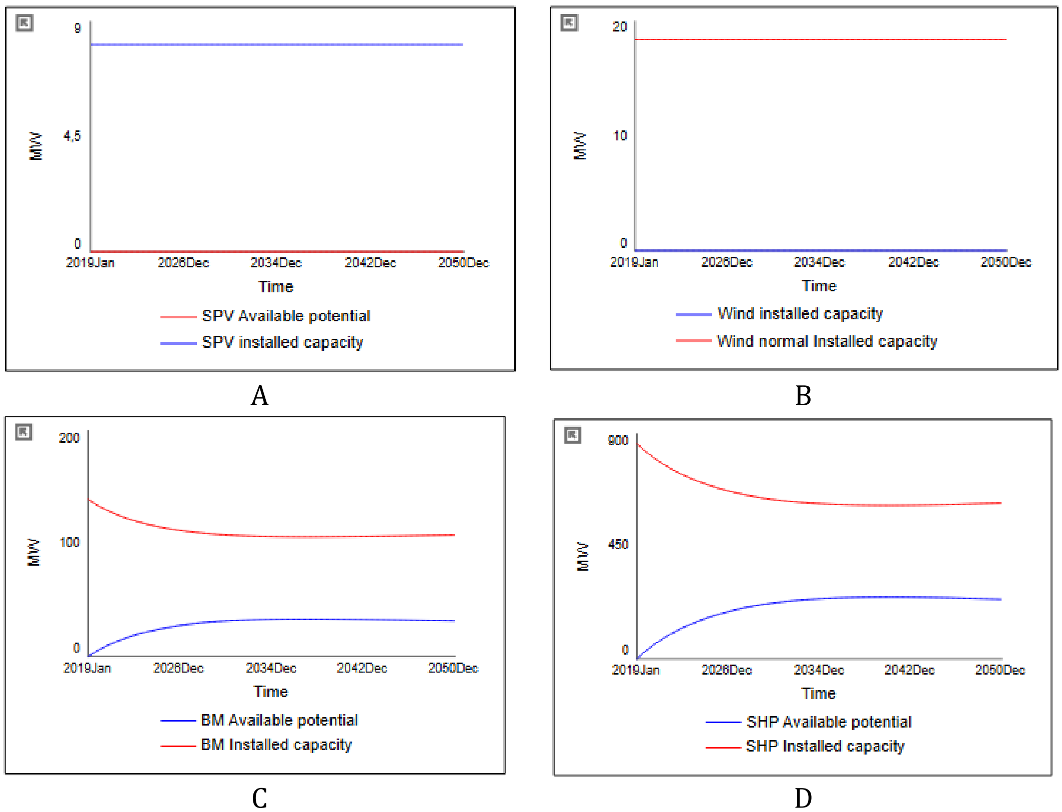


Figure D-2: Available potential and installed capacity for microworld's extreme conditions test.

Source: Own elaboration.

E. Microworld's register sheet

The register sheet is available at https://forms.gle/CHQv2CDTAHeQombn8

Microworld's Register sheet - Hoja de registro de micromundo

English:

You have been invited to participate in this exercise that is part of the development of a microworld to understand the dynamics of the diffusion of non-conventional renewable generation technologies in Colombia, which is part of the master's degree of the student Verónica Marrero, of the National University of Colombia, within the framework of the project "Strategy for the transformation of the Colombian energy sector in the horizon of 2030", financed in call 778 of the Scientific Ecosystem Sciences. Contract FP44842-210-2018

This form seeks to know the scope of the microworld from its participants, for which we will request certain information and guarantee the confidentiality of the information and the treatment of the data with exclusively scientific use.

Your participation is completely voluntary. You can withdraw at any time.

Español:

Usted ha sido invitado a participar en este ejercicio que hace parte del desarrollo de un micromundo para comprender la dinámica de la difusión de las tecnologías de generación renovables no convencionales en Colombia, el cual hace parte de la tesis de maestría de la estudiante Verónica Marrero, de la Universidad Nacional de Colombia, en el marco del proyecto "Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" financiado en la convocatoria 778 de Minciencias Ecosistema Científico. Contrato FP44842-210-2018

El presente formulario busca conocer el alcance del micromundo desde sus participantes, por lo que le solicitaremos cierta información y garantizamos la confidencialidad en la información y el tratamiento de los datos con uso exclusivamente científico.

Su participación es totalmente voluntaria. Usted puede retirarse en cualquier momento.

Microworld's Register sheet - Hoja de registro de micromundo

*Obligatorio

Name - Nombre

Tu respuesta

Age - Edad *

Tu respuesta

Country - País *

Tu respuesta

Gender - Género *

- ○ Male - Masculino
- ○ Female - Femenino
- ○ Prefer not to answer - Prefiero no responder
- ○ Otro: ____________

Education - Educación *

- ○ Less than a high school diploma - Menos que un diploma de bachiller
- ○ High school degree or equivalent - Bachiller o quivalente
- ○ Barchelor student - Estudiante de pregrado
- ○ Barchelor's degree - Profesional
- ○ Master's degree - Máster
- ○ Doctorate - Doctorado
- ○ Otro: ____________________

Occupation - Ocupación *

Tu respuesta

Organization - Organización

Tu respuesta

Atrás

Enviar

F. Pre and post microworld's session questionnaire

Introduction

This questionnaire aims to evaluate microworld's player's knowledge before and after playing in the microworld. We tested topics related to renewable energies, the renewable energy context in Colombia, the objectives in emissions reduction, and energy matrix diversification.

Informed consent

You have been invited to participate in this exercise that is part of the development of a microworld to understand the dynamics of the diffusion of non-conventional renewable generation technologies in Colombia, which is part of the master's thesis of the student Verónica Marrero, of the National University of Colombia, within the framework of the project "Strategy for the transformation of the Colombian energy sector in the horizon of 2030" financed in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018.

You will have to answer some questions, to evaluate if the microworld generates learning for users.

No personal information will be requested, we guarantee the confidentiality of the information and the treatment of the data with exclusively scientific use. For this purpose, you have been assigned a player number that will be requested if you accept this informed consent.

Your participation is completely voluntary. You can withdraw at any time.

Do you declare that you understand the above information and your rights and commitments during the exercise and acknowledge that you can withdraw at any time from the game?

☐ Yes

☐ No

Please enter the player number that was assigned to you: ________

Questionnaire

We marked the correct answers.

Table F-9: *Pre and post microworld's questionnaire*

Renewable energy-related questions		
1.	What is a non-conventional renewable generation source?	
	A. Those in which the expense or depletion of its generating source is incurred.	☐
	B. Those that are inexhaustible, due to the immense amount they contain or because they can be regenerated by natural means and that are also not widely marketed in the country.	☒
	C. Those that are inexhaustible, due to the immense amount they contain or because they can be regenerated by natural means but that are widely marketed in the country.	☐
	D. I do not know.	☐
2.	Which of the following are unconventional renewable generation technologies in Colombia?	
	A. Solar photovoltaic.	☒
	B. Hydropower.	☐

C. Biomass. ☒

D. Natural gas. ☐

E. Wind. ☒

F. Small Hydropower. ☒

G. Coal. ☐

H. Diesel. ☐

I. Geothermal. ☒

J. I don´t know. ☐

3. What is biomass?

A. A part of biology. ☐

B. Fossil fuel. ☐

C. Organic matter created in industrial processes. ☒

D. None of the above. ☐

E. I do not know ☐

Colombian electricity market-related questions

4. How is the energy matrix composed (percentage of each generation technology) in Colombia?

A. Biomass: 5% Wind: 10% Hydraulic: 45% Solar: 20% Thermal: 30% ☐

B. Biomass: 0.9% Wind: 0.1% Hydraulic: 68.1% Solar: 0.2% Thermal: 30.7% ☒

C. Biomass: 1.5% Wind: 5.3% Hydraulic: 20.5% Solar: 20.2% Thermal: 52.2% ☐

D. I do not know. ☐

5. Why is it important for Colombia to diversify its energy matrix?

A. To reduce greenhouse gas emissions. ☒

B. To increase the reliability of the energy supply, due to the variability of generation resources. ☒

C. To comply with the commitments agreed in the Paris agreement. ☒

D. To increase the amount of electrical energy that can be delivered to Colombians. ☒

E. I do not know. ☐

6. What is the role of the electricity market regulator?

A. Consume the energy generated by the national electricity system. ☐

B. Issue regulations for the electricity sector. ☒

C. Acquire the energy and then commercialize it to the end-user. ☐

D. Produce the energy that is delivered by the national electricity system. ☐

E. I do not know. ☐

Energy and power-related questions

7. What is the difference between power and power generation?

A. There is no difference. ☐

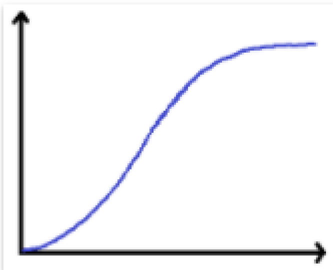
B. Generation is the amount of energy produced over time (MWh), while power is the amount that a plant is capable of delivering (MW). ☒

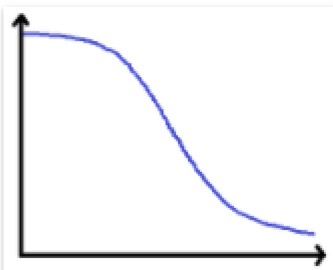
C. Power is the amount of energy produced over time (MWh), while generation is the amount that a plant is capable of delivering (MW). ☐

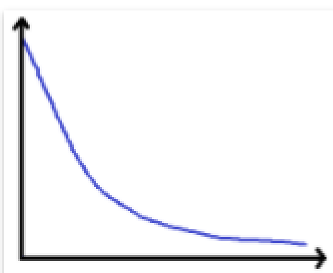
D. I do not know. ☐

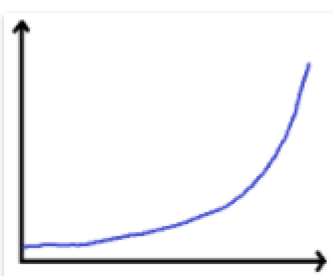
Capacity installation related questions

8. Which of the following graphs best represents the behavior of the available potential of solar technology over time?

A.  ☐

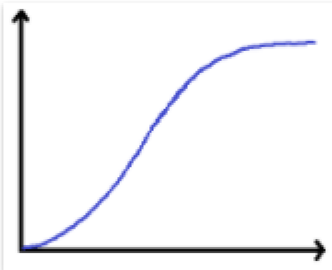
B.  ☒

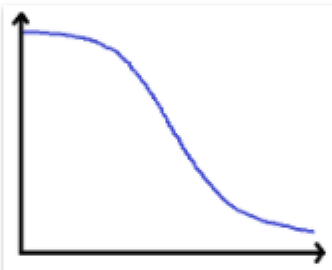
C.  ☐

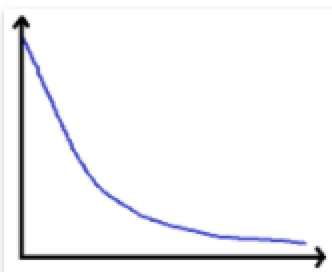
D.  ☐

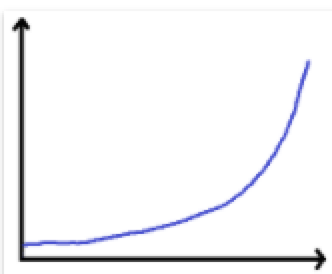
E. I do not know what the available potential is. ☐

9. Which of the following graphs best represents the behavior of the installed capacity of solar technology over time?

A.  ☒

B.  ☐

C.  ☐

D.  ☐

E. I do not know what the installed capacity is. ☐

10. What is the Levelized Cost of Energy?

A. These are the costs incurred to produce a generation unit over its entire useful life and include added taxes. ☐

B. These are the costs incurred to produce a generating unit over its entire useful life, excluding added taxes. ☒

C. They are the costs incurred to produce a generating unit and include added taxes. ☐

D. These are the costs incurred to produce a generation unit without including added taxes. ☐

E. I do not know. ☐

11. What is the difference between carbon credits and carbon taxes?

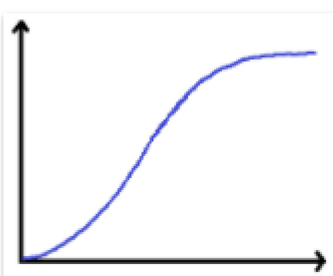
A. They are the same. ☐

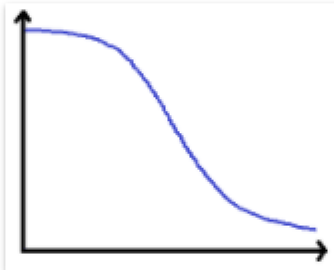
B. Carbon credits are the money that I have to pay for each ton of carbon I emit, while carbon taxes are the amount of money, I receive from the sale of emissions that I stopped emitting. ☐

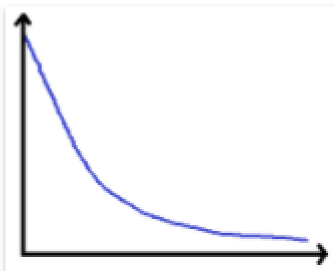
C. The carbon tax is the money that I have to pay for each ton that I emit of carbon, while the carbon credits are the amount of money that is received from the sale of the emissions that I stopped emitting. ☒

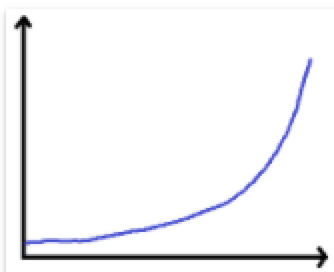
D. I do not know. ☐

12. What is the expected behavior of investment costs per unit for solar technology over time?

A.  ☐

B.  ☐

C.  ☒

D.  ☐

E. I do not know. ☐

Criterion questions

13. If the price of electricity is $ 30 / MWh and the Levelized Costs of Energy are $ 20 / MWh, would you decide to invest in the construction of a power generation plant?

A. Yes. ☐

B. Not. ☐

C. I do not know*. ☒

14. If the price of electricity is 30 USD / MWh, the Levelized Energy Costs are 20 USD / MWh, and the taxes you must pay are 15 USD / MWh, would you decide to invest in the construction of a generation plant of energy?

A. Yes. ☒

B. Not. ☐

C. I do not know. ☐

15. What happens to private investment if a country constantly changes its policies and regulations?

A. Investors do not consider changes in policies and regulations to carry out their projects. ☐

B. If the country constantly makes changes, investors' confidence in market stability decreases, and therefore investment decreases. ☒

C. If the country constantly makes changes, the confidence investors have in the stability of the market increases, and therefore investment increases. ☐

D. I do not know. ☐

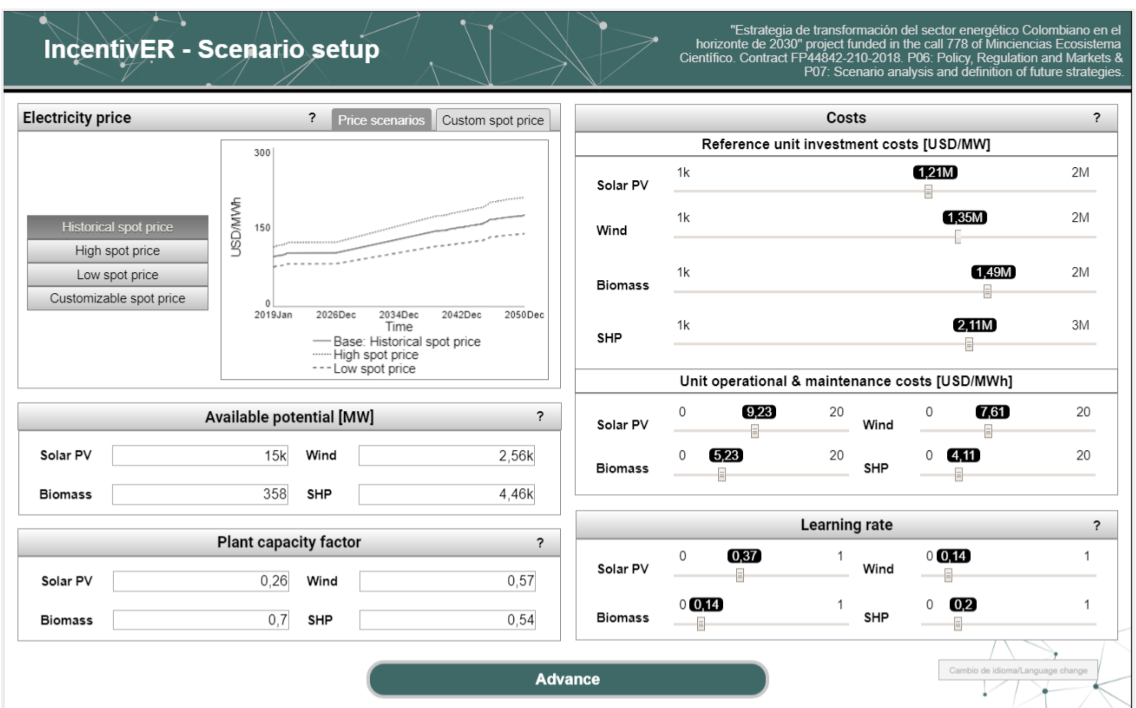
*The answer “I do not know” is correct because there is missing information to make that decision.

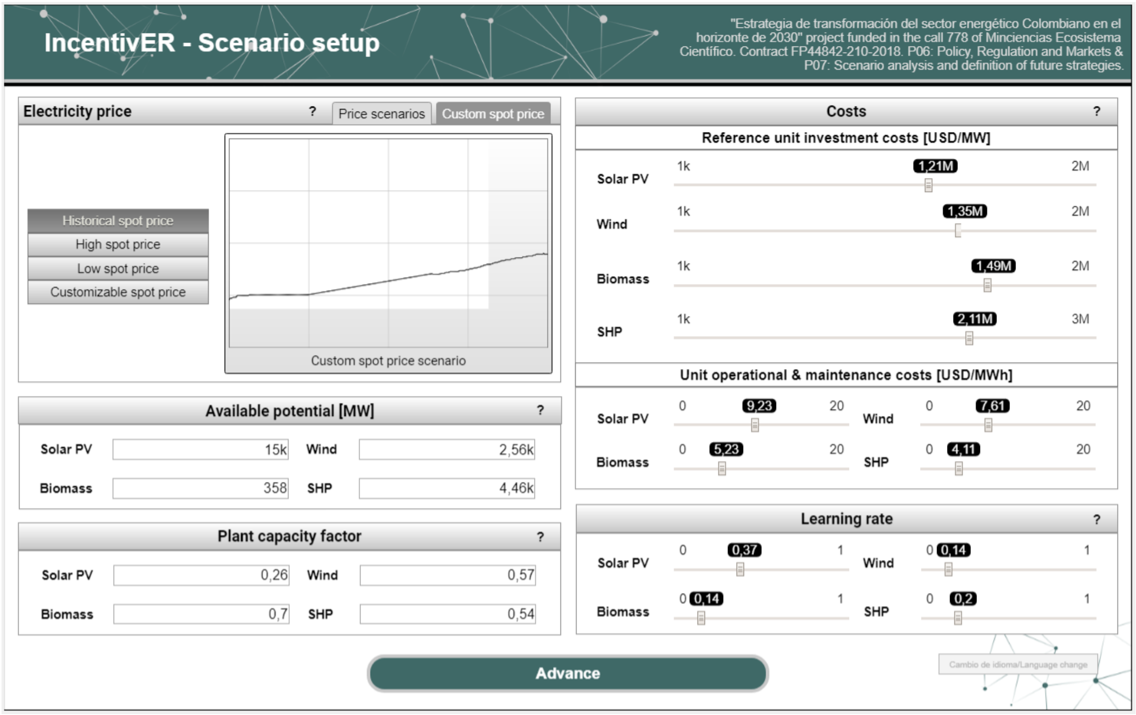
Source: Own elaboration.

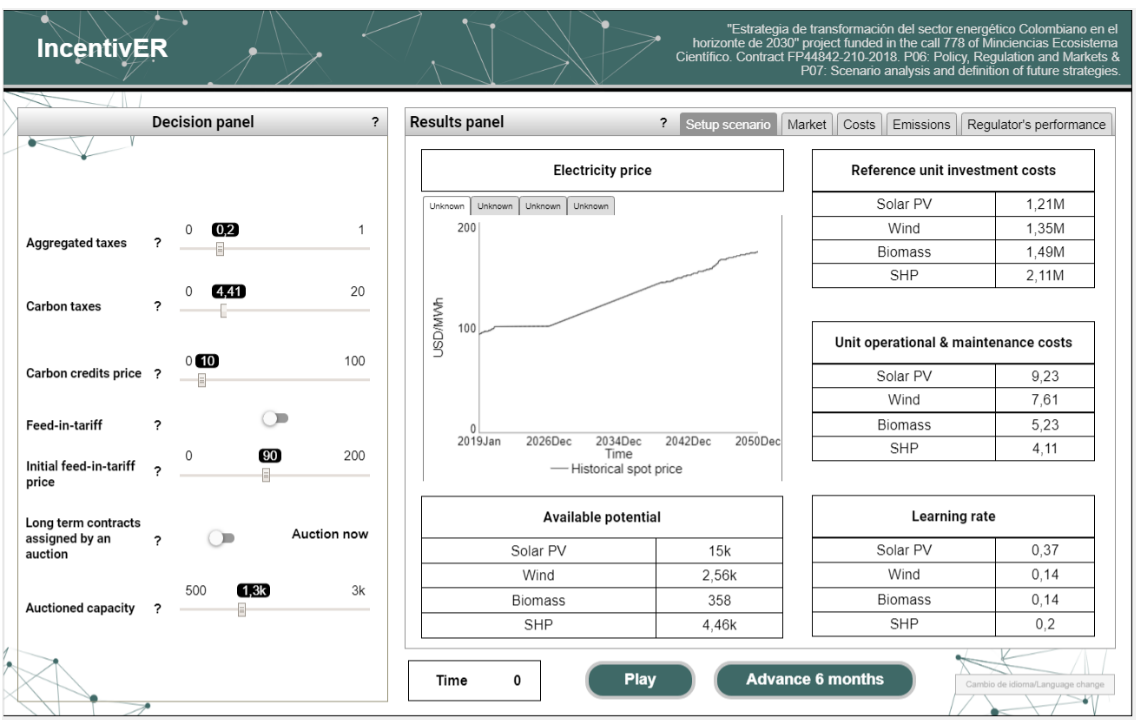
G. Microworld's interface

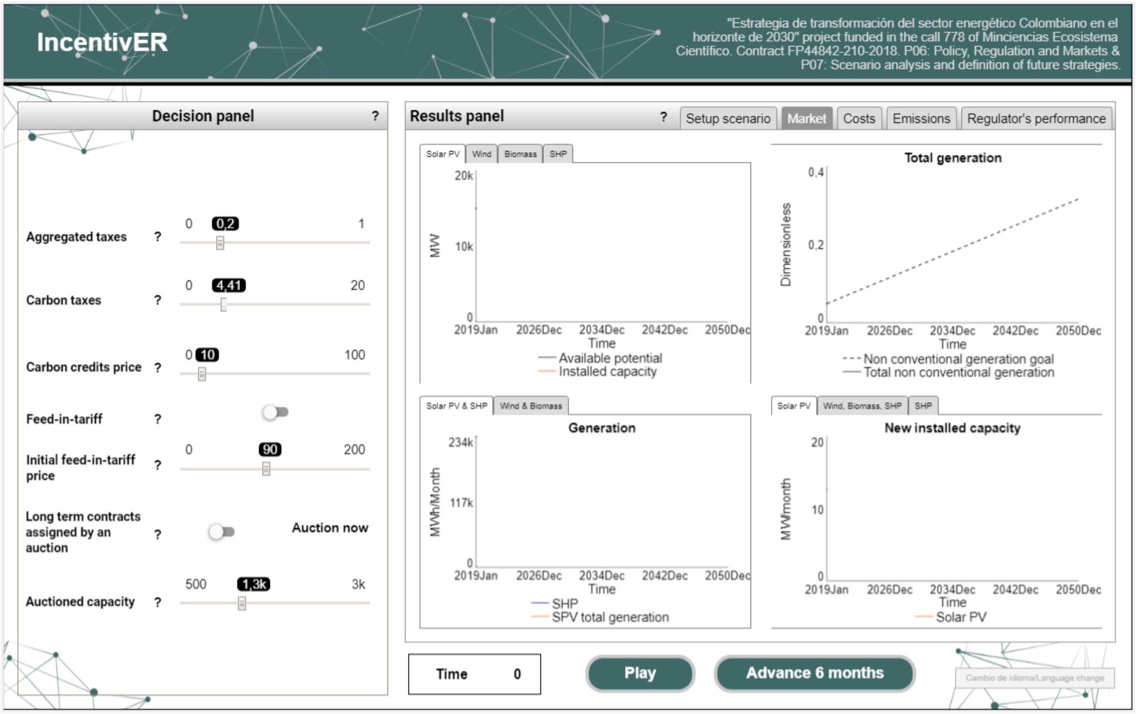
The microworld has a complete English and Spanish interface, here we present the English interface:

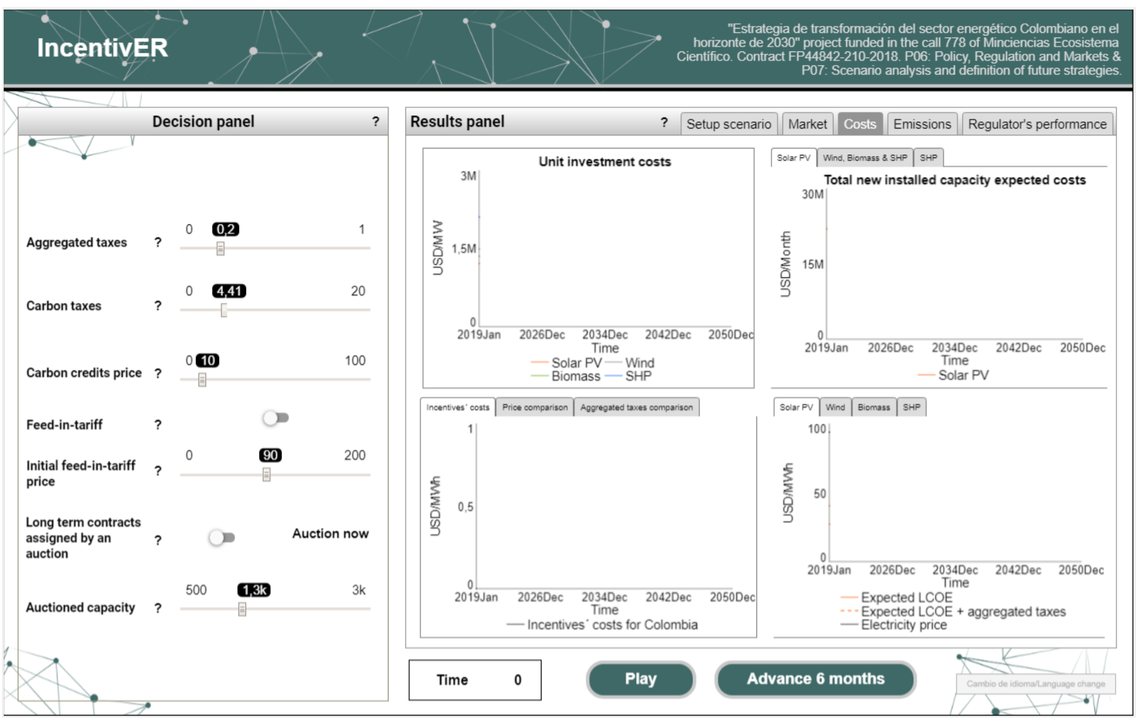

Renewable energy microworld
Micromundo de energías renovables
ENERGÉTICA 2030
IncentivER
As this is a educational tool, we kindly ask you to complete the following register sheet before start playing.
Register sheet
Continue to the game
Proyecto "Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" financiado en la convocatoria 778 de Minciencias Ecosistema Científico. Contrato FP44842-210-2018. P06: Política, Regulación y Mercados y P07: Análisis de escenarios y definición de estrategias futuras.
Desarrollado por: Verónica Marrero Trujillo, Jessica Arias Gaviria, Santiago Arango Aramburo y Erik Reimer Larsen.
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Developed by: Verónica Marrero Trujillo, Jessica Arias Gaviria, Santiago Arango Aramburo & Erik Reimer Larsen.
AARHUS UNIVERSITY
COLOMBIA CIENTÍFICA
UNIVERSIDAD NACIONAL DE COLOMBIA
Cambio de idioma/Language change

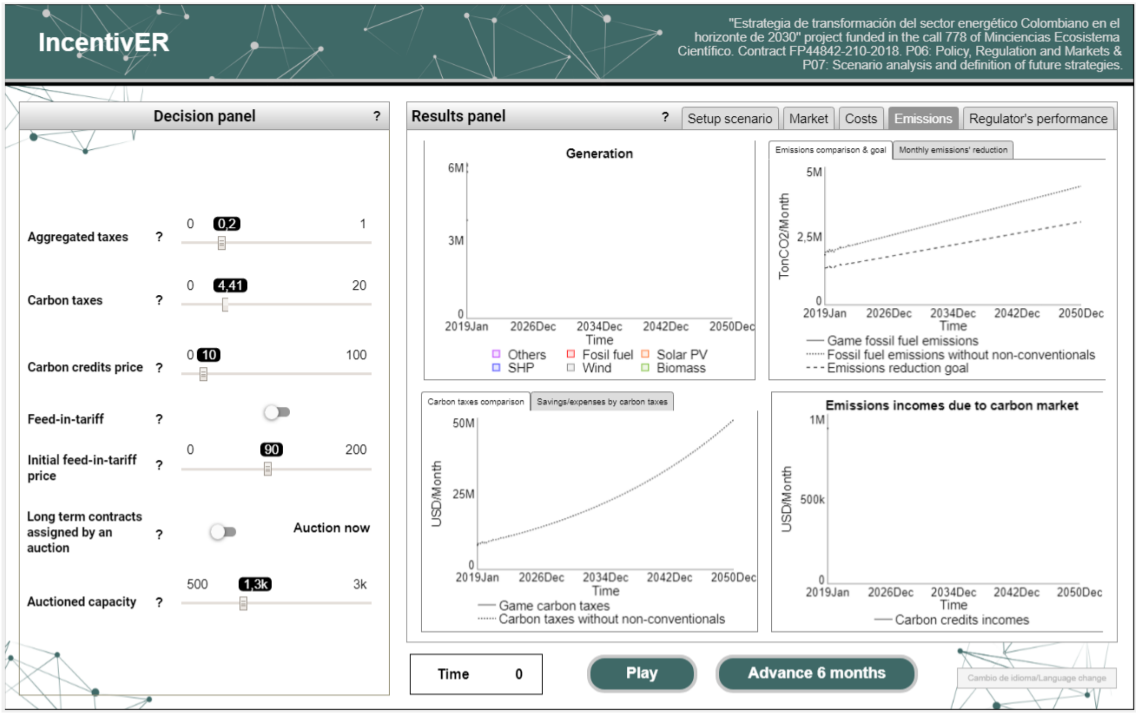

IncentivER - Scenario setup
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Electricity price
?
Price scenarios
Custom spot price
Historical spot price
High spot price
Low spot price
Customizable spot price
USD/MWh
300
150
0
2019Jan
2026Dec
2034Dec
2042Dec
2050Dec
Time
Base: Historical spot price
High spot price
Low spot price
Available potential [MW]
Solar PV 15k
Wind 2,56k
Biomass 358
SHP 4,46k
Plant capacity factor
Solar PV 0,26
Wind 0,57
Biomass 0,7
SHP 0,54
Costs
Reference unit investment costs [USD/MW]
Solar PV 1k 1,21M 2M
Wind 1k 1,35M 2M
Biomass 1k 1,49M 2M
SHP 1k 2,11M 3M
Unit operational & maintenance costs [USD/MWh]
Solar PV 0 9,23 20
Wind 0 7,61 20
Biomass 0 5,23 20
SHP 0 4,11 20
Learning rate
Solar PV 0 0,37 1
Wind 0 0,14 1
Biomass 0 0,14 1
SHP 0 0,2 1
Advance
Cambio de idioma/Language change


IncentivER - Scenario setup
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Electricity price
Price scenarios
Custom spot price
Historical spot price
High spot price
Low spot price
Customizable spot price
Custom spot price scenario
Available potential [MW]
Solar PV 15k
Wind 2,56k
Biomass 358
SHP 4,46k
Plant capacity factor
Solar PV 0,26
Wind 0,57
Biomass 0,7
SHP 0,54
Costs
Reference unit investment costs [USD/MW]
Solar PV 1k 1,21M 2M
Wind 1k 1,35M 2M
Biomass 1k 1,49M 2M
SHP 1k 2,11M 3M
Unit operational & maintenance costs [USD/MWh]
Solar PV 0 9,23 20
Wind 0 7,61 20
Biomass 0 5,23 20
SHP 0 4,11 20
Learning rate
Solar PV 0 0,37 1
Wind 0 0,14 1
Biomass 0 0,14 1
SHP 0 0,2 1
Advance


IncentivER
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Decision panel
Aggregated taxes 0 0,2 1
Carbon taxes 0 4,41 20
Carbon credits price 0 10 100
Feed-in-tariff
Initial feed-in-tariff price 0 90 200
Long term contracts assigned by an auction
Auction now
Auctioned capacity 500 1,3k 3k
Results panel
Setup scenario
Market
Costs
Emissions
Regulator's performance
Electricity price
USD/MWh
2019Jan 2026Dec 2034Dec 2042Dec 2050Dec
Time
Historical spot price
Reference unit investment costs
Solar PV 1,21M
Wind 1,35M
Biomass 1,49M
SHP 2,11M
Unit operational & maintenance costs
Solar PV 9,23
Wind 7,61
Biomass 5,23
SHP 4,11
Available potential
Solar PV 15k
Wind 2,56k
Biomass 358
SHP 4,46k
Learning rate
Solar PV 0,37
Wind 0,14
Biomass 0,14
SHP 0,2
Time 0
Play
Advance 6 months


IncentivER
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Decision panel ?
Aggregated taxes ? 0 0,2 1
Carbon taxes ? 0 4,41 20
Carbon credits price ? 0 10 100
Feed-in-tariff ?
Initial feed-in-tariff price ? 0 90 200
Long term contracts assigned by an auction ? Auction now
Auctioned capacity ? 500 1,3k 3k
Results panel ? Setup scenario Market Costs Emissions Regulator's performance
Solar PV Wind Biomass SHP
MW
Available potential
Installed capacity
Total generation
Dimensionless
Non conventional generation goal
Total non conventional generation
Solar PV & SHP Wind & Biomass
Generation
MWh/Month
SHP
SPV total generation
Solar PV Wind, Biomass, SHP SHP
New installed capacity
MW/month
Solar PV
Time
2019Jan 2026Dec 2034Dec 2042Dec 2050Dec
Time 0
Play
Advance 6 months


IncentivER
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Decision panel ?
Aggregated taxes ? 0 0,2 1
Carbon taxes ? 0 4,41 20
Carbon credits price ? 0 10 100
Feed-in-tariff ?
Initial feed-in-tariff price ? 0 90 200
Long term contracts assigned by an auction ? Auction now
Auctioned capacity ? 500 1,3k 3k
Results panel ? Setup scenario Market Costs Emissions Regulator's performance
Unit investment costs
USD/MW
Solar PV Wind Biomass SHP
Solar PV Wind, Biomass & SHP SHP
Total new installed capacity expected costs
USD/Month
Solar PV
Incentives´ costs Price comparison Aggregated taxes comparison
USD/MWh
Incentives´ costs for Colombia
Solar PV Wind Biomass SHP
Expected LCOE
Expected LCOE + aggregated taxes
Electricity price
Time
2019Jan 2026Dec 2034Dec 2042Dec 2050Dec
Time 0
Play
Advance 6 months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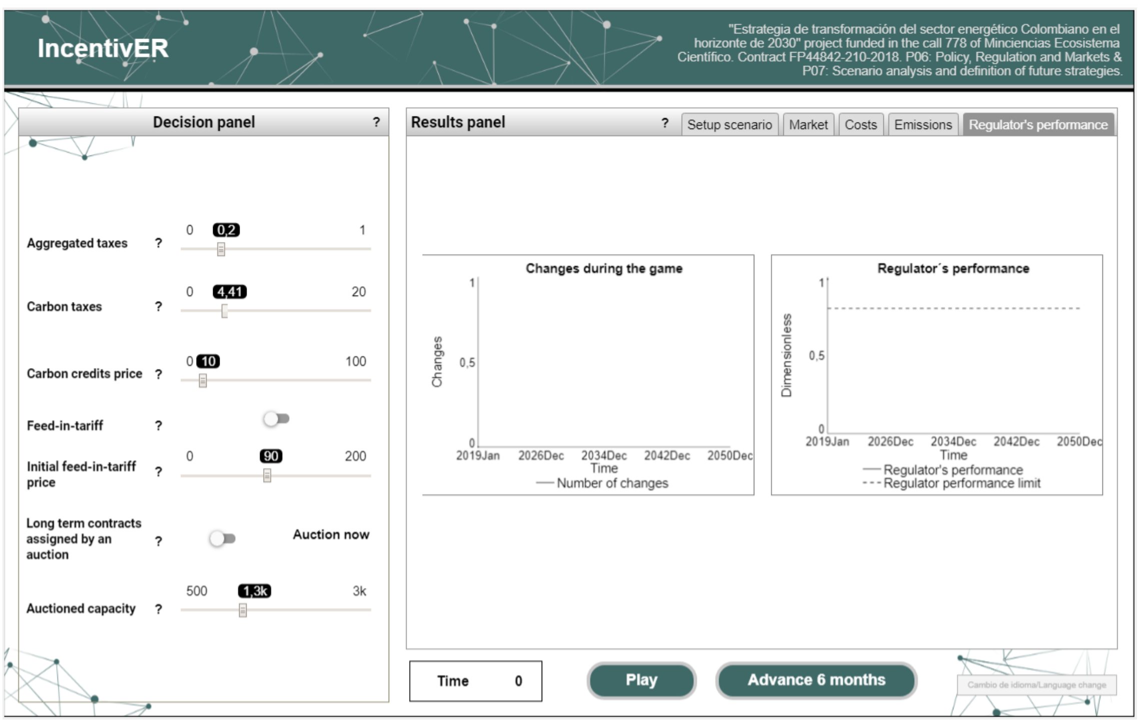
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Decision panel
Aggregated taxes 0 0,2 1
Carbon taxes 0 4,41 20
Carbon credits price 0 10 100
Feed-in-tariff
Initial feed-in-tariff price 0 90 200
Long term contracts assigned by an auction
Auction now
Auctioned capacity 500 1,3k 3k
Results panel
Setup scenario
Market
Costs
Emissions
Regulator's performance
Generation
Others
Fossil fuel
Solar PV
SHP
Wind
Biomass
Emissions comparison & goal
Monthly emissions' reduction
TonCO2/Month
Game fossil fuel emissions
Fossil fuel emissions without non-conventionals
Emissions reduction goal
Carbon taxes comparison
Savings/expenses by carbon taxes
USD/Month
Game carbon taxes
Carbon taxes without non-conventionals
Emissions incomes due to carbon market
Carbon credits incomes
Time
Time 0
Play
Advance 6 months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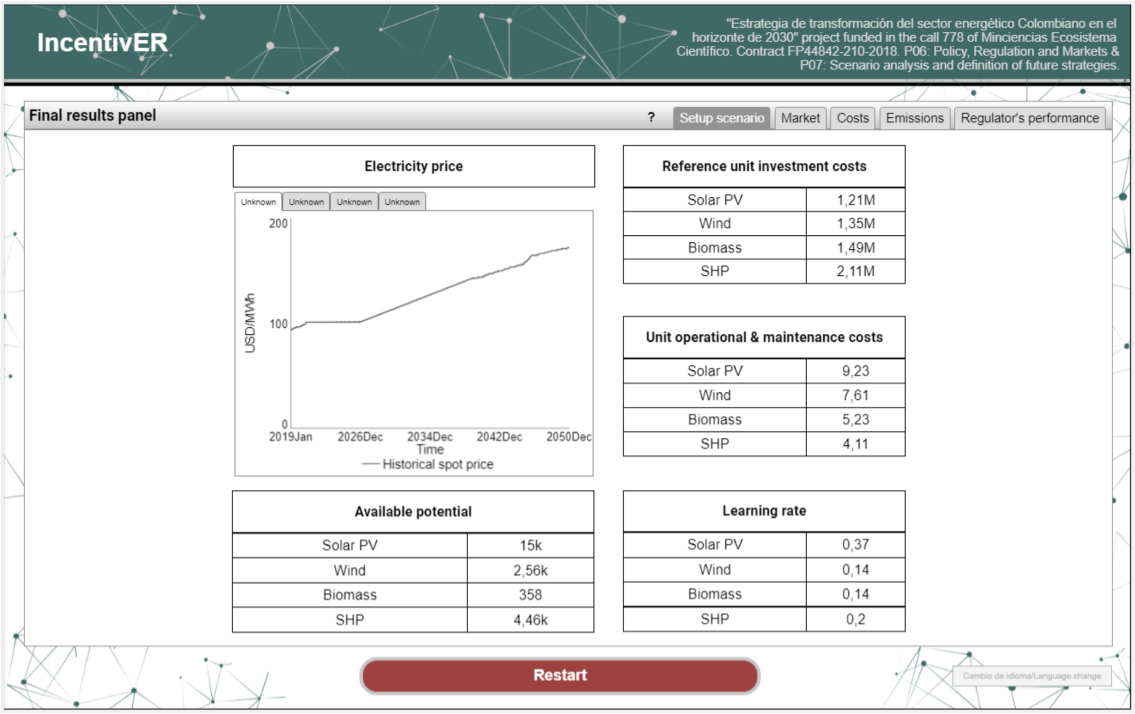
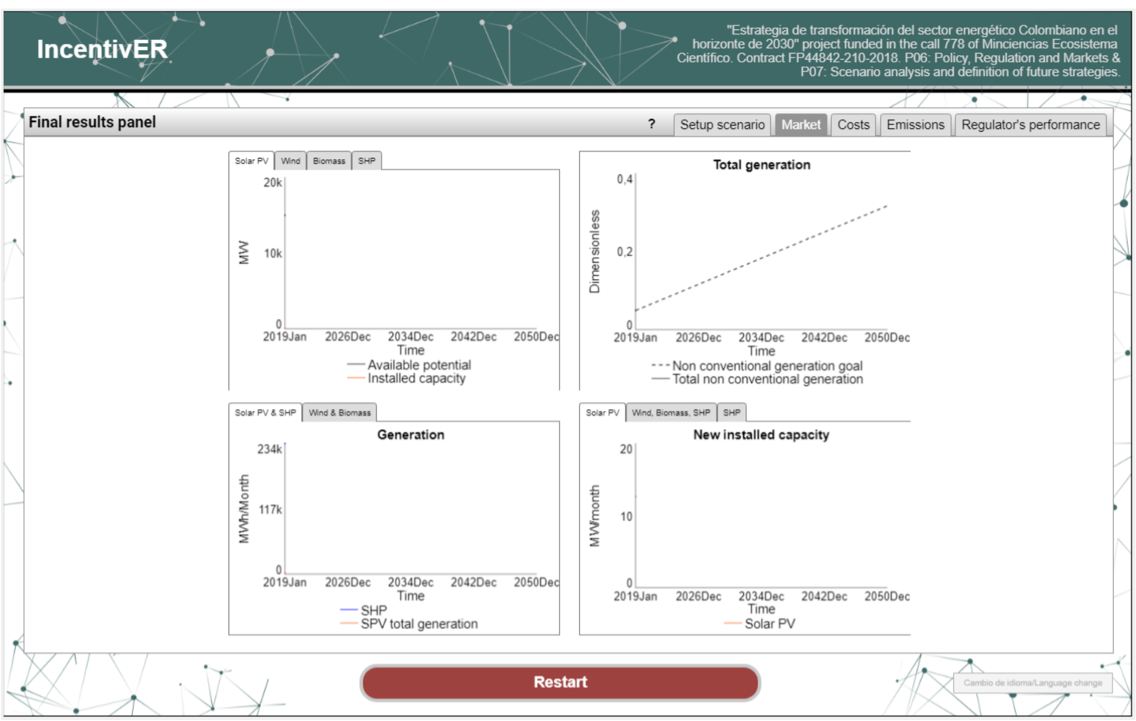
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Decision panel
Aggregated taxes 0 0,2 1
Carbon taxes 0 4,41 20
Carbon credits price 0 10 100
Feed-in-tariff
Initial feed-in-tariff price 0 90 200
Long term contracts assigned by an auction
Auction now
Auctioned capacity 500 1,3k 3k
Results panel
Setup scenario
Market
Costs
Emissions
Regulator's performance
Changes during the game
Changes
Number of changes
Regulator´s performance
Dimensionless
Regulator's performance
Regulator performance limit
Time
Time 0
Play
Advance 6 months


IncentivER
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Final results panel
?
Setup scenario
Market
Costs
Emissions
Regulator's performance
Electricity price
Unknown
Unknown
Unknown
Unknown
200
100
0
USD/MWh
2019Jan
2026Dec
2034Dec
2042Dec
2050Dec
Time
Historical spot price
Reference unit investment costs
Solar PV 1,21M
Wind 1,35M
Biomass 1,49M
SHP 2,11M
Unit operational & maintenance costs
Solar PV 9,23
Wind 7,61
Biomass 5,23
SHP 4,11
Available potential
Solar PV 15k
Wind 2,56k
Biomass 358
SHP 4,46k
Learning rate
Solar PV 0,37
Wind 0,14
Biomass 0,14
SHP 0,2
Restart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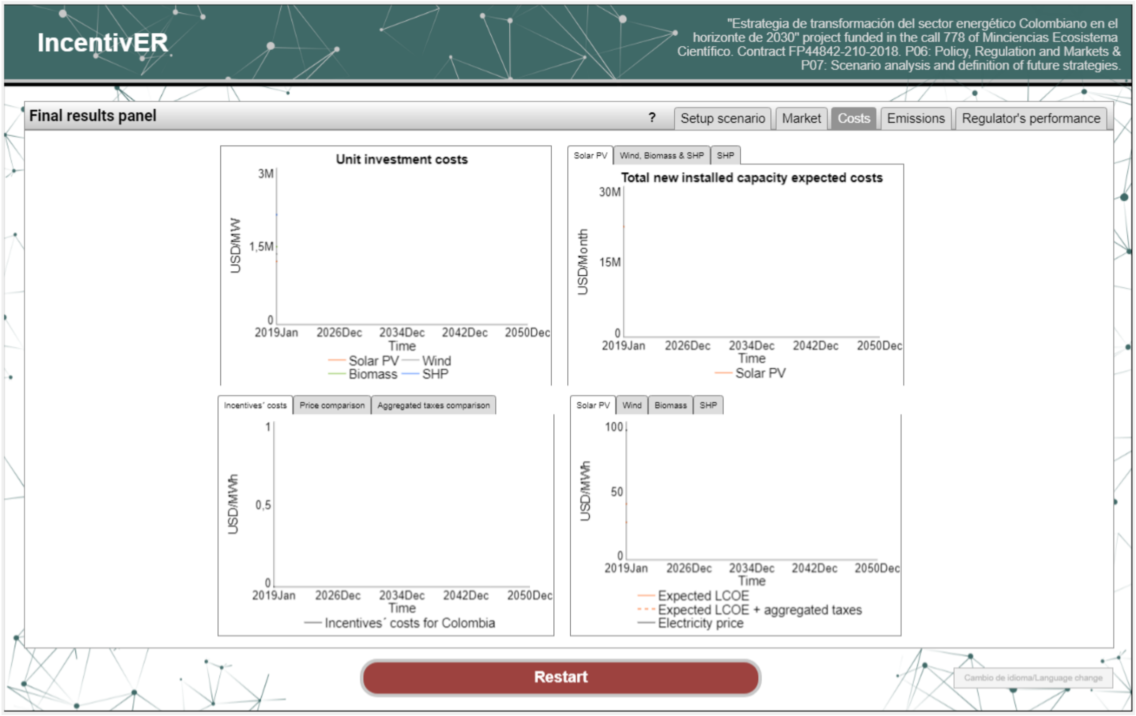
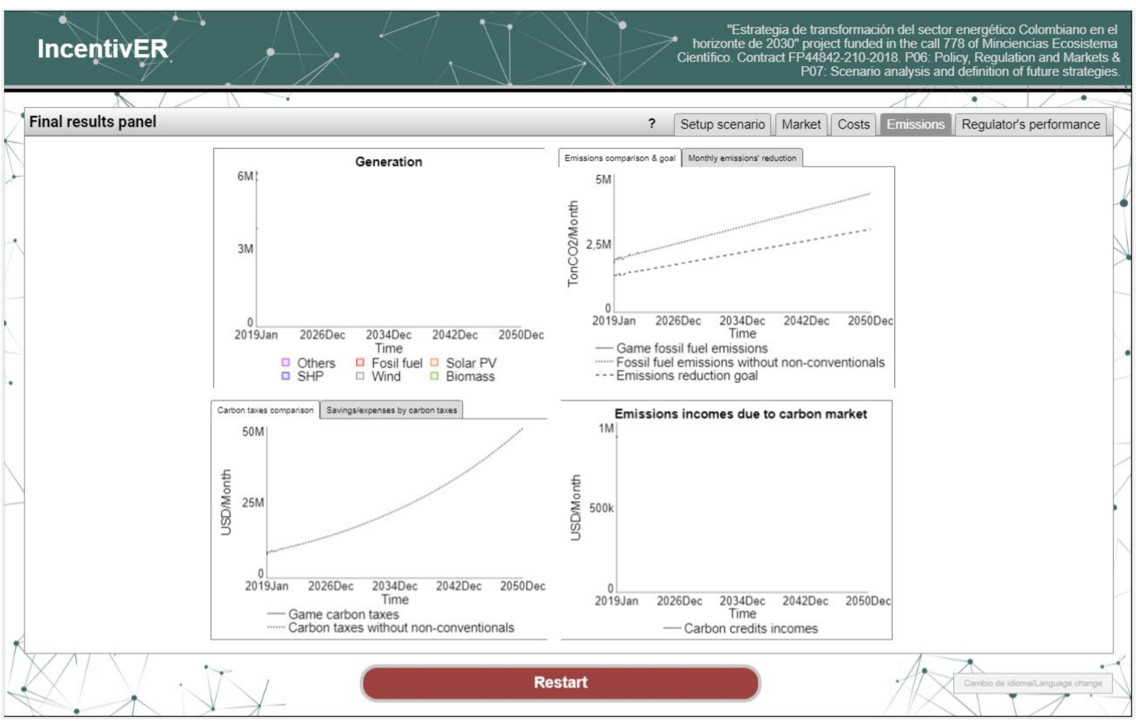
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Final results panel
?
Setup scenario
Market
Costs
Emissions
Regulator's performance
Solar PV
Wind
Biomass
SHP
20k
10k
0
MW
2019Jan
2026Dec
2034Dec
2042Dec
2050Dec
Time
Available potential
Installed capacity
Total generation
0,4
0,2
0
Dimensionless
2019Jan
2026Dec
2034Dec
2042Dec
2050Dec
Time
Non conventional generation goal
Total non conventional generation
Solar PV & SHP
Wind & Biomass
Generation
234k
117k
0
MWh/Month
2019Jan
2026Dec
2034Dec
2042Dec
2050Dec
Time
SHP
SPV total generation
Solar PV
Wind, Biomass, SHP
SHP
New installed capacity
20
10
0
MW/month
2019Jan
2026Dec
2034Dec
2042Dec
2050Dec
Time
Solar PV
Restart


IncentivER
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Final results panel
?
Setup scenario
Market
Costs
Emissions
Regulator's performance
Unit investment costs
USD/MW
Time
Solar PV
Wind
Biomass
SHP
Solar PV
Wind, Biomass & SHP
SHP
Total new installed capacity expected costs
USD/Month
Incentives´ costs
Price comparison
Aggregated taxes comparison
USD/MWh
Incentives´ costs for Colombia
Expected LCOE
Expected LCOE + aggregated taxes
Electricity price
Restart


IncentivER
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in the call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.
Final results panel
?
Setup scenario
Market
Costs
Emissions
Regulator's performance
Generation
Others
Fosil fuel
Solar PV
SHP
Wind
Biomass
Emissions comparison & goal
Monthly emissions' reduction
TonCO2/Month
Game fossil fuel emissions
Fossil fuel emissions without non-conventionals
Emissions reduction goal
Carbon taxes comparison
Savings/expenses by carbon taxes
USD/Month
Game carbon taxes
Carbon taxes without non-conventionals
Emissions incomes due to carbon market
Carbon credits incomes
Restart

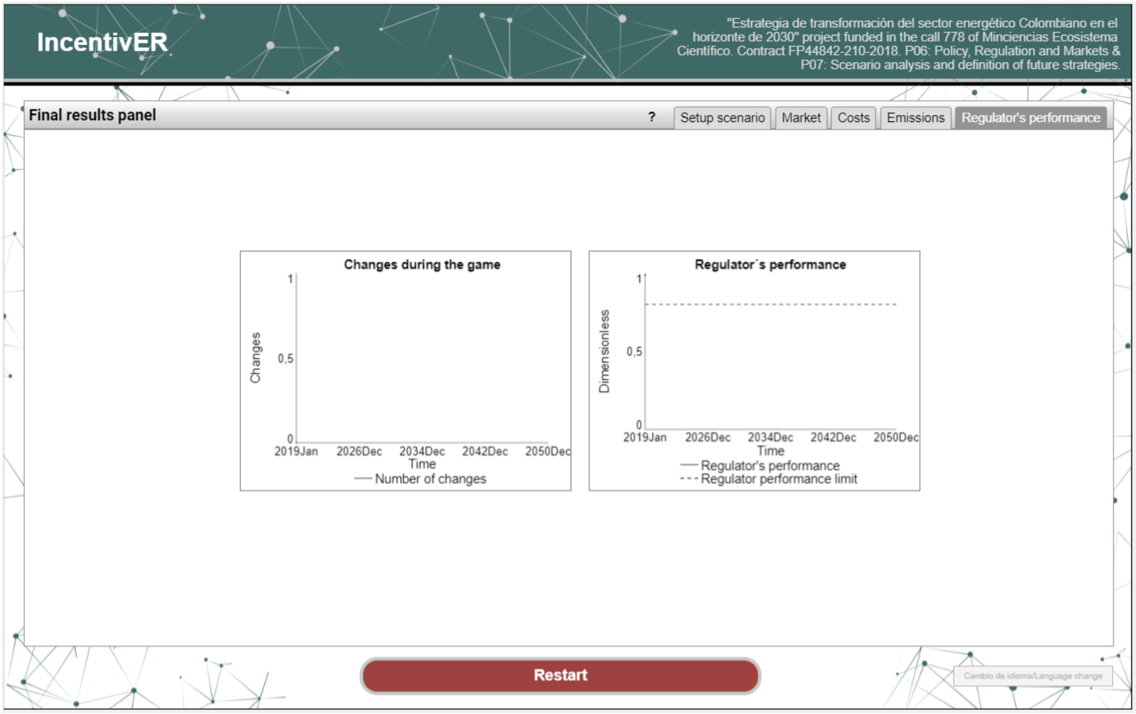


Figure G-1: Microworld complete interface.

Source: Own elaboration.

H. Microworld's introduction and users' guide

Introduction

Dear player, you are now the regulator of the electricity market in Colombia. You have to choose between different incentives to non-conventional renewable energy technologies to promote their installation, reduce carbon emissions, and maintain the investors happy. The microworld considers four technologies: solar PV, wind, biomass, and small hydropower.

Each round you can:

1. Change the aggregates taxes value
2. Change the carbon taxes
3. Change the carbon bonds price
4. Apply feed-in tariffs
5. Make auctions

Also, you can set your game scenario:

1. Choosing different spot prices
2. Set different available potentials
3. Set different plant capacity factors
4. Set different costs
5. Set the learning rate

You have three objectives:

1. Reach a percentage of the total energy generation in Colombia with non-conventional technologies:

   i. 10% of the demand in 2025
   ii. 15% of the demand in 2030
   iii. 24% of the demand in 2040
   iv. 32% of the demand in 2050

2. Reach a carbon emissions reduction of 30% by 2030, compared with the projected emissions.

3. Maintain the investors' confidence in the country's regulator (you) above 80%:

   i. If you change your decisions a lot, the perception of the market stability of investors will be bad, so their confidence will be reduced, and will not invest.
   ii. If you manage your decisions to be stable, the investors will be confident in your decisions and will invest.

Microworld horizon time

The game will last until 2050. You can go forward to your results or you can play by timesteps of six months.

Definitions

i. Available potential: The available potential is the maximum capacity that can be installed on each technology. *Measured in MW*.

ii. Installed capacity: Available power for generating electricity, i.e. capacity that has been installed using the available potential. *Measured in MW*.

iii. Generation: Transformation of the installed capacity into electricity. *Measured in MWh/month*.

iv. Operational costs: These are the economic expenses that must be assumed for the operation of the plant, such as the rental of the workspace and administrative expenses, fuel (for some technologies), etc. *Measured in USD/Month*.

v. Investment costs: The total costs of installing new capacity, such as equipment or infrastructure construction. *Measured in USD/Month*.

vi. Electricity price: The electricity price is paid to the generators for energy sales. This value can be predefined, like the following:

Spot price: historical and projected spot price until the end of the simulation.
High Spot Price: high and projected spot price scenario until the end of the simulation.
Low Spot Price: low and projected spot price scenario until the end of the simulation.

Or it can be a custom scenario, in which you can set the value you want on the graph that will appear when you select that option. *Measured in USD/MWh*.

vii. Levelized Cost of Energy (LCOE): The total costs of the electricity including total capital construction costs, operational and maintenance costs, fuel costs, and carbon costs per generated electricity unit. The LCOE is measured for all the technology lifetime. *Measured in USD/MWh*.

viii. Renewable incentives: Support mechanisms for renewable generation technologies, to promote installation in the electricity sector. *Units depend on each incentive.*

ix. Carbon emissions: Emissions per generation unit of each type of technology. *Measured in* TonCO_2*/MWh*.

x. Incomes: Income from energy sales in the electricity market, or carbon bonds. *Measured in USD/Month*.

xi. Expected profitability: For an investor to decide to install new capacity, he must consider the expected profitability of the plant, that is, the profitability of the capacity he wants to install under existing market conditions. It is calculated as the price of electricity divided by the LCOE. *Dimensionless.*

xii. Plant capacity factor: The plant capacity factor is the proportion of productive hours of a power plant during a month. *Dimensionless.*

xiii. Learning rate: Reduction rate of investment costs when the installed capacity doubles its value. *Dimensionless.*

xiv. Aggregates taxes: Percentage of taxes for the electricity generators. If the generators' incomes are greater than their total costs, they will have to pay taxes. *Measured in USD/Month*.

xv. Carbon taxes: It is the tax charged to generators for each ton of carbon emitted. *Measured in USD/TonCO*$_2$.

xvi. Carbon bonds: It is the price paid to renewable generators for the avoided carbon emissions, assuming that each new renewable pant is replacing a potential coal plant. *Measured in USD/ TonCO*$_2$.

xvii. Feed-in-tariff: The feed-in-tariff is a fixed price paid to renewable electricity generators, which grows with the consumer price index. *Measured in USD/MWh*.

xviii. Long term contracts assigned by an auction: Is a contract made between the generator and the marketer of the electricity market to promote the installation by setting a fixed price for the electricity during the plant lifetime. In the game, the price paid to the auctioned capacity will be the lowest Levelized Cost of Energy (LCOE) of renewable generation technologies and will increase according to the producer price index. The auction capacity will start operation two years after the auction execution (IRENA et al., 2015). *Measured in USD/MWh*.

xix. New installed capacity: The capacity that is added every month to the system due to investments in each technology. *Measured in MW/Month*.

xx. Incentives costs: Is the cost that has to pay the country for the implementation of some incentives. For example, if the aggregated taxes are reduced, the government will perceive lower incomes from tax collection, and the reduction in such tax collection would have to be assumed by the government or by the final electricity user. *Measured in USD/MWh*.

xxi. Carbon taxes savings or expending: This value represents the total savings or expenses due to the reduction or increment of the carbon taxes. For example, if the carbon tax increases from 4 USD/TonCO$_2$ to 6 USD/TonCO$_2$ the Green House Gas (GHG) emitting technologies will have additional spending of 2 USD/TonCO$_2$. On the other hand, if the tax is reduced from 6 USD/TonCO$_2$ to 4 USD/TonCO$_2$ then the GHG emitting companies will save 2 USD/TonCO$_2$. *Measured in USD/Month*.

xxii. <u>Regulator's performance:</u> Is the level of confidence that the investors have in the decisions of the regulator of the electricity market. To keep the investments unaffected, it is necessary to maintain the regulator's performance above 80%. *Dimensionless.*

Microworld interface

To access the microworld platform you can use the following direct link: https://exchange.iseesystems.com/public/santiagoarango/incentiver. Also, you can find additional material at https://www.energetica2030.co/micromundo/ .

When you access the microworld you will see the following window:

Figure H-1: Initial microworld's page.

Source: Own elaboration.

When you choose your language, you will be redirected to a voluntary register sheet, we will be very thankful if you complete it. Your registration will help us to know the scope of the microworld and to continue improving it. After completing the registration, you can continue to the game.

i. Scenario setup

The first window you will see is the scenario setup, in this window you can choose the electricity spot price, the available potential, the plant capacity factor, the costs, and the learning rate for each non-conventional technology. The microworld includes the simulation of four non-conventional renewable technologies: solar photovoltaic, wind, biomass, and small hydropower.

The window will look like this:

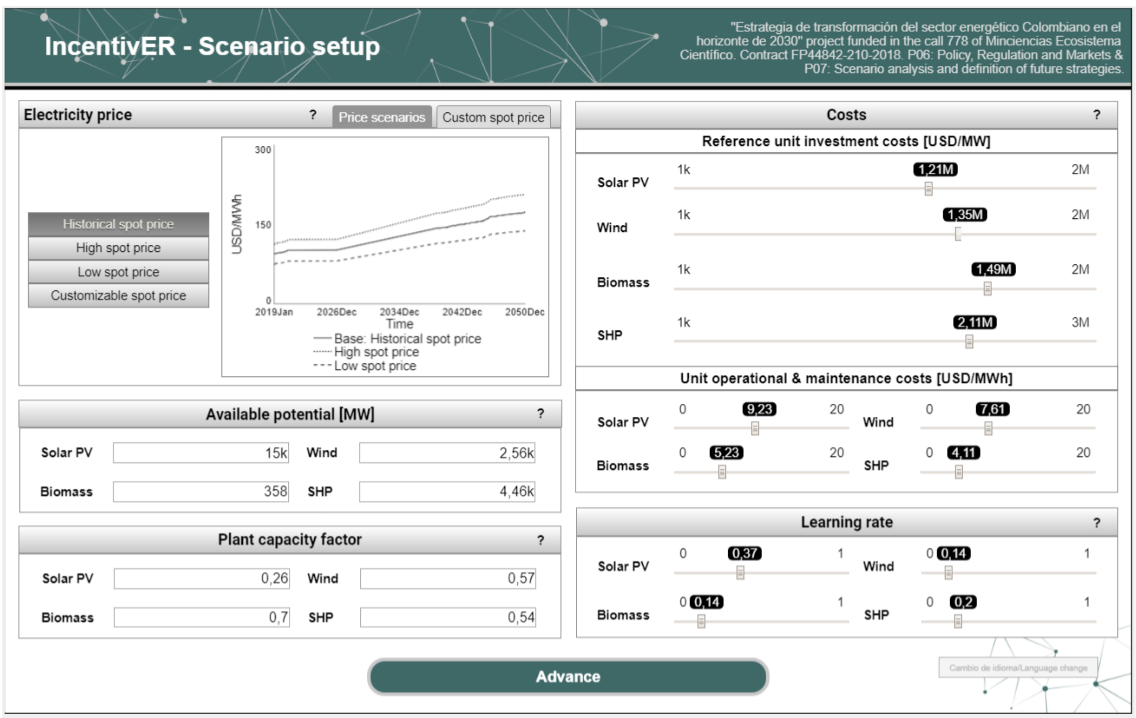


Figure H-2: Microworld's scenario setup.

Source: Own elaboration.

The preset scenario has real approximate values for each variable, you can set the game scenario as you want, but these changes will last all the game and you cannot change them until you start a new game.

All the windows in the microworld include question marks, you can click on them to read again the definition for the different variables. Additionally, if you select the wrong language you can change it anytime during the game with the bottom-right button.

- *Spot price setting*

You can set the electricity spot price following three preset scenarios as follows:

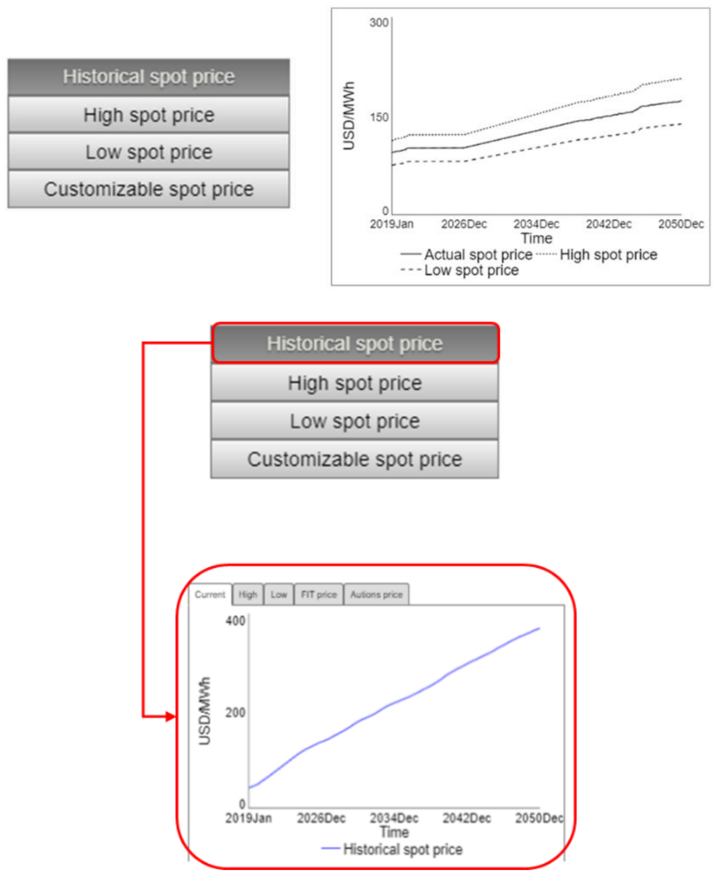


Figure H-3: Microworld’s electricity price setup.

Source: Own elaboration.

Or you can customize your price, by clicking on the custom spot price sheet, and moving the mouse drawing in the customizable graph:

Figure H-4: Microworld's custom electricity price setup.

Source: Own elaboration.

- *Available potential and plant capacity factor setting*

You can set any value that you want in the available potential and the capacity factor for each technology by typing it:

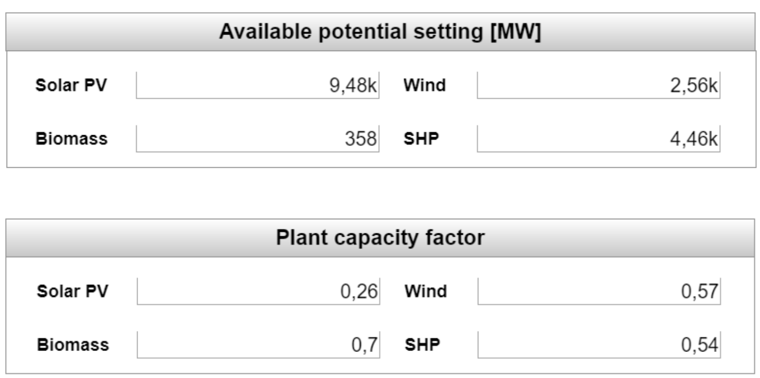


Figure H-5: Available potential and plant capacity setup.

Source: Own elaboration.

- *Costs and learning rate setting*

For the unit operational and maintenance costs, such as the reference unit investment costs and the learning rate, you can change it by moving the slider bars:

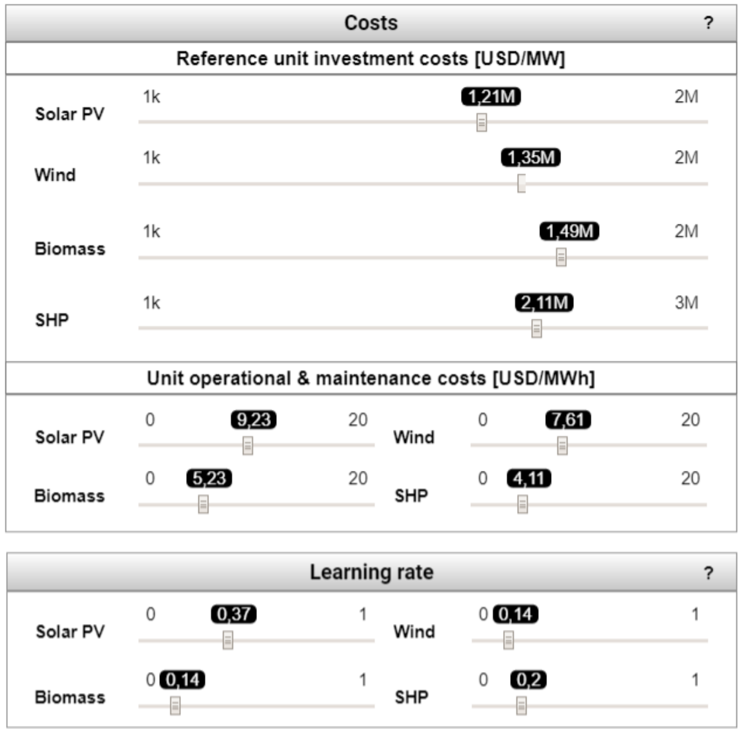


Figure H-6: Costs and learning rate setup.

Source: Own elaboration.

When you are ready with the scenario setup you can click the "advance" button.

ii. The interface

When you click on the advance button you will continue to the decisions and results panel. This panel contains some functionalities such as the question marks, a time record box, and play and 6-months-forward buttons. In the game, you can choose between making decisions every six months and play step by step, or you can go further to the end of the simulation whenever you want.

You will see the following window:

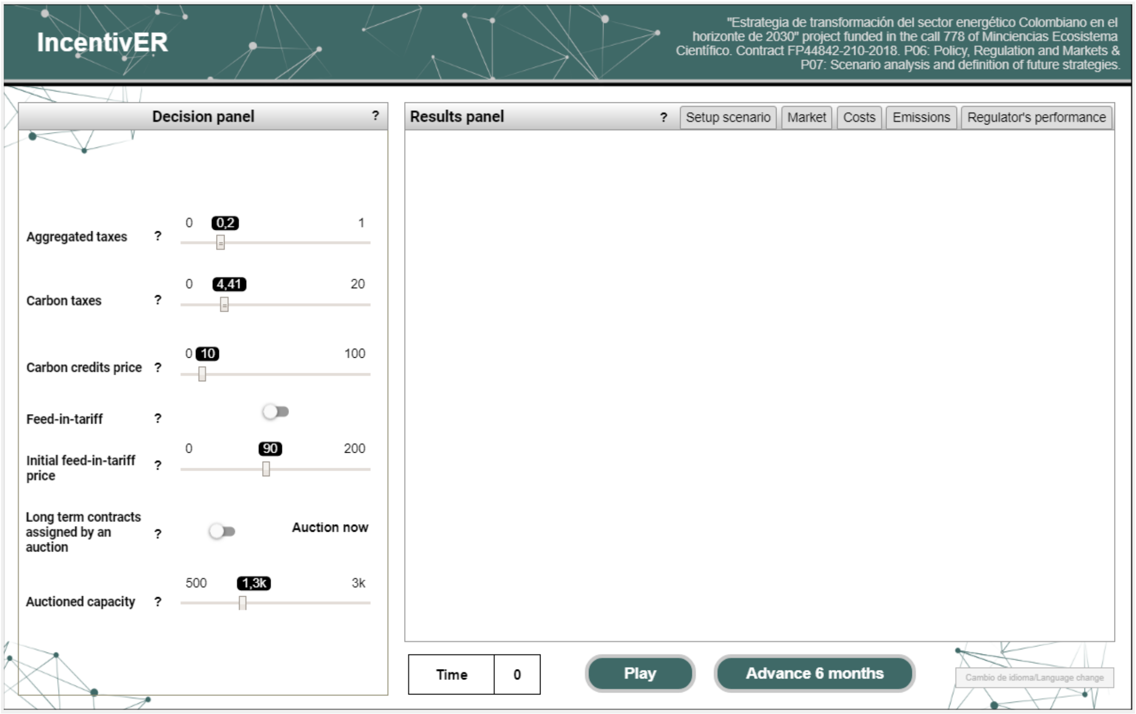


Figure H-7: Microworld's decision and results panel.

Source: Own elaboration.

This window contains the decision and results panel. The decision panel contains all the incentives that you can change or apply, such as the aggregated taxes, the carbon taxes, the carbon bond price, the feed-in-tariff, and its initial price and the long-term contracts assigned by an auction as well as the amount of capacity you want to auction.

In the decision panel, you can change the value for most of the variables using a slider bar, for the feed-in-tariff and the long-term contracts, as they are On/Off variables you can use them by turning the button on.

The feed-in-tariff is a fixed value for the electricity price which growths at a constant rate, but you can change the initial value as you want. On the other side, the auction can only be made every four years, so when you activate them and auction any capacity, the microworld will not let you make another auction for the next four years. The actioned capacity has an installation delay of two years.

In the decisions panel you will see different windows, which we are going to explore here:

- *Setup scenario*

This window shows the settled scenario for the game, you can check it whenever you want during the game, but you cannot change any of these parameters during the simulation:

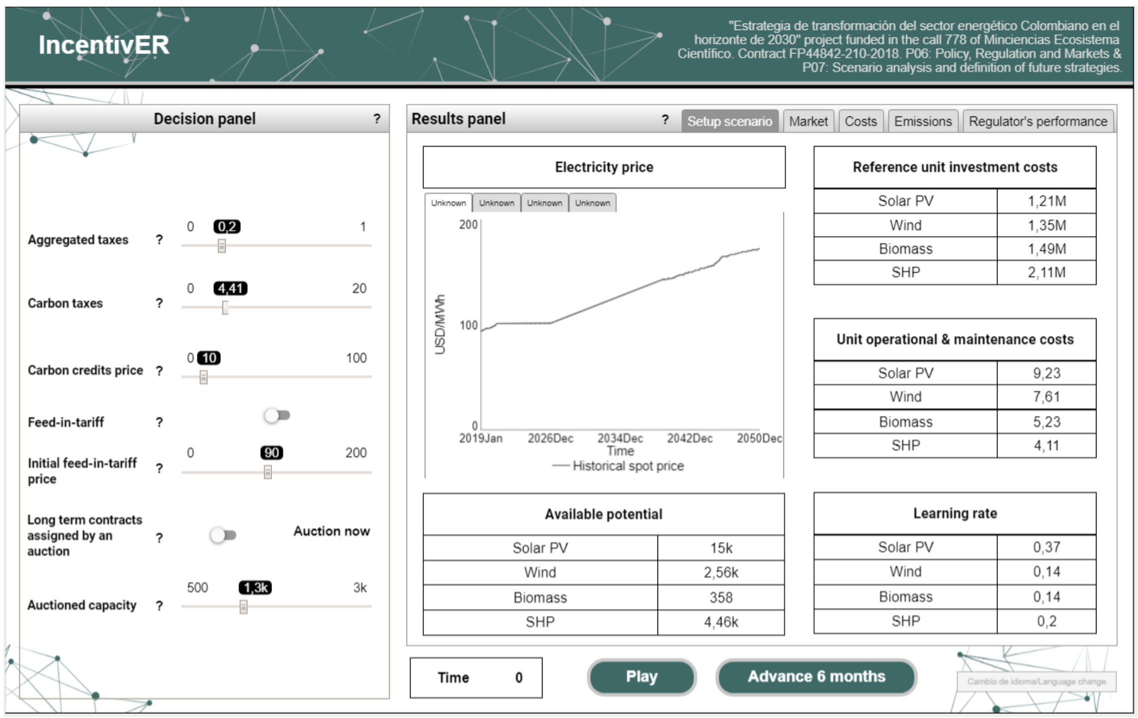


Figure H-8: Microworld's setup scenario window.

Source: Own elaboration.

- *Market window*

The market window displays the results for the available and installed capacity of each technology, each technology generation, the total non-conventional generation compared to the goal, and the new installed capacity for each technology:

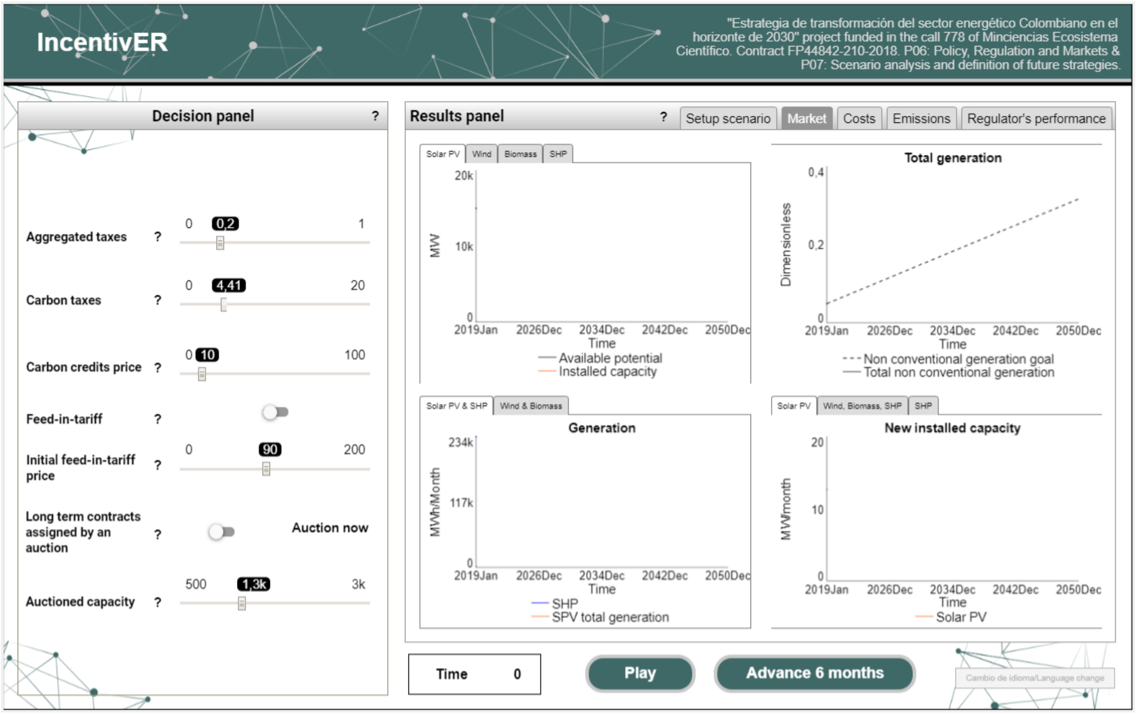


__Figure H-9:__ Microworld's market window.

Source: Own elaboration.

- *Costs window*

In this window, you will see the results for the unit investment costs, the total new installed capacity costs for each technology, the incentive's costs, the spot price comparison, the aggregated taxes, and the comparison between the LCOE and the electricity price.

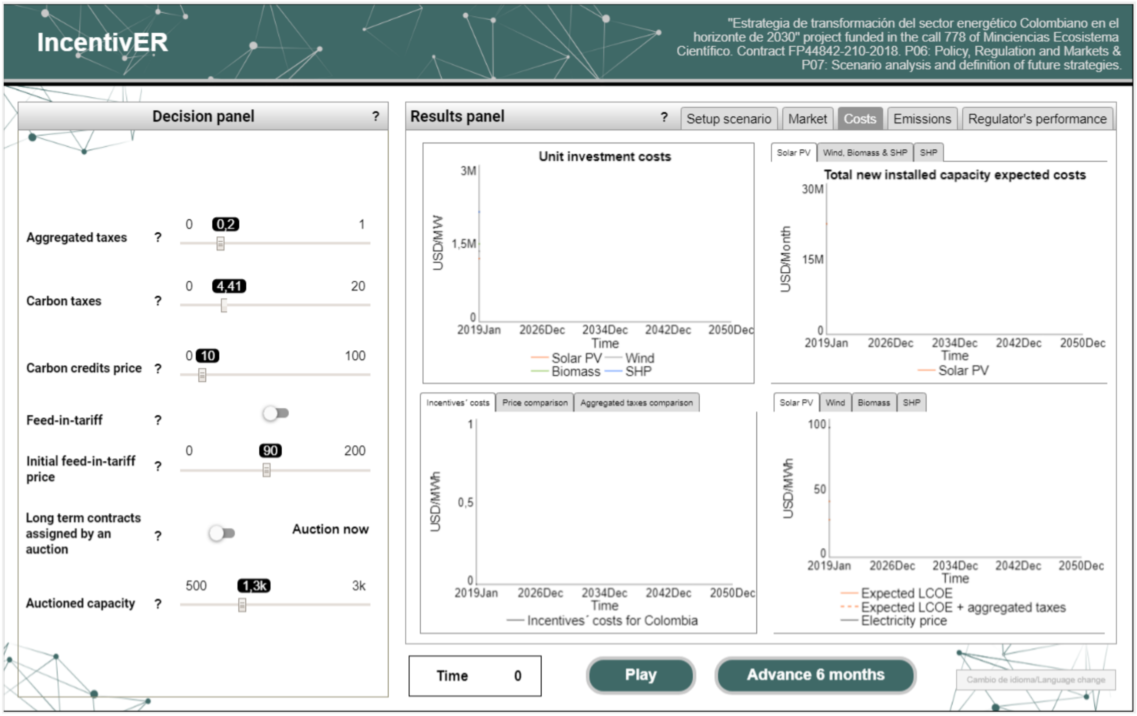


Figure H-10: Microworld's costs window.

Source: Own elaboration.

- *Emissions window*

In this window, you will see the generation share of each technology, the total emissions compared to the goal, and the emissions for a scenario without non-conventional renewable energy. Also, you will see the carbon tax comparison, the savings, or expenses of GHG emitting technologies due to the carbon taxes, and finally the carbon market incomes for non-emitting technologies.

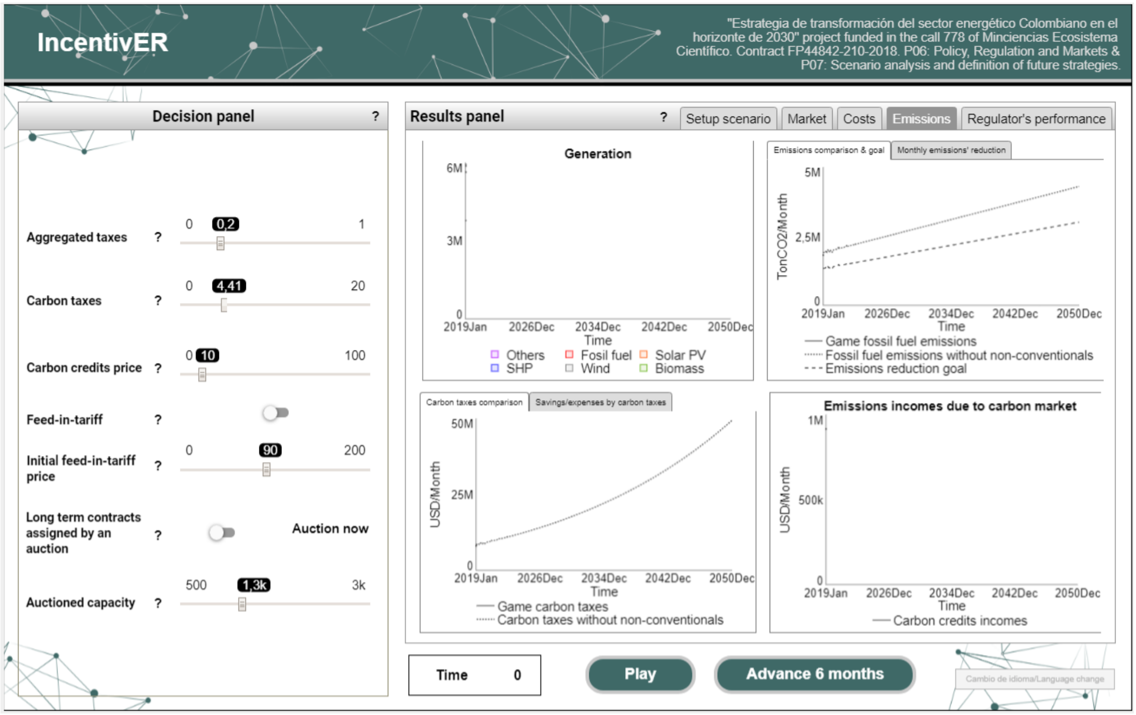


Figure H-11: Microworld's emissions window.

Source: Own elaboration.

- *The regulator's performance window*

In this window, you will see the changes made during the game as well as the regulator's performance and its limit.

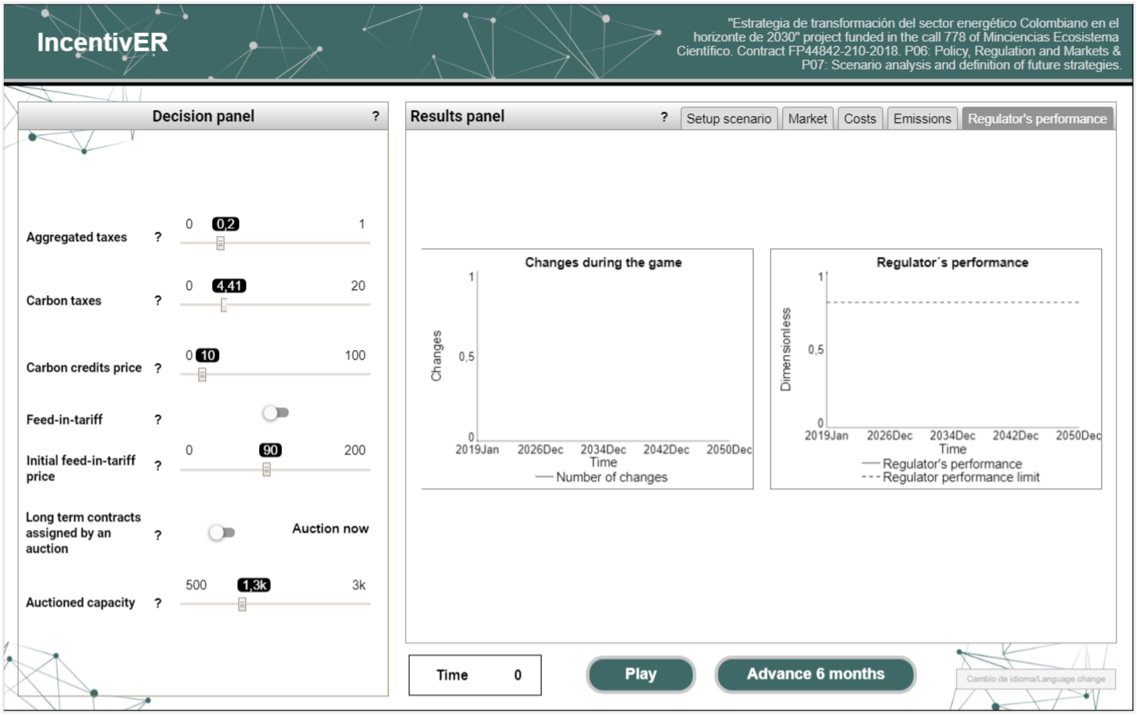


Figure H-12: Microworld's regulator's performance window.

Source: Own elaboration.

During the game, you can navigate through the different windows to see the behavior of each variable as time advances.

<u>¡From now on you can start making your decisions to reach the goals!</u>

iii. The results

When you have finished playing you will continue to the results window. In this section, you can review your results for all the variables of the game, and you can check again your preset scenario.

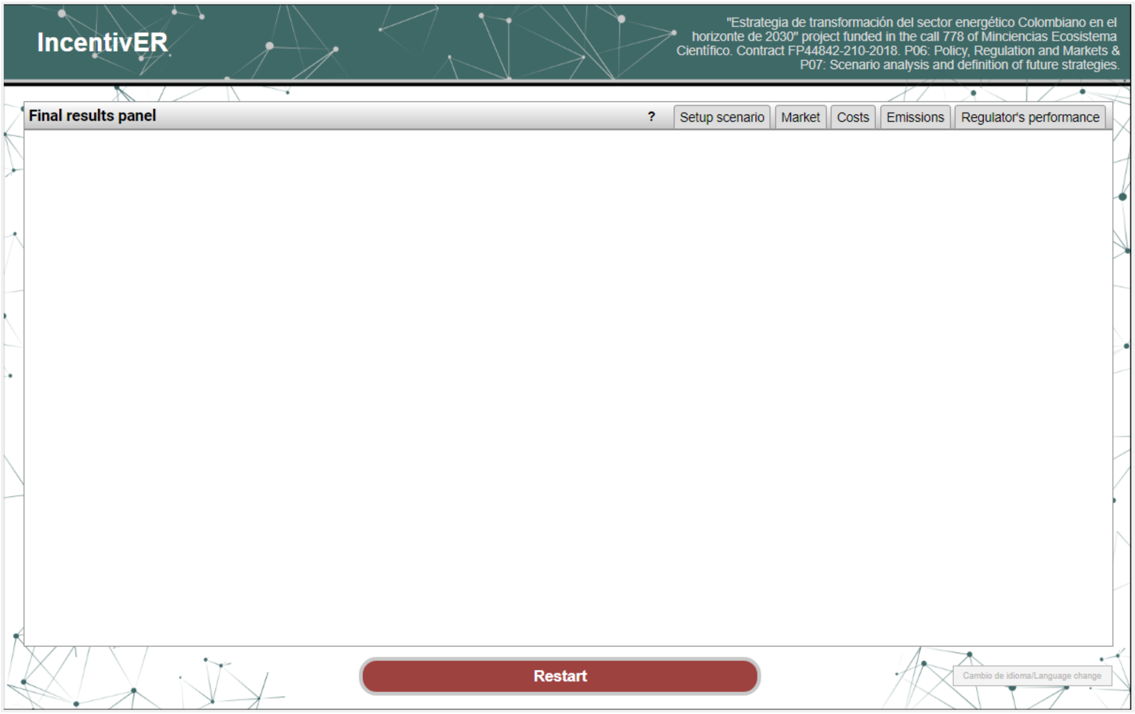


Figure H-13: Microworld's results panel.

Source: Own elaboration.

When you are ready to check your results, you can restart the game or finishing playing.

¡If you are done playing, please read the following assumptions and key lessons!

Game assumptions

i. In this game. the price is settled as an input scenario, not as a result of a daily trade between electricity supply and demand, as usually happens in real markets.

ii. Some incentives as the long-term contracts (auctions) are simplified. This game only considers the auction from the generator perspective (who sells energy) and does not include the marketer role (who buys energy).

iii. The uncertainty of the generation (e.g., water availability and wind speed) and the demand are smoothed in this game by using an average plant factor for every technology, based on the time used for turning on and off the technology and climate factors such as the sun and water availability.

Key lessons after play

The diffusion model and feedback effects for renewable energy in Colombia

The underlying model in the microworld is a modification of the F. Bass (1969) model for the adoption of new products. In this work, the new product is the installed capacity of each renewable energy technology, assuming that its cumulative capacity will follow an S-shaped curve over time. As shown in the following figure, the available potential of the new technology is exploited through the installation of new capacity, which becomes accumulated installed capacity

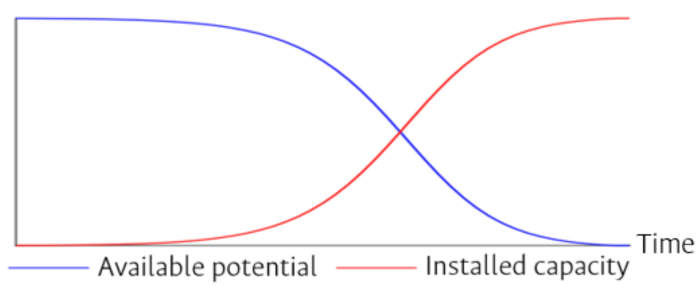


Figure H-14: Expected diffusion behavior.

Source: Own elaboration based on (Bass, 1969).

To explain the expected behavior of the diffusion of the new technology shown in **Figure H-14**, we present the causal loop diagram of **Figure H-15**[4]. This diagram shows the feedback loops of the system, and we focused on innovation and imitation loops as the main ones.

[4] If needed, see the appendix for an explanation of system dynamics diagrams.

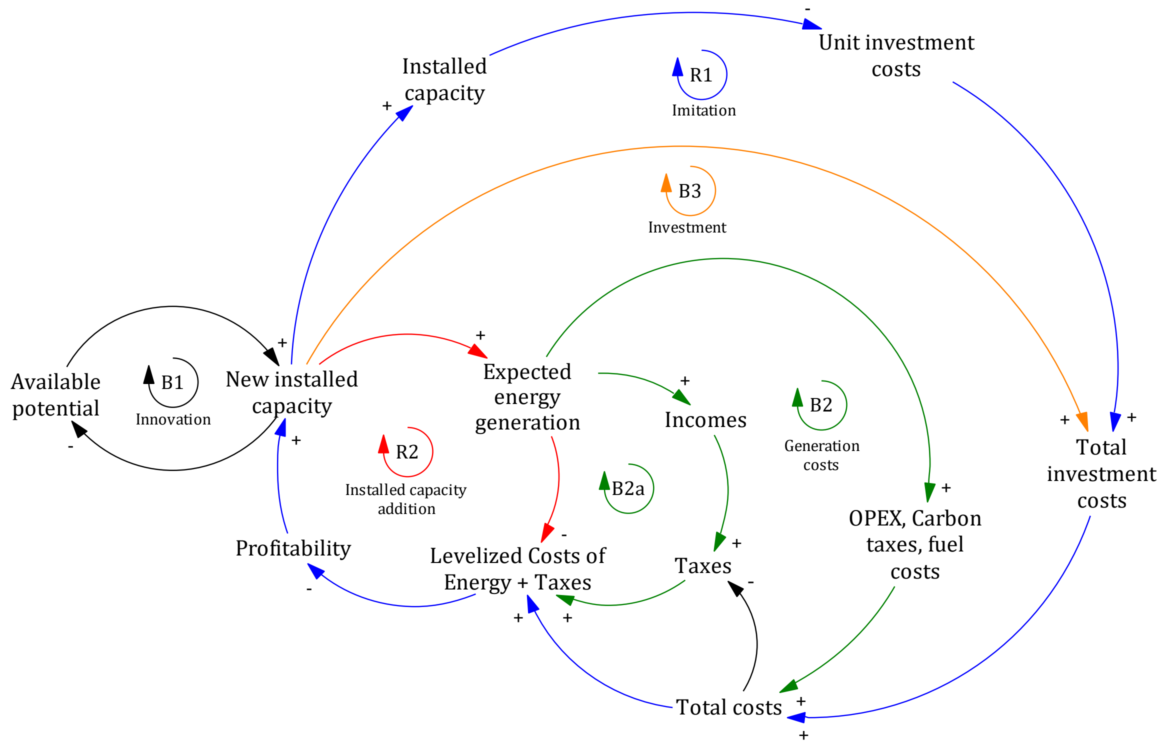


Figure H-15: Microworld's simplified causal loop diagram.

Source: Own elaboration based on (Arias-Gaviria et al., 2019).

The innovation balance loop generates a reduction in available potential as new capacity is installed, while the imitation reinforcement loop generates an increase in installed capacity. The change in the installed capacity is due to the decrease in investment costs associated with a learning curve (see **Figure H-16**). As the installed capacity increases, the unit investment costs decrease, the LCOE decreases, and thus the investment in new capacity becomes more profitable.

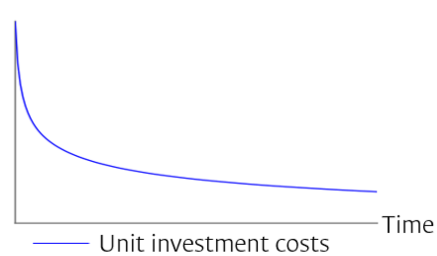


Figure H-16: Unit investment costs behavior.

Source: Own elaboration based on (Arias Gaviria, 2014).

The system has an investment limit represented by the loops of investment and generation costs. As more energy is generated, the plants have more operation and maintenance costs and carbon emissions costs (for fossil-fuel generation). Also, the higher the generation, the more income will be obtained, and the aggregated taxes will increase. On the other hand, as more capacity is installed, investment costs will increase.

The new capacity can be installed by two factors: (i) the innovation rate, which represents the installation of the available potential due to the investment in new technology alternatives, and (ii) the imitation rate, which increases the installation of the available potential due to an attraction effect generated by the existing installed capacity (See **Figure H-17**).

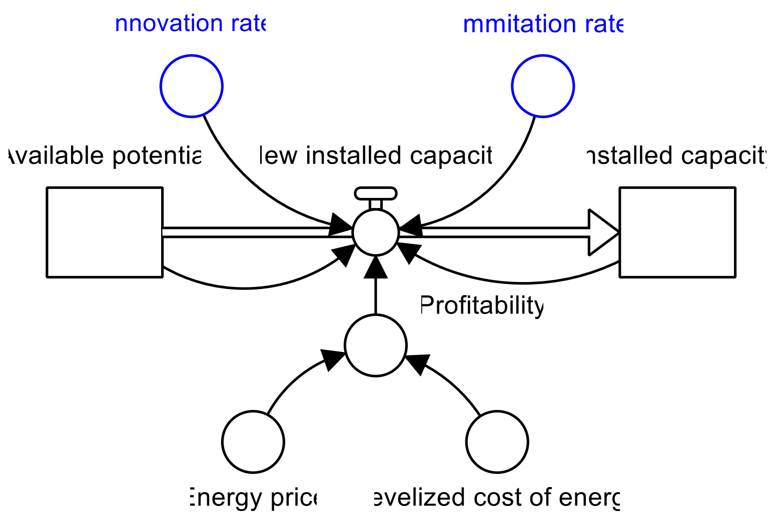


Figure H-17: Microworld's simplified stocks-and-flows diagram.

Source: Own elaboration based on (Arias-Gaviria et al., 2019).

For this work, we modified the Arias-Gaviria et al. (2019) model that enhances the imitation rate according to the profitability of the new capacity installation. We improved the modeling of the profitability, and we modeled it as the ratio between the Levelized Cost of Energy (LCOE) and the energy price. The price includes the market's price and the additional payments obtained from incentives to renewable energy. We also considered the expected profitability of the new capacity as a decision-making factor for building a new plant.

Appendix

i. Causal loop diagrams

Causal loop diagrams are a tool to explain causal relationships between variables in a model. These diagrams have great advantages since they allow a simple understanding of the behavior over time of a target variable in a model. This is done from a graphic representation of feedback loops, generated from the interactions of the model variables, which may also have delays in the effect of one variable on another (J. Sterman, 2000).

The interactions of the model variables are represented by connecting arrows, the direction of the arrows indicates how the diagram should be read. At the tip of each arrow, there will be a positive or negative sign (+ or -), this indicates if the link between the variables is a reinforcement or a balance. In a simplified way, what the variable located in the tail of the arrow (cause) causes on the variable at the tip of the arrow (effect).

In general, the link is defined as follows (J. Sterman, 2000):

- Positive (+): if both variables (cause and effect) have the same behavior (increase or decrease).
- Negative (-): if the cause increases and the effect decrease or if the cause decreases and the effect increase.

To explain the interactions of the variables, we will see the relationship between available potential and New installed capacity (**Figure H-18**). First, the positive sign means that there is a reinforcing link, the greater the available potential, the greater the new installed capacity. On the other hand, the negative sign means there is a balanced link, the greater the new installed capacity then the lower the available potential, in this example a balance loop is generated.

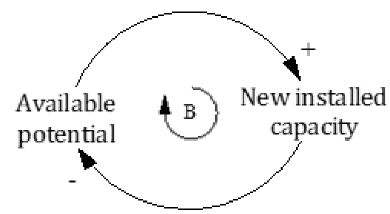


Figure H-18: Balance example loop.

Source: Own elaboration.

Another example is the relationship between the profitability, the new installed capacity, the energy generation, and the *LCOE* (**Figure H-19**), in this case, we have a reinforcing loop because if you make a change in any variable of the loop, and follows that change, the result is in the same direction as the initial change. Let´s see: if the energy generation increases, the LCOE decreases, then the profitability increases, the New installed capacity increases, and the energy generation increases. We start with an increasing change and the final result was an increase.

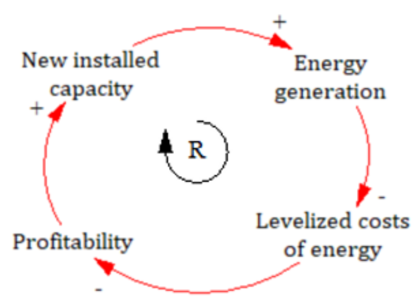


Figure H-19: Reinforcement example loop.

Source: Own elaboration.

The feedback loops of a model can be reinforcement or balance, to define the polarity of a cycle there are two methods:

1. Count the number of negative links: if the number of negative links is odd, then the loop will generate a balance (**Figure H-18**), if the number of negative bonds is even, then the loop will be reinforcing (**Figure H-19**).

2. Tracking the effect of the change around a loop: Variation is made in some of the variables of the loop and its effect is followed through the other variables in sequence, if upon reaching the original variable it has been self-reinforced, the loop constitutes a reinforcement, otherwise, if the effect when returning to the original variable is opposite to the variation made, the loop will be a balance. This method works from any variable in the cycle.

ii. Stocks-and-flows diagrams

These diagrams represent the cumulative variables and flows of a system. The flows and stocks represent systems of coupled differential equations.

The variables are the following:

- *Levels:* Cumulative variables (state variables) represented by rectangles.
- *Flows:* The inputs and outputs of the levels. Represented by valves.
- *Connectors:* Useful to establish relationships between variables. Represented by arrows.
- *Auxiliaries:* Variables that contain useful equations for the model. Represented by circles.
- *Parameters:* Variables that contain constant values of the model. Represented by a rhombus.
- *Sink/sources:* Variables that establish the limits of the model. Represented by a cloud.

I. Microworld's session instructors' guide

Abstract

The speed of changes in the policies and agents of the energy system in Colombia is a conflict when it comes to understanding such a complex system. This microworld is designed for learning and understanding the dynamics of diffusion of renewable energy technologies in Colombia, and the effect of different incentive policies in such diffusion. We used system dynamics for developing the underlying model of the microworld as a tool to understand the behavior of the available potential and the installed capacity of different electricity generation technologies in Colombia. With the diffusion model, we develop an online platform - microworld - in which the users can play and test different incentives to renewable energy and learn about the systems underlying structure and operation. The game is designed to be played by university students to senior business and government officials. Here we explain how to set the game and how to teach a class with the game, including a briefing and a debriefing.

The renewable energy microworld is an online open-access game in which players seek to promote the installation of new renewable capacity using incentives. The game exposes the players to the electricity market dynamics, a complex system with multiple interactions, and constant changes. The current version is an interactive, web-based simulation, available at https://exchange.iseesystems.com/public/santiagoarango/incentiver and with complementary material, available at https://www.energetica2030.co/micromundo/. The renewable energy microworld is a dynamic game in which players have the role of the electricity market regulator, the players seek to reach a goal for share generation to cover a percentage of the demand and an emissions reduction through the years.

The game's interface provides the players with the definition of most of the variables, to provide a better understanding of the electricity market. During the first part of the game, the players must set a scenario for the game, in which they can change the electricity price and the learning rate for the investment costs for every non-conventional renewable technology. Then the players continue playing with a timestep of six months. In every timestep until 2050, the players can make decisions about incentives for non-conventional renewables.

1. Setup and player briefing

In this part, we will provide the necessary tools for the development of a microworld session. This part contains the key lessons for playing the microworld, and they are included in the planned session on the briefing part. Also, this section contains the recommendations before running the game, the timing plan for the session, and the briefing with keynotes and suggested comments. We provide some commonly asked questions and proposed responses as well as pilot testing results as expected results for the participants.

As we know teachers and facilitators are also new users, we recommend you to firstly check the users' guide for the microworld, with which you can understand the platform functionalities. We suggest you providing the students the same user guide and complement it with the login and simulation orientation.

1.1. Key lessons

The renewable energy microworld creates the opportunity for people to learn different lessons about the electricity market, and with the complementary tools, such as the briefing and the debriefing, they can learn about other disciplines like system dynamics and technology diffusion models.

1.1.1. Technology diffusion in the electricity market

The installation of new capacity specifically for the microworld, of non-conventional renewable technologies, follows Bass's (1969) diffusion model. Assuming that the available potential and installed capacity are cumulative values, and both follow an S-shaped curve over time, the available potential is exploited to generate new installed capacity and become the accumulated installed capacity. The diffusion consists of the innovation and the imitation to go from available potential to installed capacity. The innovation parameter is constant, but the imitation parameter depends on the confidence that the investors have in the regulator. The higher the confidence, the higher the imitation rate. Also, the diffusion depends on the expected profitability for the installation of new capacity, if the technology is profitable (higher than 1) then, the installation occurs. To know if the installation is profitable or not, we used the Levelized Cost of Energy (LCOE) compared with the electricity price. When the price is higher than the LCOE, the technology is profitable, and the installation will occur All of these interactions are described in **Figure I-1**.

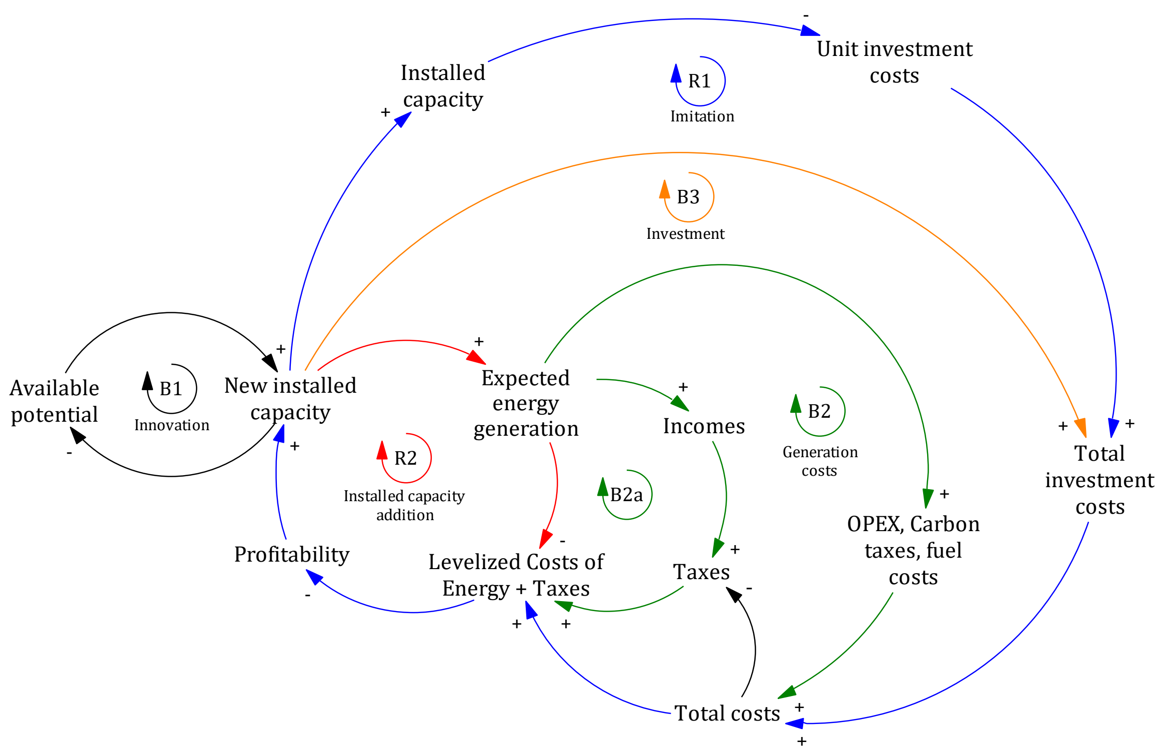


Figure I-1: Microworld's simplified causal loop diagram.

Source: Own elaboration based on (Arias-Gaviria et al., 2019).

1.1.2. Feedback effects in the system

The microworld contains feedback loops that show how the installation of new capacity depends on the decisions of the player, and also the change on the installed capacity affects different factors such as the investment costs, for example, if the installed capacity grows due to the decisions of the player, the investment costs will reduce as a consequence of learning, the total costs will reduce, and the technology will be more profitable, generating a reinforcement loop.

1.1.3. Energy and power

The microworld contains some energy and power fundaments and variables such as installed capacity and total generation, in some cases, it might be necessary to explain the difference between them, depending on the background of the students or users.

Energy and power are closely related but are not the same, the energy is the capacity to do work, which means that is the power integrated over time. On the other side, power is the rate at which the work is done, or the energy is transmitted. For example, a light bulb has a power of 60W, but if you left it on for 30 days, then it will have an energy consumption of (Campbell Allison, Jenden James, 2014):

$$60W * 30da * 24h/da \; = \; 43{,}200 \; W/h \; or \; in \; most \; commonly \; units \; 43.2 \; kWh$$

1.2. Before you run a game

Before you run a game, it is recommendable to teach a lesson on system dynamics and the operation of the electricity market. The game briefing contains all the variable definitions needed to understand the game and play, but a previous lesson will make the experience better.

To start a class, you will need an internet connection and a computer for every player.

1.3. Class plan for a session

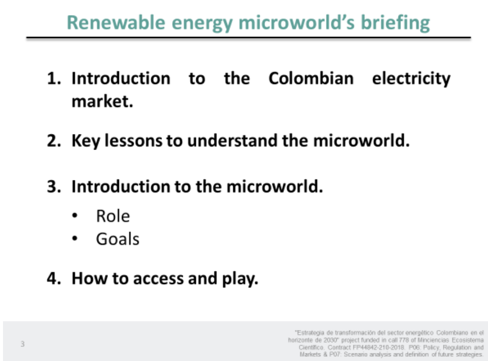
1.3.1. Time

The majority of the sessions are run in one class. Introducing and playing the game usually takes about two hours. Debriefing the game can take another hour. As a result, the game can be played in a single 3 hour session.

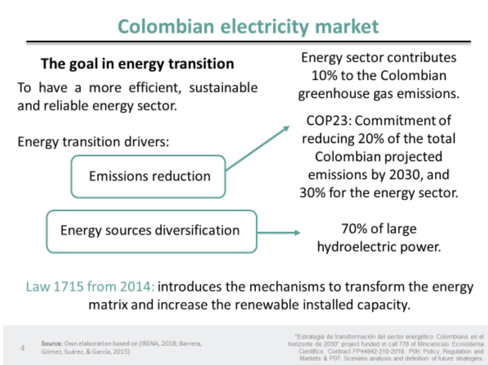
1.3.2. Briefing

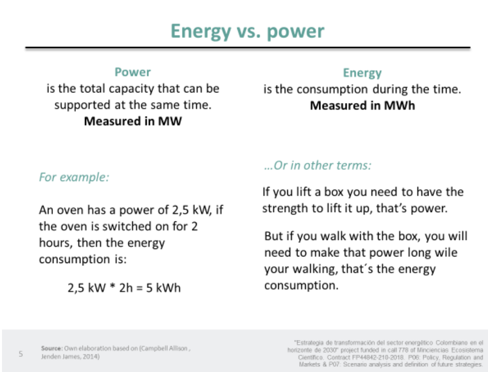
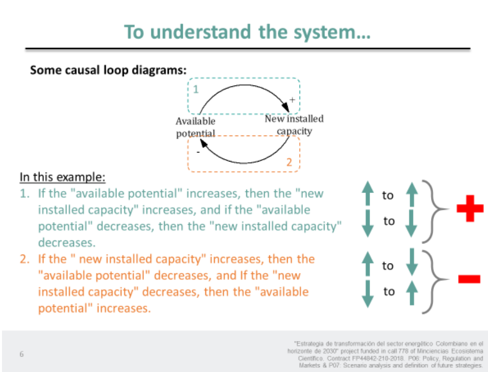
The next slides are available online for instructors and users. Walking through these slides usually takes about 40 minutes.

Table I-10: *Briefing slides.*

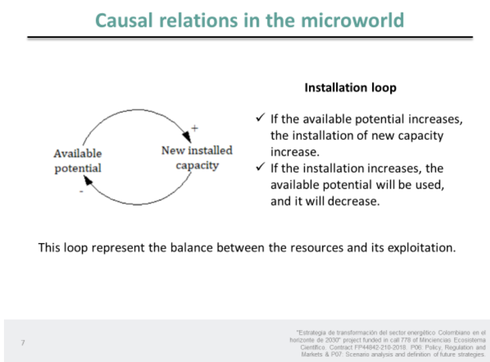
<table>
<tr><th>Slide</th><th>Keynotes and comments</th></tr>
<tr><td>
</td><td>The players are usually waiting to start, so you must keep the introduction simple:

For example:

Welcome to renewable energy microworld. In this game, you will play as the regulator of the electricity market and you have to promote renewable energy. We are playing this game to understand the dynamics of the diffusion of non-conventional renewable energy in Colombia. Today we are going to see if you can manage the challenges and reach the goal for the game. let´s see how the game works first, so you can understand the system and the decisions you have to make.</td></tr>
<tr><td>
</td><td>Depending on what is appropriate for your audience you can ask them what do they know about the electricity market, then emphasize on the complexity and difficulties to understand how does the market works, taking into account that all of that happens so fast, that even experimented market actors can´t understand it all.</td></tr>
</table>

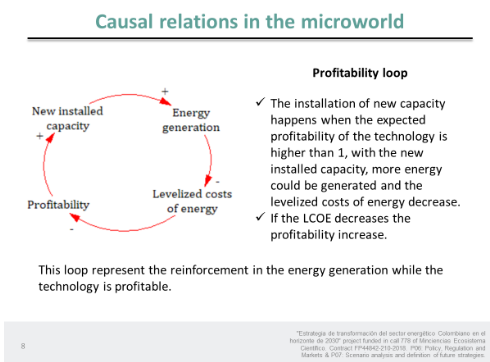
Slide	Keynotes and comments
	In general, is difficult to understand the difference between energy and generation, so in this slide, you can explain the difference between those terms. Power is the capacity that can be supported at the same, and energy is the consumption during the time. You can also add a practical example, such as the ones mentioned in the slide.
	Make a short review of system dynamics, to facilitate people to understand the next slides. You can use the following example for causal loop diagrams: *As the birth rate increase, the population in a country will increase, and also if the population increase, the birth rate will increase, generating a reinforcement in the loop, that means that any change you made in a variable in the system will generate the same effect of change at the end of the loop.* You can add: *If you start the loop in any variable and with any change (increasing or decreasing) the loop will be the same, for example in population one, if you start decreasing the population, then the birth rate will decrease, and in consequence, the population will continue decreasing. So, you have the same change at the end and the beginning. If the change is the opposite, then it is a balance loop.*

Slide	Keynotes and comments



Some slides like this one, explain the loops on the underlying model of the microworld.

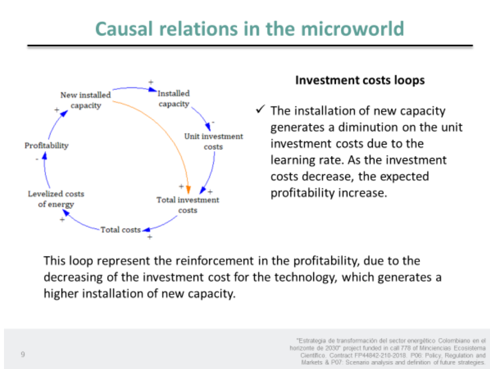
In this one, you can explain how the installation of new capacity happens, following Bass´s diffusion model.



For the profitability loop, you can explain how the LCOE works.

For example:

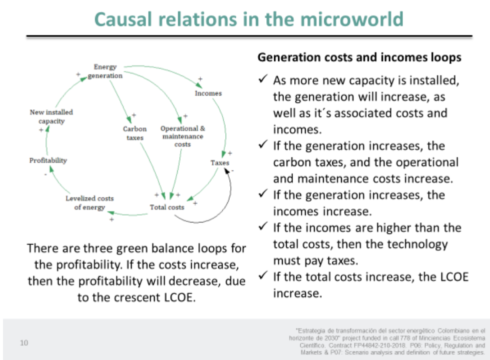
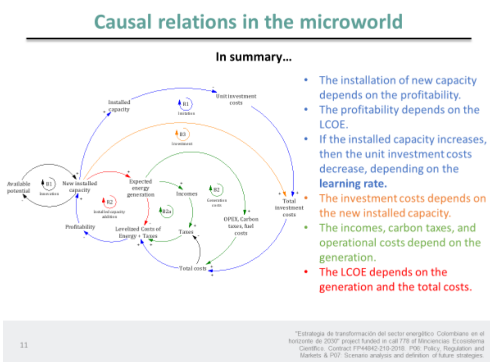
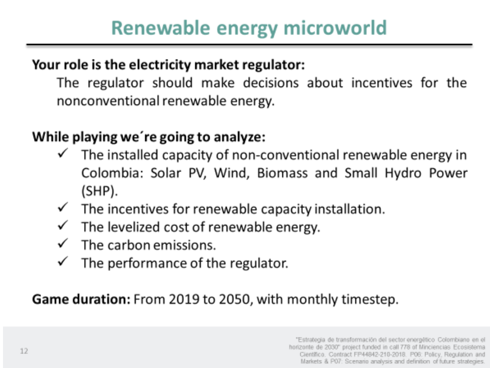
The LCOE is the cost per generation unit during the lifetime of the technology, which means, if the LCOE is lower than the electricity price, the investors will have the confidence to invest because the installation will be affordable.



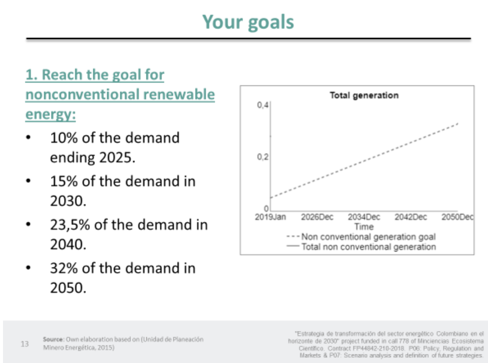
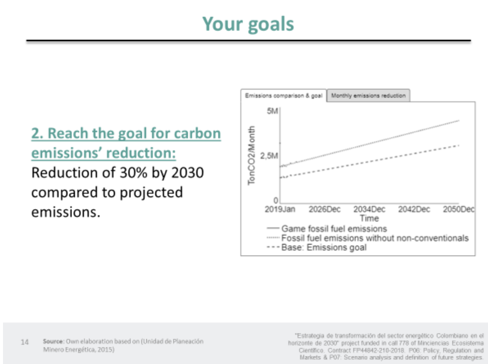
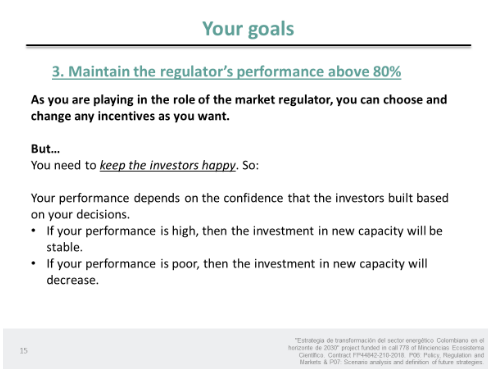
For the investment costs loop, you can explain how the learning rate works.

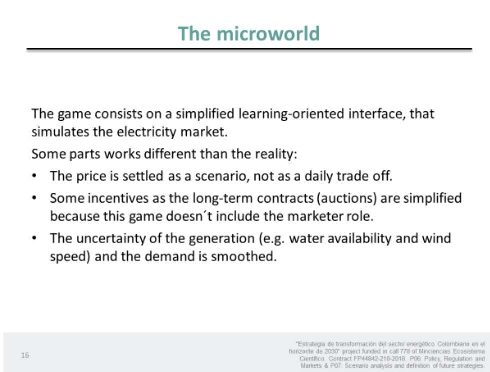
For example:

The investment costs for a technology depends on the amount of installed capacity and the learning rate, which means, when you know the technology and it becomes more popular, it becomes cheaper, as some products in the economy. So, if the learning rate is higher and the installed capacity grows, the investment becomes more accessible, increasing the installation of new capacity and generating a reinforcement loop.

<table>
<tr><th>Slide</th><th>Keynotes and comments</th></tr>
<tr><td>
</td><td>The costs for the generation of electricity are the operational and maintenance costs, but there are other costs involved in the generation, like carbon taxes, and the aggregated taxes.
For the LCOE calculation, we consider the investment, operational and maintenance, the carbon taxes, and the total generation, but for the installation decision, is also considered the aggregated tax.</td></tr>
<tr><td>
</td><td>Finally, this slide shows the general causal loop diagram, and each color explains the causal loops previously described. It is recommendable to make a summary of the principal relations to make people remember it.</td></tr>
<tr><td>
</td><td>By this slide, you can start saying by telling the players that this is the game introduction. First, describe the player's role as the electricity market regulator. You can explain the work of the regulator for the game as the person who decides which incentives for promoting renewable energy will be active and how long it will work.

Then you can say that the purpose of the game is to analyze the dynamics of the installed capacity, the LCOE, the carbon emissions, and the players' performance in the game. Comment that the players will have specific goals, but that is important to understand the underlines of the model.</td></tr>
</table>

Slide	Keynotes and comments
	Finally, tell the players that the game will last until 2050, and they can make timesteps of 6 months or go directly to the end of the simulation.
	Describe the goal for the total share of non-conventional renewable energy in Colombia, settled as 10% of the generation in 2025, 15% in 2030, 23.5% in 2040, and 32% in 2050. And tell the players that in the game they could see the renewables generation goal every time.
	Describe the goal for emissions reduction, as a reduction of 30% of the projected emissions for 2030. Also, the graph shows the emission without any non-conventional renewable energy, to provide the players' analysis point.
	For this slide, you can start explaining to the players what the regulator’s performance is. The regulator’s performance consists of the confidence that the investors have over the regulator of the electricity market. This performance will depend on the number of changes that the regulator makes over time. If you make five changes every timestep, then the regulator´s performance will decrease, and the investors will reduce the installation of new capacity. This behavior is based on the expected stability of the investment.

Slide	Keynotes and comments
	In the game, the regulator's performance will affect the amount of new installed capacity due to imitation.
	In the final slide of the briefing, you can introduce the players to the microworld interface, and explain that the game is simplified for learning purposes. There are some assumptions, as the price setting, the incentives, and the generation, as is shown in the slide.

Source: Own elaboration.

1.3.3. Game assumptions

i. In this game. the price is settled as an input scenario, not as a result of a daily trade between electricity supply and demand, as usually happens in real markets.

ii. Some incentives as the long-term contracts (auctions) are simplified. This game only considers the auction from the generator perspective (who sells energy) and does not include the marketer role (who buys energy).

iii. The uncertainty of the generation (e.g. water availability and wind speed) and the demand are smoothed in this game by using an average plant factor for every technology, based on the time used for turn on and off the technology and climate factors such as the sun and water availability.

1.3.4. Log in and simulation orientation

In this part, you must log in to the microworld and invite the players to do it too. The link to access directly is:

https://exchange.iseesystems.com/public/santiagoarango/incentiver

The players start the game by filling a short registration form and then clicking on the start button. You can provide them the users' guide, which includes instructions on how to use the microworld and all of its functionalities. Also, it is recommendable to make some practice runs to let the users familiarize themselves with the interface and the platform functions. *Estimated time: 20 minutes.*

We propose some practice runs as follows, you can use all of them or you can select the ones you prefer:

i. *Preset setting runs:* In these runs, you must skip the initial setting window as it is and let the game settled with the preset scenario. The scenario setting is easier to understand when players have already dealt with the decisions during the game, so the first practice runs will explain how to make decisions on incentives.

   In this practice run, you can tell the players the platform functioning and components such as language change setting, question marks, how to visualize the microworld windows, and how to advance by timesteps or to the final results.

   - *Aggregated taxes run:* Change the aggregated taxes value and check the results. In particular, for this change, you can check the incentive costs, the aggregated tax comparison, and the regulator's performance. The usual results show that if the aggregated taxes are high, then the installation of the new capacity is not that profitable because the electricity price is lower than the total costs per unit.

   - *Carbon taxes and carbon bonds:* Change the value for the carbon taxes and carbon bonds, in particular, you can check the results for the carbon tax comparison, and the savings and spending are due to carbon taxes. The usual results show that if the carbon taxes and the carbon bonds are high then the technologies become more profitable due to the reduction of the share generation of fossil fuel technologies, and to the extra incomes because of the carbon bonds.

- *Auctions:* the model includes Long term contracts auctions, the players can auction a specific capacity, you can make some auctions during the time, and analyze the delay time for the auctioned capacity to start operating, and some results such as the new installed capacity.

ii. *Initial setting run:* in this run, you must set different game scenarios, you can explain that depending on each player, the scenario can vary, but this configuration can only be made at the begging of the game.

- *Price setup:* Show the players how to select different price scenarios, and that they can set their price scenario by accessing to custom spot price and using the customizable graph. Set the price on the preset scenarios and check variables such as the LCOE vs. price, and the speed of the diffusion of every technology as a result of the price changing. You can explain that the regulator's performance will not be affected by the scenario setting.

1.3.5. Expected players results

After the briefing and microworld orientation, the players can start playing by themselves, usually, they take about an hour to familiarize and make different runs. Then they will start trying to reach the goals, and usually, they will focus only on one of the goals. Some pilot testing results show that players usually deal with oscillating regulator's performance, which reduces the investment in new capacity, creating a loop of a decision-making process, trying to reach the goals.

i. Total non-conventional generation goal results:

The results for the total generation goal show that most of the players have dealt with reaching it at the end of the game because at that point the installed capacity has reached a stable point in the S-shaped diffusion curve, so there is no more available potential to install.

In **Figure I-2** row A, the participants focus their strategies on reach the goal, and only one participant could exceed the goal. Rows B and C have different results at the end of the simulation, the players could not reach the goal.

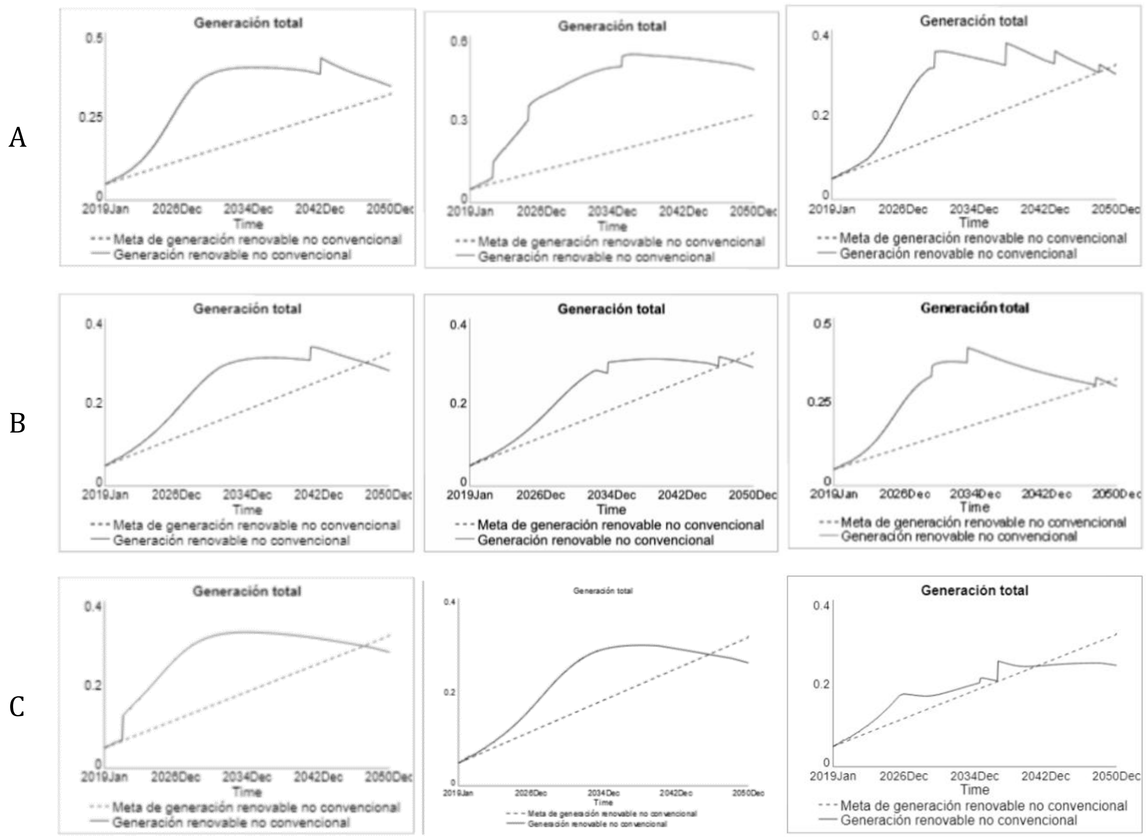


Figure I-2: Pilot testing generation results.

Source: Own elaboration.

ii. Total generated emissions goal

For the emissions goal, we have that most of the participants tried to reach the goal and were able to do it. In **Figure I-3** row A the participants exceed the goal, in row B the participants reached the goal and tried to exceed it, but it was not worth it. And finally, in Row 3 the participants could not reach the goal most of the time of the game, which could be evidence to say that those participants were managing to reach another goal.

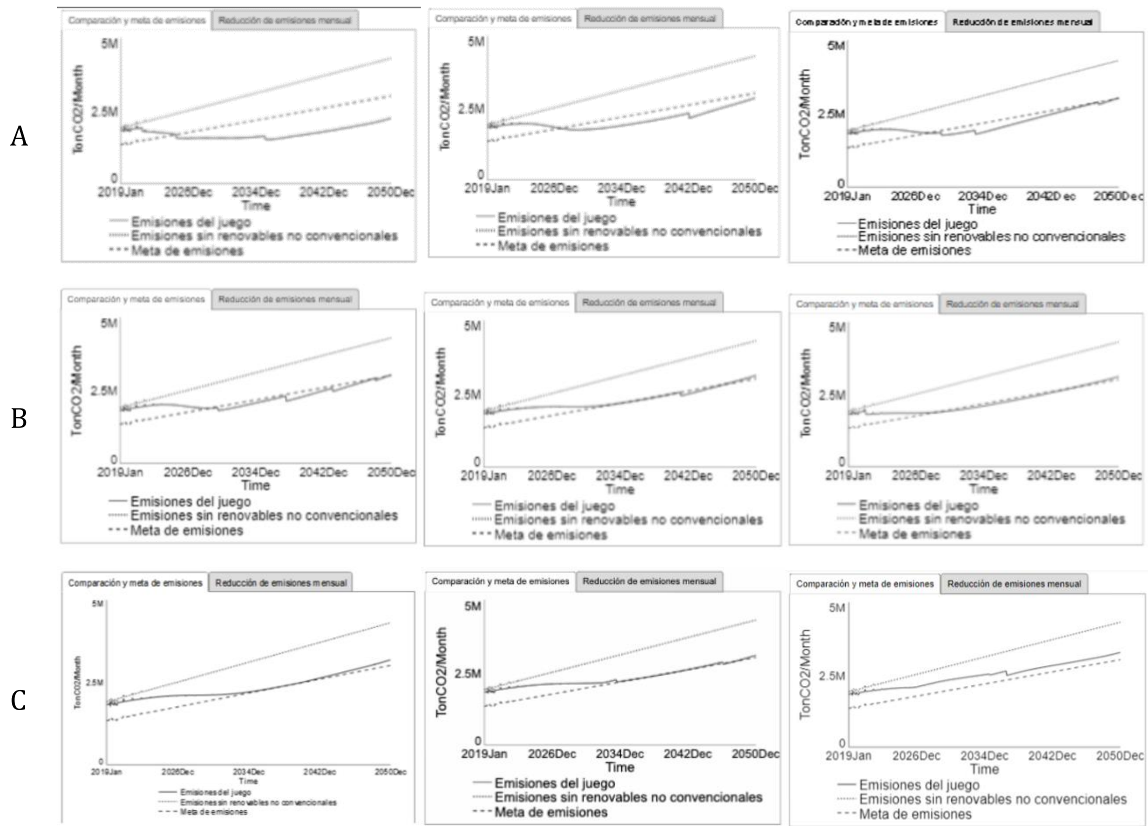


Figure I-3: Pilot testing emissions results.

Source: Own elaboration.

iii. Regulator's performance goal

For the regulator's performance goal, we have three different scenarios. In **Figure I-4** Row A the participants tried to maintain the regulator's performance over the goal, making decisions only when the confidence has increased enough to continue being over the goal, but at the end of the simulation, they start making decisions. Then final decisions making could be evidence for an extra effort to reach other goals at the end of the simulation.

In Row B The participants made a lot of changes in the system in different simulation times, but they could not stay over the goal. Finally, in Row C the participants made a lot of changes at the same simulation time, which made the regulator's performance decrease, and its evidence to say that they had different particular goals.

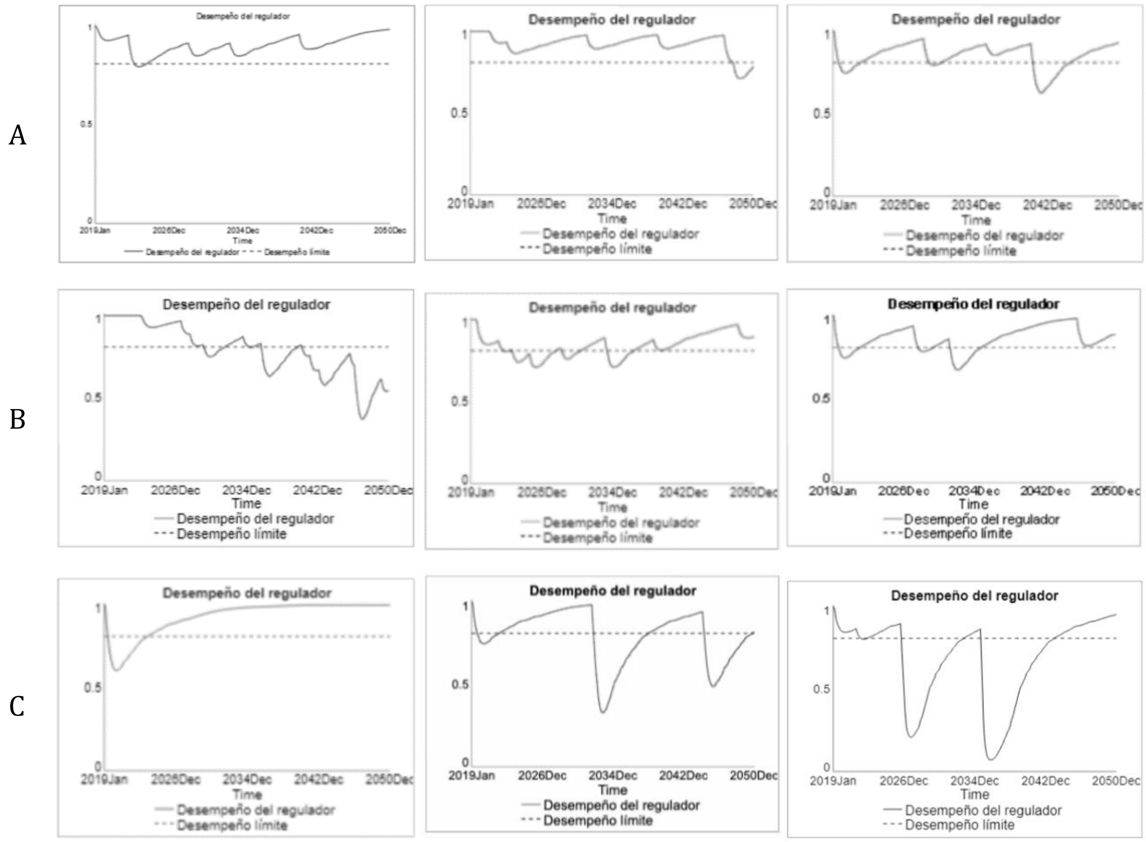


Figure I-4: Pilot testing regulator's performance results.

Source: Own elaboration.

1.3.6. Conclusion

A complete briefing for a microworld session will take about one hour, including briefing slides and log in and simulation orientation. This guide offers the slides with suggested comments and a description of the game lessons that could be used too to complement the final comments for the game. For the session we recommend giving the players the users' guide with anticipation, so they can check it before playing, but it´s not completely necessary. For the session, it is ideal to make the final comments right after playing, but it could be modified, making the briefing, and playing in one session, and the debriefing and final comments in a second session. You can also provide the players with a register sheet, such as the one available in the supporting material, so they could save their results.

2. Debriefing and teaching notes

As a learning-oriented tool, the microworld results have to be discussed with the users to provide them some feedback. We provide some debriefing slides that are oriented to have a conversational analysis of what happened during the game. In this part, we provide some keynotes and comments on the debriefing slides. The microworld debriefing also contains an underlying model debriefing which could be used with specific classes with a higher level of expertise. Finally, we provide an outline for a short debriefing composed of a set of key questions.

2.1. Overview

Start asking the players if they are ready with their runs. Then make a short review of the key messages that are proposed in the next section, about the diffusion of the technology, the incentives, the profitability, the emissions, and the energy demand. Then you can start with the debriefing slides and a conversation about what happened in the game.

2.2. Key messages

2.2.1. Diffusion

The microworlds integrate an adaptation of the Bass's diffusion model to represent the behavior of the available potential and the installed capacity of renewable energy, considering that the imitation parameter is influenced by the price-LCOE ratio and the regulator's performance. This model is based on the adoption of new products and follows an S-shaped curve over time.

2.2.2. Incentives

The player can observe different results depending on which incentives they decide to use. Each incentive has pros and contras because of its involved costs. For example, the long-term contract auctions are a good strategy to promote the installation because it ensures the electricity price, so the technologies have reliability on the profitability during the time. But maintain that stable price involves costs for Colombia and the final electricity users for example when the spot price is lower than the contract price.

In the case of other incentives such as the aggregates taxes reduction, which means an increase in the expected profitability for the technologies, there is also a counterintuitive effect in the costs for the country, because the reduction on the tax collection has to be assumed by the government or by the final users.

2.2.3. Profitability and regulator´s performance

Decision-making processes in the electricity market are complex. When it comes to deciding whether or not to invest in the installation of new capacity, investors consider the profitability of the technology but also the regulatory stability of the country. If the market's regulator makes a lot of changes in a short time, then investors will prefer to "*wait and see" and* postpone the investment until they perceive a less variable environment. In this sense, in the microworld, investors seek that the regulator's decisions are constant, that there is no great variability or changes in the decisions, and that those decisions favor the profitability of the investments.

2.2.4. Emissions and energy demand

The Colombian electricity matrix is relatively clean with about 70% of hydropower generation. (IRENA, 2018a) However, with Colombia's commitments at COP21 to reduce its projected emissions by 2030, including those from the electricity sector by 30%, it is important to diversify the energy matrix to reduce the remaining 30% of fossil generation and its emissions (Barrera et al., 2015). Emissions depend on the electricity demand and the proportion of each type of generation to supply such demand. Considering this, as demand increases over time, it is necessary that the percentage of renewable energy also increases, to replace fossil fuels, reach a cleaner matrix, and reduce emissions.

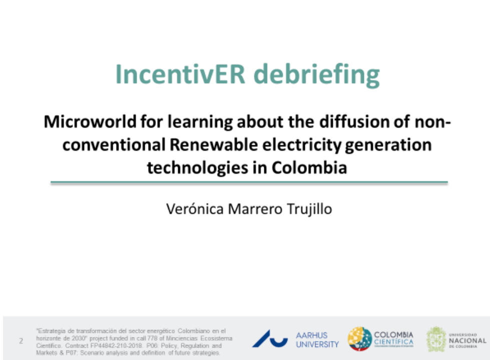
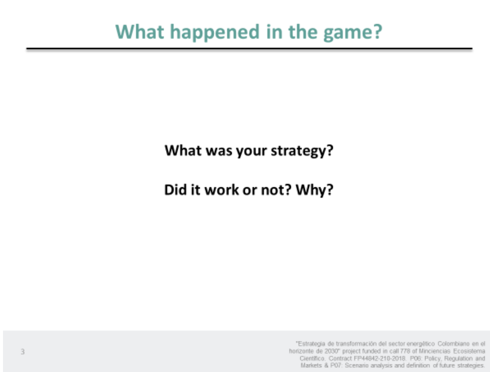
2.2.5. Learning rate

Following Arias Gaviria's (2014) diffusion and innovation of renewable energies are two processes that cannot be separated. Costs reduction increases the diffusion rate, nevertheless, the diffusion must happen to let the innovation continue happening. In the model, the unit investment costs constantly decrease, because of the learning rate. As the installed capacity increases, the unit investment costs decrease, the LCOE decreases, and thus the investment in new capacity becomes more profitable. More profitability closes the loop by increasing, even more, the installation of new capacity. It´s important to know that this costs reduction will depend on all the cumulative installed capacity for each technology, although in real life, it is a worldwide effect.

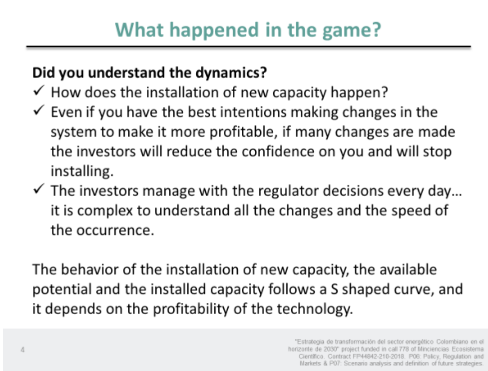
2.3. Keynotes and comments on debriefing slides

We propose the following slides to address the debriefing of the session. You can select the ones you consider appropriate for your audience, your objective, and your time availability. We recommend developing the graphs and causal diagrams mentioned above in the briefing as a complement, carefully on a blackboard, together with the students and interactively, instead of showing them as slides.

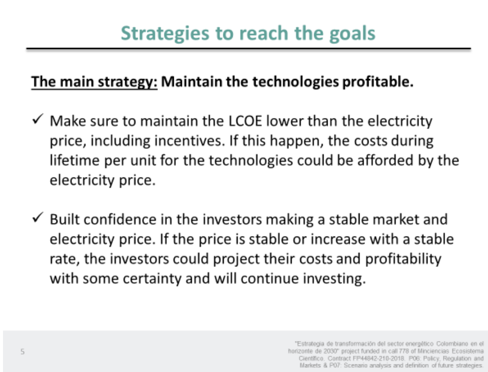
Table I-11: *Debriefing slides.*

Slide	Keynotes and comments
	Begin by asking the players how they felt playing the game, what they thought was going to happen, and what happened. Also, ask if their results were what they expected, and mention that the objective of this debriefing is that they can understand why they had such results.
	To promote feedback and participation you can use some key questions. In our pilot testing, the players often talk about their own goals and how did they reach them, so asking them what their strategy was will allow other players to know how they could reach different goals.

Slide	Keynotes and comments



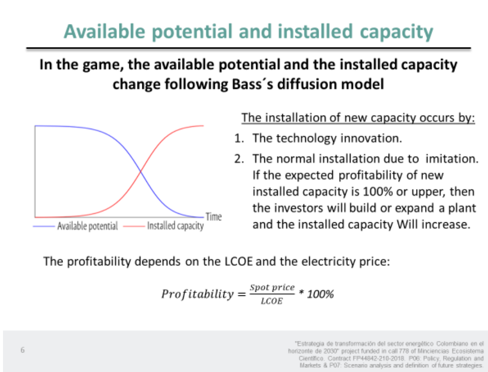
After listening to the different strategies, you can ask them more specific questions on key variables of the microworld, such as the installed capacity and available potential. Also, you can ask them if they were able to maintain the regulator's performance by over 70% while seeking their goals.



Suggest to the players to play again with some strategies such as trying to make the technologies profitable but making sure that the regulator´s performance it´s not been affected.

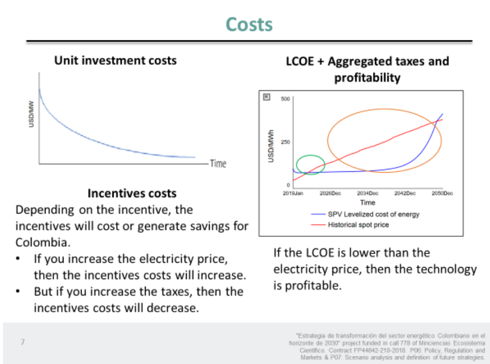
After talking with the players about their experience, you can start giving them some more information about the game's underlying model.

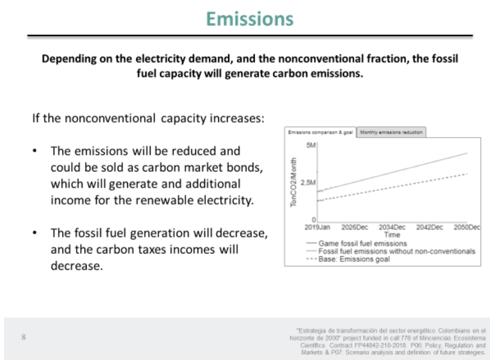
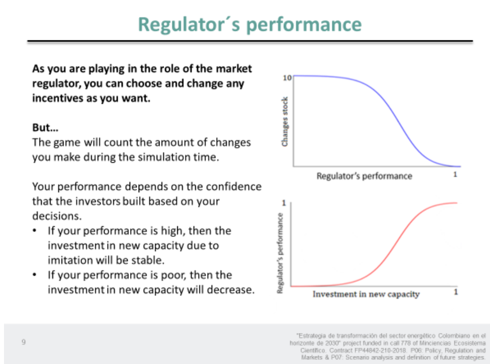
Now you can explain the key variables by discussing each of the windows of the results. It is important to make clear that neither window is independent of the other windows' results.



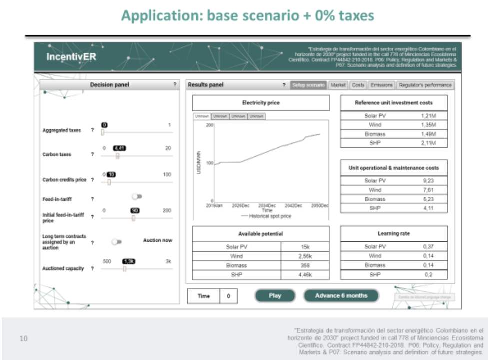
Available potential and installed capacity window:

The model works following Bass´s diffusion model, you can explain it as a bottle of water that is serving on glass: The available potential is the water in the bottle, and the installed capacity ready to use is the water in the glass. Also, there is a flow from available potential to the installed capacity. This flow depends on what is in the bottle and what is in the glass. If the glass is empty

Slide	Keynotes and comments
	and the bottle is full, you can activate the flow, but if the bottle is empty you cannot serve any more water. So, the behavior will be an S-shaped curve, because as the water in the bottle decreases, the water in the glass increases. In the electricity market, the installation depends on the amount of “water in the glass” but also on the expected profitability of the installation.
	**Costs window:** In the microworld, the profitability depends on the electricity price and the costs for each technology. As explained before, if the installed capacity increases, the investment costs decrease, because of the learning rate. Typically, the LCOE models do not consider the effect of taxes. Thus, even if LCOE is lower than the electricity price the technology may not be profitable. The installation decision considers LCOE and the aggregated taxes: If the LCOE + aggregated taxes are lower than the electricity price, then the investors expect that the technology is profitable, and they will invest.

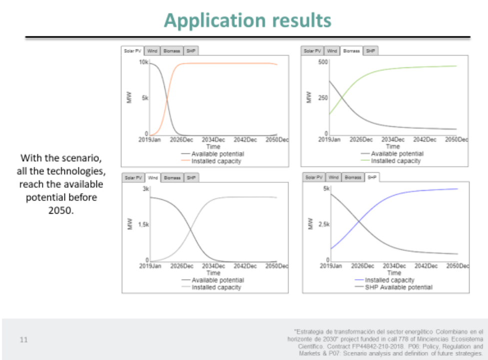
Slide	Keynotes and comments
	**Emissions window:** The total emissions will depend on the installation of renewable energy, because of the renewable share generation that will support the electricity demand. You can talk about the benefits in terms of emissions of the installation of non-conventional renewables, such as the extra incomes due to the carbon bonds, and the extra government incomes in different carbon tax scenarios.
	**Regulator’s performance window:** The regulator’s performance is a non-linear variable that depends on the number of changes that the player makes during the game. If the number of changes is high, then the regulator’s performance will decrease, but there is a *“forgetting factor”* considered, every change is forgotten in 5 years. Also, the regulator’s performance affects the investment in new capacity, if the regulator’s performance is low, the investors will reduce the installation of new capacity.

Slide	Keynotes and comments



Now you can explain specific effects by simulating different application cases:

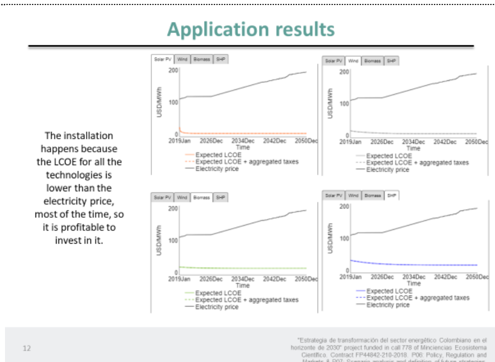
With the application case proposed in this slide, you can show what happened in the game using the base scenario combined with zero aggregated taxes for non-conventional renewables. This scenario presents a great incentive for renewable installation because of the cost reduction.



With the preset scenario, all the generation technologies reach the available potential.

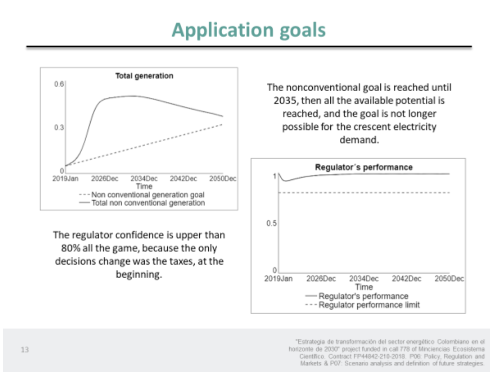
This preset scenario considers the energy potential as the total capacity that could be installed with the current formulated and registered projects in Colombia.

It is noticeable that, in reality, the available potential could increase through the years as new projects are formulated and new potential sites are confirmed.



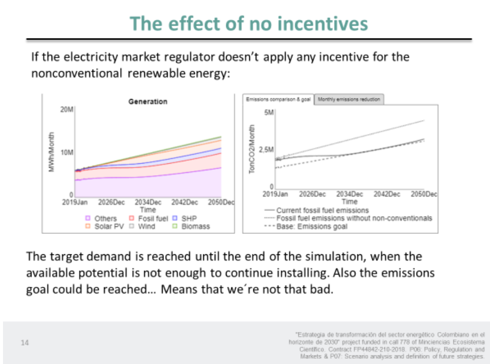
Ask players to remember what was explained in the briefing, if the LCOE is lower than the electricity price, then the technology is profitable, and the investors will install new capacity.

Slide	Keynotes and comments

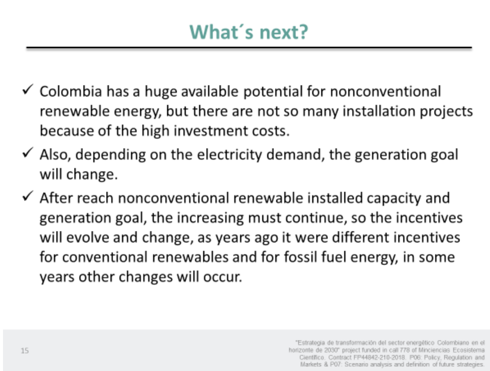


With this scenario, only one decision was made at the beginning of the game: reduce the aggregated taxes to zero.

As a result, the non-conventional generation was over the generation goal because the technology was always profitable, and the installation was not affected by the regulator's performance.



You can also explain a no-incentives scenario, in which the electricity generation will be dominated by conventional renewables (large hydro) and fossil fuels. In this case, the emissions goal could not be reached.



Since this microworld approximates the real system for learning purposes, there are some limitations and simplifications that should be discussed:

- The available potential
- The changing goals.
- The electricity demand increment.

Also, you can mention that the electricity market is always changing, so different incentives could be applied over the years.

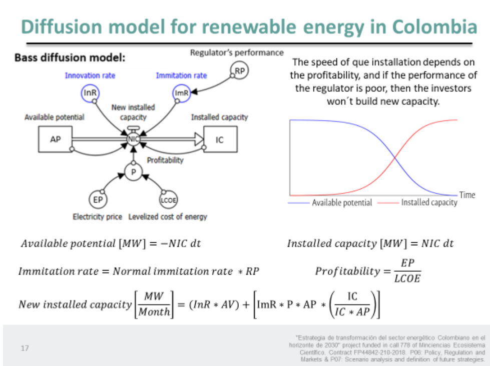
Source: Own elaboration.

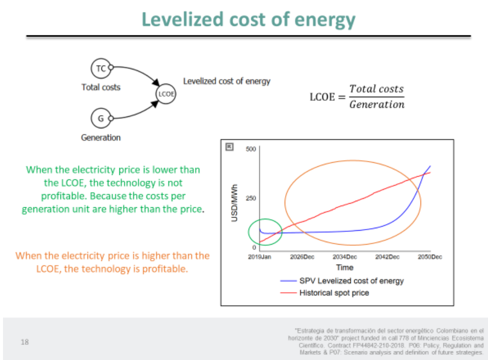
At this point, you can decide if it is useful for the game modeling debriefing for your participants, and you can use the keynotes and comment on the next section to complement the debriefing part.

2.3.1. Keynotes and comments on modeling debriefing slides

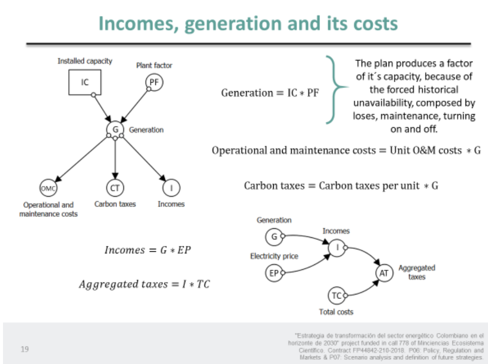
We recommend the use of the modeling debriefing for advanced course players. We also recommend the development of diagrams interactively with them.

Table I-12: *Modelling debriefing slides.*

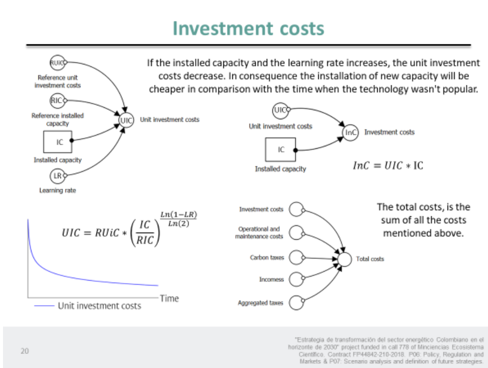
<table>
<tr><th>Slide</th><th>Keynotes and comments</th></tr>
<tr><td>
</td><td>Depending on the participants you can choose if they can understand the underlying model of the microworld. This model will show the mathematical bases of the game.</td></tr>
<tr><td>
</td><td>The first part explains the equation for the Bass diffusion model, modified to include the profitability and the regulator's performance.</td></tr>
</table>



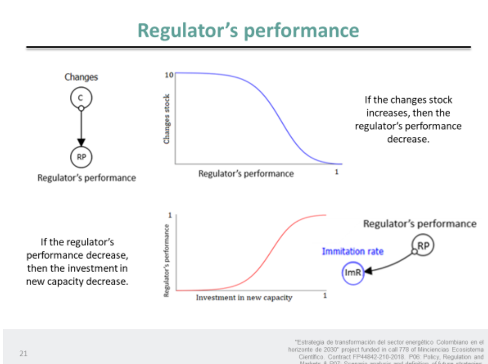
The LCOE equation and the graphical explanation for a non-profitable and profitable technology.



In reality, the generation of renewable energy depends on climate factors, such as irradiation for solar photovoltaic technology and wind speed for wind technology. In this microworld, a plant factor was used to simplify such variations and represent the average availability of the energy resource during the month.



For the investment costs, you can explain the learning rate graph, including the cumulative installed capacity.



The regulator's performance is modeled with a non-linear, graphical function, which behaves as it is shown in the graphs.

Source: Own elaboration.

2.3.2. Outline for a short debriefing

If the time for final comments is limited, we suggest the following questions to making a short debriefing:

Q: How can the non-conventional renewables installation of new capacity be sped up?

In this case, the installation depends on Bass's (1969) diffusion model, which considers two fundamental factors. The first one is innovation; this factor involves everything that is installed as new technology. The second is imitation, in which most of the installation occurs by imitating the technologies that are already on the market. In the microworld, the players have to deal with the installation by imitation.

In this microworld, investors decide to install if the installation is expected to be profitable, which means that the price of the electricity must be higher than the total costs. Among these costs are aggregated taxes, investment costs, operational and maintenance costs, fuel costs, and carbon taxes.

Through the different incentives of the microworld, the players seek to generate a reduction in some costs or increase the installation by ensuring a stable price for the energy delivered to the system (auctions). A good combination of incentives will not only speed up the installation, but also reduce the emissions, reach the renewable generation goals, and keep a low cost for the country (government and citizens).

Q: What if there were no non-conventional renewable technologies on the market?

If the installation of non-conventional renewable generation technologies did not occur, the market would continue to function with conventional renewable technologies such as large-scale hydropower and with fossil fuel technologies. It would not be possible to achieve the goals established in the Paris agreement, on the reduction of emissions from the energy sector, also the diversification of the energy matrix could not happen. Furthermore, it would not increase the reliability of the energy supply, since in Colombia there is a high dependence on the water cycle for energy generation.

Q: What strategies did you use?

Although the objectives of the game are presented in the briefing, each player usually focuses on one specific goal according to their context, and they tend to forget the other goals. Thus, the strategies vary according to the purpose of each player.

Common strategies include constantly running auctions, and reducing costs like aggregated taxes, to promote the rapid installation of new technologies. Other players focused on increasing the value of carbon taxes and the value of carbon bonds to make installation in non-conventional sources more attractive, avoiding incurring tax costs.

Q: What is a responsible strategy?

This question sparks a debate on the nature of responsibility, as some players will focus on diversification of the energy matrix and security of energy supply while others will focus on reducing emissions, as the instructor you can try to reach a consensus between the players, managing to balance both objectives. It is also important to discuss the consequences of over-incentivize, which typically involves a high cost for the country in terms of reduced tax collection or high electricity tariffs for the final user.

2.3.3. Five minutes debriefing summary

End the general discussion in time to make a quick conclusion to the game.

i. Diffusion:

- Depends on the profitability and performance of the regulator.
- It is different for each technology since some may have previously developed S-shaped behavior and had stabilized.

ii. System dynamics:

- The model consists of feedback loops, and all decisions will affect all the variables in the model.

- Like most of the dynamic systems, the electricity market is complex and presents delays, the interaction between agents, and very fast changes. The game includes simplifications to facilitate learning and understanding.

iii. Stability in the system:

- The stability of the system, represented by the regulator's performance, is difficult to achieve, because of the feedback on the decision-making in the game.

J. Microworld's session briefing slides

Renewable energy microworld's briefing

1. **Introduction to the Colombian electricity market.**
2. **Key lessons to understand the microworld.**
3. **Introduction to the microworld.**
   - Role
   - Goals
4. **How to access and play.**

3 "Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.

Colombian electricity market

The goal in energy transition

To have a more efficient, sustainable and reliable energy sector.

Energy transition drivers:

- Emissions reduction → Energy sector contributes 10% to the Colombian greenhouse gas emissions. COP23: Commitment of reducing 20% of the total Colombian projected emissions by 2030, and 30% for the energy sector.
- Energy sources diversification → 70% of large hydroelectric power.

Law 1715 from 2014: introduces the mechanisms to transform the energy matrix and increase the renewable installed capacity.

4 **Source:** Own elaboration based on (IRENA, 2018; Barrera, Gómez, Suárez, & García, 2015) "Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.

Energy vs. power

Power
is the total capacity that can be supported at the same time.
Measured in MW

For example:

An oven has a power of 2,5 kW, if the oven is switched on for 2 hours, then the energy consumption is:

2,5 kW * 2h = 5 kWh

Energy
is the consumption during the time.
Measured in MWh

...Or in other terms:

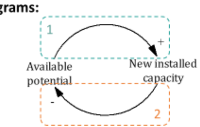
If you lift a box you need to have the strength to lift it up, that's power.

But if you walk with the box, you will need to make that power long wile your walking, that´s the energy consumption.

5 **Source:** Own elaboration based on (Campbell Allison , Jenden James, 2014) "Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.

To understand the system...

Some causal loop diagrams:



In this example:

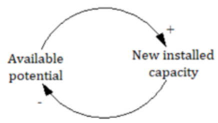
1. If the "available potential" increases, then the "new installed capacity" increases, and if the "available potential" decreases, then the "new installed capacity" decreases.
2. If the " new installed capacity" increases, then the "available potential" decreases, and If the "new installed capacity" decreases, then the "available potential" increases.

↑ to ↑, ↓ to ↓ : +

↑ to ↓, ↓ to ↑ : −

6 "Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.

Causal relations in the microworld



Installation loop

- ✓ If the available potential increases, the installation of new capacity increase.
- ✓ If the installation increases, the available potential will be used, and it will decrease.

This loop represent the balance between the resources and its exploitation.

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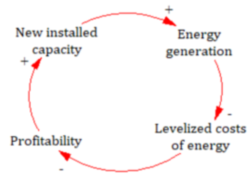
Causal relations in the microworld



Profitability loop

- ✓ The installation of new capacity happens when the expected profitability of the technology is higher than 1, with the new installed capacity, more energy could be generated and the levelized costs of energy decrease.
- ✓ If the LCOE decreases the profitability increase.

This loop represent the reinforcement in the energy generation while the technology is profitable.

8

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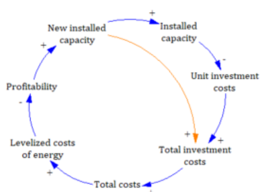
Causal relations in the microworld



Investment costs loops

- ✓ The installation of new capacity generates a diminution on the unit investment costs due to the learning rate. As the investment costs decrease, the expected profitability increase.

This loop represent the reinforcement in the profitability, due to the decreasing of the investment cost for the technology, which generates a higher installation of new capacity.

9

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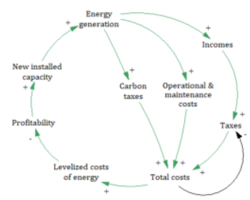
Causal relations in the microworld



There are three green balance loops for the profitability. If the costs increase, then the profitability will decrease, due to the crescent LCOE.

Generation costs and incomes loops

- ✓ As more new capacity is installed, the generation will increase, as well as it´s associated costs and incomes.
- ✓ If the generation increases, the carbon taxes, and the operational and maintenance costs increase.
- ✓ If the generation increases, the incomes increase.
- ✓ If the incomes are higher than the total costs, then the technology must pay taxes.
- ✓ If the total costs increase, the LCOE increase.

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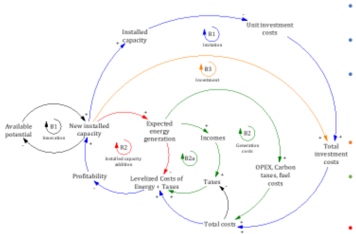
Causal relations in the microworld

In summary…



- The installation of new capacity depends on the profitability.
- The profitability depends on the LCOE.
- If the installed capacity increases, then the unit investment costs decrease, depending on the **learning rate.**
- The investment costs depends on the new installed capacity.
- The incomes, carbon taxes, and operational costs depend on the generation.
- The LCOE depends on the generation and the total costs.

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Renewable energy microworld

Your role is the electricity market regulator:

The regulator should make decisions about incentives for the nonconventional renewable energy.

While playing we´re going to analyze:

- ✓ The installed capacity of non-conventional renewable energy in Colombia: Solar PV, Wind, Biomass and Small Hydro Power (SHP).
- ✓ The incentives for renewable capacity installation.
- ✓ The levelized cost of renewable energy.
- ✓ The carbon emissions.
- ✓ The performance of the regulator.

Game duration: From 2019 to 2050, with monthly timestep.

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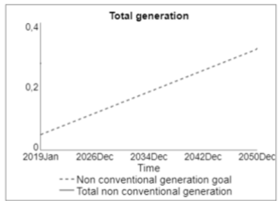
Your goals

1. Reach the goal for nonconventional renewable energy:

- 10% of the demand ending 2025.
- 15% of the demand in 2030.
- 23,5% of the demand in 2040.
- 32% of the demand in 2050.



13 **Source:** Own elaboration based on (Unidad de Planeación Minero Energética, 2015)

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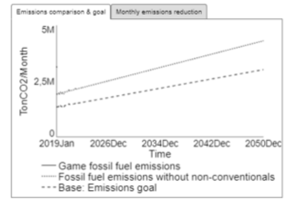
Your goals

2. Reach the goal for carbon emissions' reduction:

Reduction of 30% by 2030 compared to projected emissions.



14 **Source:** Own elaboration based on (Unidad de Planeación Minero Energética, 2015)

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Your goals

3. Maintain the regulator's performance above 80%

As you are playing in the role of the market regulator, you can choose and change any incentives as you want.

But…
You need to *keep the investors happy*. So:

Your performance depends on the confidence that the investors built based on your decisions.

- If your performance is high, then the investment in new capacity will be stable.
- If your performance is poor, then the investment in new capacity will decrease.

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The microworld

The game consists on a simplified learning-oriented interface, that simulates the electricity market.

Some parts works different than the reality:

- The price is settled as a scenario, not as a daily trade off.
- Some incentives as the long-term contracts (auctions) are simplified because this game doesn´t include the marketer role.
- The uncertainty of the generation (e.g. water availability and wind speed) and the demand is smoothed.

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K. Microworld's session debriefing slides

IncentivER debriefing

Microworld for learning about the diffusion of non-conventional Renewable electricity generation technologies in Colombia

Verónica Marrero Trujillo

"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.

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What happened in the game?

What was your strategy?

Did it work or not? Why?

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What happened in the game?

Did you understand the dynamics?

- ✓ How does the installation of new capacity happen?
- ✓ Even if you have the best intentions making changes in the system to make it more profitable, if many changes are made the investors will reduce the confidence on you and will stop installing.
- ✓ The investors manage with the regulator decisions every day… it is complex to understand all the changes and the speed of the occurrence.

The behavior of the installation of new capacity, the available potential and the installed capacity follows a S shaped curve, and it depends on the profitability of the technology.

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Strategies to reach the goals

<u>The main strategy:</u> Maintain the technologies profitable.

- ✓ Make sure to maintain the LCOE lower than the electricity price, including incentives. If this happen, the costs during lifetime per unit for the technologies could be afforded by the electricity price.

- ✓ Built confidence in the investors making a stable market and electricity price. If the price is stable or increase with a stable rate, the investors could project their costs and profitability with some certainty and will continue investing.

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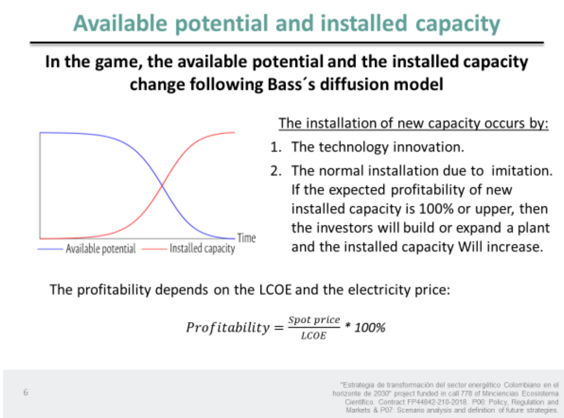
Available potential and installed capacity
In the game, the available potential and the installed capacity change following Bass´s diffusion model
Available potential
Installed capacity
Time
The installation of new capacity occurs by:
1. The technology innovation.
2. The normal installation due to imitation. If the expected profitability of new installed capacity is 100% or upper, then the investors will build or expand a plant and the installed capacity Will increase.
The profitability depends on the LCOE and the electricity price:
Profitability = Spot price / LCOE * 100%
6
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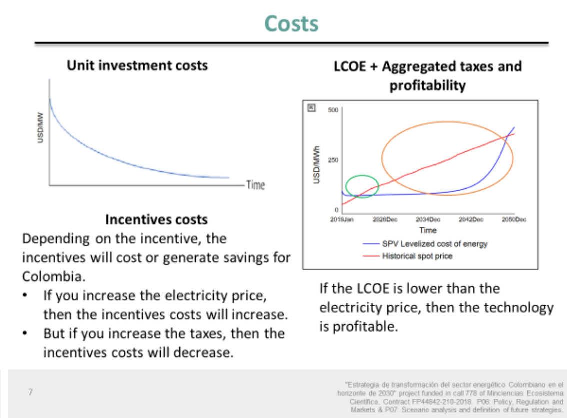
Costs
Unit investment costs
USD/MW
Time
Incentives costs
Depending on the incentive, the incentives will cost or generate savings for Colombia.
• If you increase the electricity price, then the incentives costs will increase.
• But if you increase the taxes, then the incentives costs will decrease.
LCOE + Aggregated taxes and profitability
USD/MWh
500
250
0
2019Jan 2026Dec 2034Dec 2042Dec 2050Dec
Time
SPV Levelized cost of energy
Historical spot price
If the LCOE is lower than the electricity price, then the technology is profitable.
7
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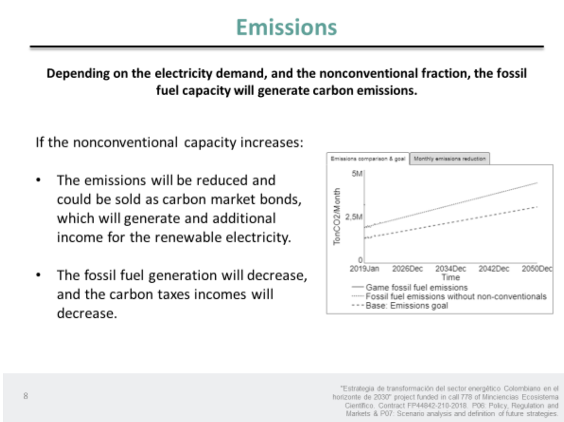
Emissions
Depending on the electricity demand, and the nonconventional fraction, the fossil fuel capacity will generate carbon emissions.
If the nonconventional capacity increases:
• The emissions will be reduced and could be sold as carbon market bonds, which will generate and additional income for the renewable electricity.
• The fossil fuel generation will decrease, and the carbon taxes incomes will decrease.
Emissions comparison & goal
Monthly emissions reduction
TonCO2/Month
5M
2.5M
0
2019Jan 2026Dec 2034Dec 2042Dec 2050Dec
Time
Game fossil fuel emissions
Fossil fuel emissions without non-conventionals
Base: Emissions goal
8
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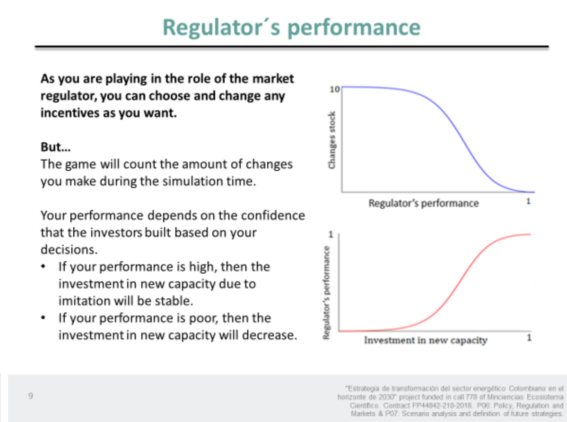
Regulator´s performance
As you are playing in the role of the market regulator, you can choose and change any incentives as you want.
But...
The game will count the amount of changes you make during the simulation time.
Your performance depends on the confidence that the investors built based on your decisions.
• If your performance is high, then the investment in new capacity due to imitation will be stable.
• If your performance is poor, then the investment in new capacity will decrease.
10
Changes stock
Regulator's performance
1
1
Regulator's performance
Investment in new capacity
1
9
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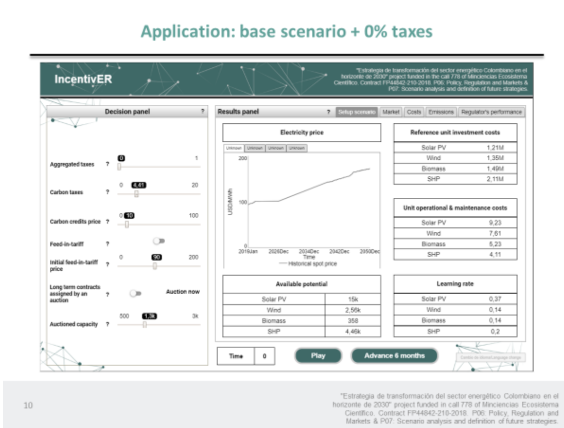
Application: base scenario + 0% taxes
IncentivER
Decision panel
Aggregated taxes
Carbon taxes
Carbon credits price
Feed-in-tariff
Initial feed-in-tariff price
Long term contracts assigned by an auction
Auction now
Auctioned capacity
Results panel
Setup scenario
Market
Costs
Emissions
Regulator's performance
Electricity price
USD/MWh
Historical spot price
Reference unit investment costs
Solar PV 1.21M
Wind 1.38M
Biomass 1.49M
SHP 2.11M
Unit operational & maintenance costs
Solar PV 9.23
Wind 7.61
Biomass 5.23
SHP 4.11
Available potential
Solar PV 15k
Wind 2.56k
Biomass 358
SHP 4.46k
Learning rate
Solar PV 0.37
Wind 0.14
Biomass 0.14
SHP 0.2
Time
Play
Advance 6 months
10
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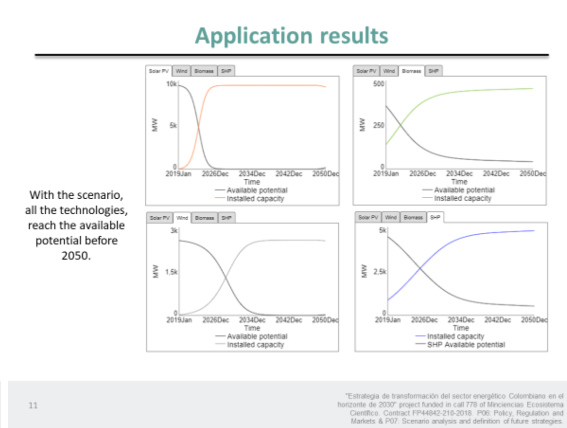
Application results
With the scenario, all the technologies, reach the available potential before 2050.
Solar PV
Wind
Biomass
SHP
MW
Time
Available potential
Installed capacity
SHP Available potential
11
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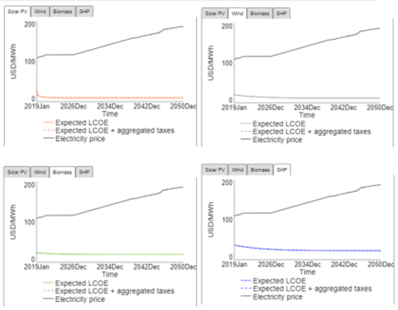
Application results

The installation happens because the LCOE for all the technologies is lower than the electricity price, most of the time, so it is profitable to invest in it.



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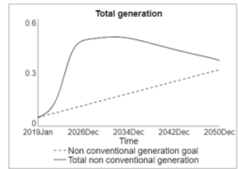
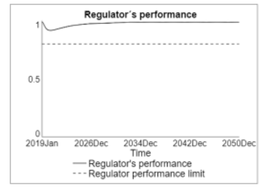
Application goals



The nonconventional goal is reached until 2035, then all the available potential is reached, and the goal is not longer possible for the crescent electricity demand.

The regulator confidence is upper than 80% all the game, because the only decisions change was the taxes, at the beginning.



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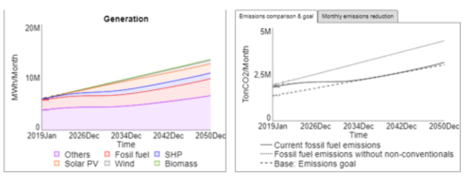
The effect of no incentives

If the electricity market regulator doesn't apply any incentive for the nonconventional renewable energy:



The target demand is reached until the end of the simulation, when the available potential is not enough to continue installing. Also the emissions goal could be reached… Means that we´re not that bad.

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What´s next?

- ✓ Colombia has a huge available potential for nonconventional renewable energy, but there are not so many installation projects because of the high investment costs.
- ✓ Also, depending on the electricity demand, the generation goal will change.
- ✓ After reach nonconventional renewable installed capacity and generation goal, the increasing must continue, so the incentives will evolve and change, as years ago it were different incentives for conventional renewables and for fossil fuel energy, in some years other changes will occur.

15 "Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.

IncentivER debriefing: game modeling

Microworld for learning about the diffusion of non-conventional Renewable electricity generation technologies in Colombia

Verónica Marrero Trujillo

16 "Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.

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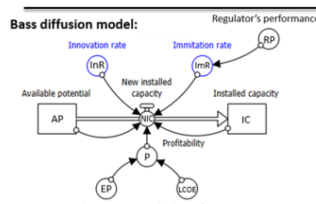
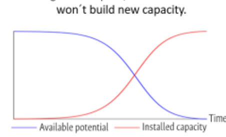
Diffusion model for renewable energy in Colombia

Bass diffusion model:



The speed of que installation depends on the profitability, and if the performance of the regulator is poor, then the investors won´t build new capacity.



$$Available\ potential\ [MW] = -NIC\ dt \qquad Installed\ capacity\ [MW] = NIC\ dt$$

$$Immitation\ rate = Normal\ immitation\ rate * RP \qquad Profitability = \frac{EP}{LCOE}$$

$$New\ installed\ capacity\left[\frac{MW}{Month}\right] = (InR * AV) + \left[\mathrm{ImR} * \mathrm{P} * \mathrm{AP} * \left(\frac{\mathrm{IC}}{IC * AP}\right)\right]$$

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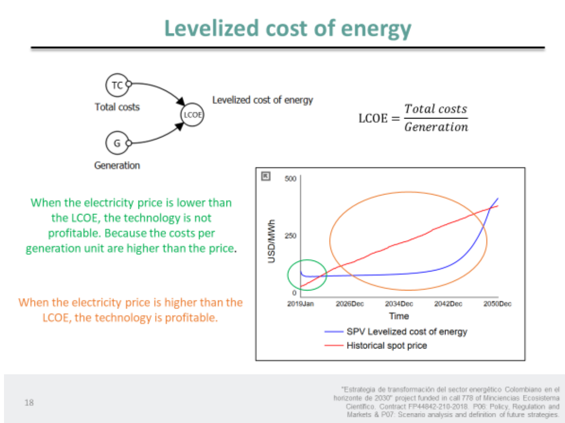
Levelized cost of energy
TC
Total costs
LCOE
Levelized cost of energy
G
Generation
LCOE = Total costs / Generation
When the electricity price is lower than the LCOE, the technology is not profitable. Because the costs per generation unit are higher than the price.
When the electricity price is higher than the LCOE, the technology is profitable.
USD/MWh
500
250
0
2019Jan
2026Dec
2034Dec
2042Dec
2050Dec
Time
SPV Levelized cost of energy
Historical spot price
18
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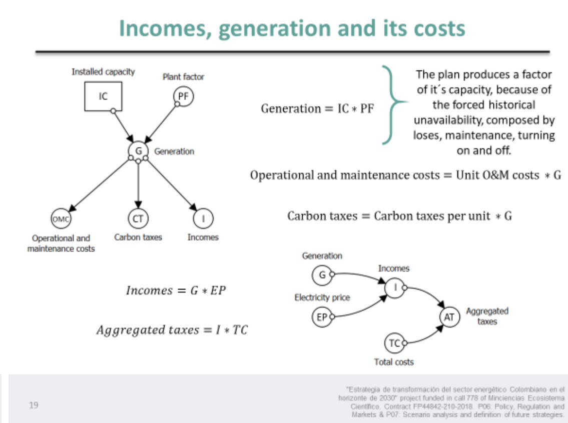
Incomes, generation and its costs
Installed capacity
IC
Plant factor
PF
G
Generation
OMC
Operational and maintenance costs
CT
Carbon taxes
I
Incomes
Generation = IC * PF
The plan produces a factor of it´s capacity, because of the forced historical unavailability, composed by loses, maintenance, turning on and off.
Operational and maintenance costs = Unit O&M costs * G
Carbon taxes = Carbon taxes per unit * G
Incomes = G * EP
Aggregated taxes = I * TC
Generation
Incomes
Electricity price
EP
AT
Aggregated taxes
TC
Total costs
19
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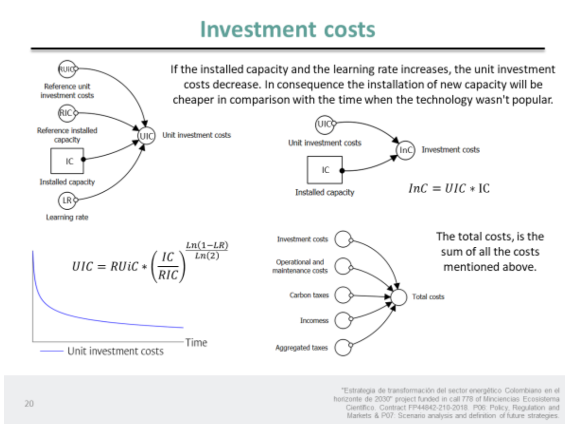
Investment costs
RUIC
Reference unit investment costs
RIC
Reference installed capacity
IC
Installed capacity
LR
Learning rate
UIC
Unit investment costs
If the installed capacity and the learning rate increases, the unit investment costs decrease. In consequence the installation of new capacity will be cheaper in comparison with the time when the technology wasn't popular.
Unit investment costs
InC
Investment costs
Installed capacity
InC = UIC * IC
UIC = RUiC * (IC / RIC)^(Ln(1−LR) / Ln(2))
Time
Unit investment costs
Investment costs
Operational and maintenance costs
Carbon taxes
Incomess
Aggregated taxes
Total costs
The total costs, is the sum of all the costs mentioned above.
20
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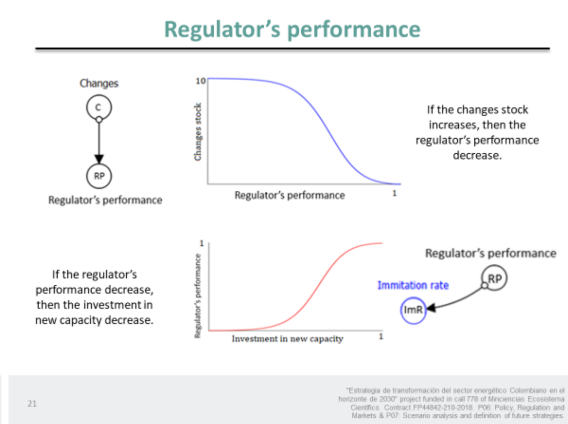
Regulator's performance
Changes
C
RP
Regulator's performance
10
Changes stock
Regulator's performance
1
If the changes stock increases, then the regulator's performance decrease.
If the regulator's performance decrease, then the investment in new capacity decrease.
1
Regulator's performance
Investment in new capacity
1
Regulator's performance
Immitation rate
RP
ImR
21
"Estrategia de transformación del sector energético Colombiano en el horizonte de 2030" project funded in call 778 of Minciencias Ecosistema Científico. Contract FP44842-210-2018. P06: Policy, Regulation and Markets & P07: Scenario analysis and definition of future strategies.

L.Player’s results register sheet

Player: ____________________________

Date: ____________________________

Session: ____________________________

Course: ____________________________

Initial setup

Please copy and paste here the scenario setup (you can use the snipping tool):

Decisions over time

Please register your decisions and the time you made them. In the On/Off variables please mark the check box.

Time	Aggregated taxes	Carbon taxes	Carbon bonds price	Feed-in tariff	Initial feed-in tariff	Long term contracts price	Auctioned capacity
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	

Time	Aggregated taxes	Carbon taxes	Carbon bonds price	Feed-in tariff	Initial feed-in tariff	Long term contracts price	Auctioned capacity
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	
				☐On ☐Off		☐On ☐Off	

Results

Please copy and paste your results. You can select only one technology and paste all the results for it.

<u>Market results</u>

Costs results

Emissions results

<u>Regulator’s performance results</u>

M. Statistical calculations for the pilot testing's result analysis

i. Minimum sample size calculation:

$$n = \frac{N * Z_{\propto}^2 * p * q}{e^2 * (N-1) + Z_{\propto}^2 * p * q} = 67{,}2 \approx 67$$

$Where$:

$$n = Sample\ size$$

$$N = Population\ size = 9986$$

$$\propto = 1 - Confidence\ level = 10\%$$

$$Z = Critical\ value\ of\ the\ normal\ distribution\ at\ the\ required\ confidence\ level \propto$$

$$Z_{90\%} = 1{,}645$$

$$p = Sample\ proportion = 0{,}5$$

$$q = 1 - p = 0{,}5$$

$$e = Margin\ of\ error = 0{,}1$$

ii. Normality test for the pre-microworld questionnaire scores:

$$H_0: The\ scores\ for\ the\ pre-microworld\ test\ follow\ a\ normal\ distribution$$

$$H_1: The\ scores\ for\ the\ pre-microworld\ test\ does\ not\ follow\ a\ normal\ distribution$$

```
        One-sample Kolmogorov-Smirnov test

data:  Samples$Pre
D = 0.17231, p-value = 0.02781
```

iii. Normality test for the post-microworld questionnaire scores:

$$H_0\text{: } The\ scores\ for\ the\ post - microworld\ \ test\ follows\ a\ normal\ distribution$$

$$H_1\text{: } The\ scores\ for\ the\ post - microworld\ test\ does\ not\ follows\ a\ normal\ distribution$$

```
        One-sample Kolmogorov-Smirnov test

data:  Samples$Post
D = 0.13719, p-value = 0.133
```

iv. T-Student test for the comparison of paired simples means:

$$H_0\text{: } Pre\ microworld\ test\ scores\ mean = Post\ microworld\ test\ scores\ mean$$

$$H_1\text{: } Pre\ microworld\ test\ scores\ mean < Post\ microworld\ test\ scores\ mean$$

We transformed the hypotheses to make use of the mean of the difference between the samples:

$$d_i = Post\ microworld\ test\ score_i - Pre\ microworld\ test\ scores_i$$

$$i = 1, \dots, 72$$

$$H_0\text{: } \mu_d = 0\ (The\ scores\ mean\ is\ the\ same\ before\ and\ after\ the\ microworld)$$

$$H_1\text{: } \mu_d > 0\ (The\ scores\ mean\ is\ higher\ after\ playing\ the\ microworld)$$

```
        One Sample t-test

data:  Samples$d
t = 15.864, df = 71, p-value < 2.2e-16
alternative hypothesis: true mean is greater than 0
```