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Social Analysis Modeling with System Dynamics Approach in a Uruguayan Case of Green Hydrogen Production

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Abstract

The deployment of green hydrogen production is increasingly considered a strategic opportunity for energy-exporting countries. However, beyond technological and environmental aspects, large-scale industrial projects may generate complex and uncertain social and economic impacts at the regional level. This study investigates the potential social implications of introducing a green hydrogen production plant in the Department of Paysandú, Uruguay, using a System Dynamics modeling approach. It proposes an initial system model designed to establish a foundational Modeling and Simulation framework. The model explicitly represents feedback mechanisms linking public finance, education, labor competencies, productivity, and social behavior impact, allowing the exploration of long-term socio-economic trajectories under alternative institutional and policy conditions. It is used as an exploratory decision-support tool to assess conditional pathways, trade-offs, and risks. Results indicate that positive social outcomes, such as human capital accumulation and regional income growth, are possible but not automatic; they depend critically on governance capacity, fiscal sustainability, labor market coordination, and social acceptance, and may be attenuated or delayed under adverse scenarios. While this framework provides a strategic engineering lens on the social dimension, it represents a first step toward a comprehensive decision-making tool. The study analyzes a complex system by integrating energy, production, economic, social, and environmental aspects from strategic engineering lens and contributes to the literature by integrating social dimension and institutional constraints into a Modeling and Simulation framework applied to green hydrogen industrialization, offering insights into policy design under uncertainty in emerging energy-export contexts.

Keywords: system dynamics; strategic engineering; Modeling and Simulation; social behavior modeling; social impact; decision-making support

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1. Introduction

Modeling and Simulation (M&S) applied to complex systems is a well-recognized methodology for supporting decision-making processes [1]. Considering that a nation can inherently be viewed as a complex system or even a system of systems, the strategic engineering approach enables the analysis of the interconnections among multiple and evolving variables, making it possible to identify, organize, and manage them effectively [2].

Complex systems exhibit emergent properties and nonlinear dynamics, often displaying behaviors that cannot be easily predicted by analyzing each of their components individually. Their complexity arises from interdependencies and feedback mechanisms among elements, which generate evolving and dynamic patterns [3,4].

A nation, as a complex system, can thus be examined to conduct prevention and management activities in areas such as disaster and emergency response [5], protection of critical infrastructures [6], reconstruction support [7], or to estimate the impacts and repercussions on operations and investments [8].

Owing to major industrial policies promoting green energy for domestic consumption, Uruguay has achieved a remarkable milestone in environmental sustainability—an accomplishment that positions it among the most proactive and forward-thinking nations globally in the field of energy transition [9–11].

Human capacity to grasp the evolution of impacts is inherently limited. In an era where social systems grow ever more complex and changes unfold at an accelerating pace—often producing unforeseen side effects and facing social resistance in decision-making—systemic thinking emerges as a valuable approach. It consists of viewing the world as an interconnected web of relationships, where each element influences and is influenced by the others [12].

Consequently, understanding resistance within social dynamics requires not only insight into systemic complexity but also into the mental models through which we interpret and act upon those systems. Systems often present high combinatorial complexity [13], which can lead to dynamic complexity manifesting as counterintuitive behaviors and time-dependent interactions [14].

Of course, this aspect is advantaged by industrial development policies that the country has given itself over time, without the need to respond to the pressing energy demand coming from the industrial production system, for the most part composed of agricultural activities, pastoralism, agri-food production, cellulose production, and with its own logistics system and the presence of minor industries to support it, which, however, create a new territorial economy.

With these premises and the interest of developing new implementation strategies on the energy transition, it seems interesting to analyze a new system of industrial production [15] in view of the competitive advantage that the country imagines obtaining by placing itself in the condition of Blue Ocean [16] that can be foreshadowed in the near future.

For these reasons, we address the work on the analysis, effectiveness and impact of artificial intelligence techniques on data analytics and Modeling and Simulation systems, as an element of originality configured in the introduction of a predictive process in a complex and dynamic geopolitical framework.

Considering the complexity of an industrial system, a strategic approach is used that takes into account not only qualitative methods but works with tools that allow to operate with a certain flexibility according to the behavior of the actors and the boundary conditions, providing useful and assessable quantitative elements, reducing uncertainty. Strategic engineering considers the social, political, environmental, and other impacts of outputs, with a holistic perspective that allows us to learn information faster and more effectively, identify any critical leverage points, and make consistent decisions even in terms of sustainability, environment and resilience [17].

The research approach begins with an analysis of data and information to understand the interplay between human behavior and socio-economic variables. The primary objective is to develop a macro-level simulation to assess the social sustainability and benefits of a system, and to achieve this, we constructed a System Dynamics (SD) model [18,19] using AnyLogic software. While this research focuses on building the model at a high level of abstraction, its practical real-world implementation is reserved for future studies.

Bibliographic analysis finds its main relevance in exploring the social dynamics underlying perception and contextual factors that influence the impact of a new industrial plant, particularly regarding production methods, managerial competencies, and the collective need for knowledge and maturity on the topic. In this perspective, attention is directed toward the developmental potential of human and economic resources, allowing, through a model of social interaction among key drivers, to forecast the temporal distribution of workforce directly and indirectly related to the plant and the surrounding population [20,21]. The study of social behavior within SD may enable the correlation between employment outcomes and the degree of social acceptance and well-being associated with industrial urbanization. However, the literature still offers limited impact analyses on this emerging production paradigm, both geographically and academically. While some studies explore complex hybrid simulation models [22] or hydrogen supply chain (HSC) analyses [23], the Latin American context remains notably underexplored, representing a significant opportunity for advancing research on M&S applied to green hydrogen-based socio-economic development.

This literature gap is relevant for policymakers because regional outcomes depend not only on investment size, but also on institutional capacity, policy timing, and local legitimacy. In response to this, this study develops a macro-regional SD model to investigate the potential socio-economic pathways associated with a prospective green H_2 plant, linking production dynamics to fiscal revenues and public services, education and competency formation, labor market outcomes, and—critically—social acceptance as a moderating mechanism affecting implementation speed and policy effectiveness. It is designed as an exploratory decision-support tool: it aims to clarify leverage points, feedback-driven risks, and scenario-dependent trade-offs rather than to deliver point predictions. Data and literature-informed parameterization, transparent calibration and validation procedures, and systematic sensitivity and scenario analyses are employed to support model credibility and reproducibility.

The authors address the size of complex systems and some requirements and steps for the use of SD, illustrating its application starting from a Uruguayan case study on a new green hydrogen (H_2) production plant, as a part of an economic context and a territory mainly linked to the existing traditional agricultural production, largely small and medium-sized enterprises, opening up the prospect of implementing to estimate large effects of institutions on income per capita and their impact on economic performance [24].

Research Objective and Guiding Question

While green H_2 is often discussed in terms of energy transition, technological feasibility, or environmental sustainability, this study deliberately shifts the analytical focus toward the social and institutional dynamics associated with the introduction of a new industrial production system at the regional level. Accordingly, the objective of this research is not to promote green hydrogen development, nor to assess its technical or environmental performance, but to explore the socio-economic conditions under which a green H_2 production plant may generate net positive social outcomes in a peripheral and predominantly rural territory.

The core research question addressed by this work makes highlights 'under what structural, fiscal and institutional conditions can a green hydrogen production plant generate net positive social outcomes—such as employment, human capital accumulation and regional well-being—when feedback mechanisms between public investment, education, labor competencies and productivity are explicitly modelled'.

SD is adopted as an analytical framework to explore these interactions over time, allowing the identification of reinforcing and balancing feedbacks, time delays, and nonlinear effects that are typically difficult to capture through static or sectoral analyses. Consequently, the contribution of this study lies in the exploratory and policy-oriented interpretation of social impacts, rather than in forecasting precise quantitative outcomes or advocating a predetermined development pathway.

The rest of the paper is structured as follows: Section 2 explores the reason for the approach with the SD method to develop the model in the complex system of interest, while Section 3 proposes the working methodology and architecture of the model through the creation of the causal loop diagram (CLD) that allows to show the interactions between the elements considered; Section 4 is dedicated to the socio-economic behavior analysis and some results of the case study and Section 5 for the discussion of the mathematical equations adopted to obtain the results sought, delegating the conclusions of the research to Section 6.

2. Toward System Dynamics Approach

SD is employed to analyze the evolving behavior of complex systems over time. Its core premise is that every element within a system interacts through causal relationships. What distinguishes SD from other approaches to studying complex systems—and from conventional applications in social policy modeling—is its reliance on stocks, feedback flows, and loops [25]. This methodology emphasizes dynamic complexity rather than detailed complexity [12]: while the latter involves a multitude of possible solutions, dynamic complexity focuses on how changes unfold across different time horizons. These temporal variations are examined using stock-and-flow diagrams, where stocks indicate different forms of accumulation and flows represent the movement of quantities between them.

Moreover, SD modeling primarily aims to identify and represent feedback mechanisms [26]; it captures the system's dynamics by defining stock–flow structures, time delays, and nonlinear relationships. Consequently, the interplay among variables is depicted through a CLD, a simplified visual representation of the system and its interrelated components.

Conducting 'what if' simulations on such models enables researchers and decision-makers to explore how a system might respond to various strategies or policies, thus enhancing the understanding of its temporal evolution. Typically, an SD model is built upon system-level state variables, which encapsulate aggregated information [27]. These variables do not represent individual entities and are therefore unsuitable for simulating components that exhibit heterogeneity. This aggregation can lead to a reduction in precision, which is mitigated through processes of calibration, verification, and validation, ensuring the model's reliability and supporting its use in advancing research.

In this perspective, the study is applied towards the new and innovative dynamics of green energy production, as recalled by the guidelines of the 'national program for the development of H_2 production' [28]. In this regard, it is interesting to focus the attention on the potential for development and growth of human and economic resources that allow to predict, through a model of social interaction between some main drivers, the distribution over time of the workforce directly and indirectly linked to the production plant and to the more complex system of the residing population [20,21].

Moreover, in the Latin American geopolitical context, it appears significant to address a research topic of recent development in the regional context [29], therefore it becomes topical and useful to deepen the M&S application in the new economic, environmental and social development in the green H_2 production field. In this regard, it is worth exploring the capacity for social growth of a country with an internal energy demand covered by green energy and an agricultural industrial tradition made up of small and medium-sized enterprises, located in a large regional context with its own complexities.

2.1. Research Gaps and Contribution

The model of social behavior related to the production of green H_2 in the territory of Paysandú in Uruguay does not address the topic for its own purpose in terms of covering energy needs and the use of energy as an alternative to other more invasive systems, since the country is practically self-sufficient with a production of green energy that is around 94% of the current total needs [30]. Different from what can be imagined from current sources of literature, the production of green H_2 focuses instead on the possibility of exporting and selling the product outside national borders, considering instead as the main social problems those related to the potential loss of value on work linked to traditional production, strongly characterized by agricultural and rural development, as well as on the repercussions that the start of a new industrial production can bring in terms of growth in competences, income per capita and overall well-being.

An in-depth bibliographic analysis shows that particular attention has been paid to new 'hydrogen energy technologies' (HET), considering them as a 'critical support role' in global decarbonization efforts [31]. Hence the need for social acceptance to support the vision of a 'hydrogen economy', in order to explore the degree of understanding and acceptance of the imaginary context of 'hydrogen houses' for the provision of all domestic energy services, the results of which highlight the importance of risk perception, trust dynamics and emotions in shaping consumer perceptions, and observe the economic benefits, social and environmental issues introduced.

Studies have also been developed on the acceptance or non-acceptance of the presence of wind energy production plants, a fundamental energy element for the production of green H_2, highlighting how the factors that influence the acceptance of wind energy can be classified into process-related variables, personal characteristics, perceived side effects and technical and geographical issues [32]. All these latter elements are decidedly far from what the approach of acceptance by the Uruguayan population may be, substantially devoted to assessing its impact not only on the productive and economic dimension linked to factors of greater income and economic well-being, but also on the environmental aspect—for which the country would be potentially favorable as long as water consumption and land use do not negatively affect the traditional production—as well as towards the social dimension that can orient the population towards a collective benefit of growth in the educational and cultural system of portions of the territory still behind in this respect.

Still in terms of population acceptance, other studies have been conducted with interest; among these, Buchner et al. [33] have deepened the analysis of this process, for which experiments have been conducted through surveys and interviews addressed to residents of regions with the presence of existing or planned green H_2 plants in Germany, from which to create a multiple linear regression model to identify some key factors that influence acceptance—including trust in the safety of plants, trust in project managers, information, perception of the risk/benefit ratio, experience with green hydrogen, gender, etc., all elements that can have a significant positive impact on the acceptance of plants of this type.

As regards local acceptance, studies have been developed to interpret the effectiveness of the different methods of proposal for an active participation of the population on plants such as large-scale photovoltaic plants connected to the grid, ground-mounted plants, biomass plants and wind turbines; in this perspective the study by Soland et al. [34] introduced an analysis with a multimodal research design compartment with a previous study in terms of results compatible with those of other qualitative research [35], where an innovative element was offered by the identification and discussion of correlations between factors influencing local acceptance.

Finally, in terms of sustainability, the literature offers extensive arguments on the Social Life Cycle Assessment (S-LCA) [36], on the guidelines for achieving the goals of the United Nations 2030 Agenda [37] and on the integration of environmental and social criteria [38], sustainability with indicators in the categories of impact on basic needs, such as energy poverty, water supply, health and human rights. In this latest study, especially in the context of quantitative analyses, the results indicate that the economic consideration of the respective renewable energy system, understood as a positive cost–benefit analysis by the individual, is the strongest predictor for a declared acceptance. In addition, the importance of landscape assessment and a strong correlation between procedural justice criteria, such as transparency, timely and accurate information, as well as the possibility of participating during the planning and installation process, and declared public acceptance, also emerged.

The qualitative data, analyzed with reference to the 'grounded theory', showed the relevance of the operating company's commitment at the local level, while the participation of the general public and the choice of location for the plant were among the relevant aspects for acceptance in the implementation process [38–40]. The research findings suggest that making decisions about H_2 production based solely on economic costs is not enough, underlining the importance of integrating social aspects across the entire value chain.

Based on the above, some main gaps in the research emerge, which we summarize as follows:

(a) guidance tools through effective quantitative analyses;
(b) implementation of the concept of sustainability towards a broader application through impact analysis of educational growth processes and competencies;
(c) provide scenarios capable of guiding the decision-maker to the definition of public guidelines, reducing uncertainty in choices.

With these premises and to fill some gaps in research, the proposed model aims to provide innovative and useful support to public decision-makers through some tools that strategic engineering offers in the current scientific landscape, orienting him to combine environmental sustainability, the country's workhorse, with a broader spectrum of observation and analysis points that can lead to defining choices and policies aimed at increasing the 'social' and 'cultural' sustainability and to implement a more harmonious and effective development of the territory.

SD has been increasingly adopted to support energy transition policy analysis because it can represent feedback-driven dynamics, delayed effects, and non-linear responses that are difficult to capture through static assessment methods. In the energy policy domain, SD applications often focus on the dynamics of technology diffusion, capacity expansion, subsidy effectiveness, and system-wide cost or reliability outcomes, frequently translating policy instruments (e.g., subsidy levels, market design, regulatory settings) into long-term trajectories of deployment and economic performance. This stream demonstrates the value of SD for exploring policy packages and identifying unintended consequences; however, it typically treats social impacts and institutional constraints either as exogenous assumptions or as aggregated proxies, rather than as interacting subsystems that co-determine outcomes over time.

A parallel body of work highlights that energy transitions are not purely techno-economic processes but depend on social and behavioral conditions, including public legitimacy, perceived risk, and acceptance of new infrastructures. Studies focusing on social acceptance [41–43] increasingly recognize the role of information, trust, and perceived distributional fairness in enabling or constraining implementation. Nonetheless, within SD-based energy transition modeling, acceptance is often represented indirectly (e.g., as a fixed adoption constraint) or discussed qualitatively [44,45], rather than implemented as an endogenous state variable that interacts with investment dynamics, policy effectiveness, and project delays. A second limitation concerns the treatment of distributional risks and negative pathways: many SD models emphasize best-case reinforcing dynamics and report primarily positive trajectories, while systematically exploring adverse conditions (e.g., fiscal stress, crowding-out of traditional sectors, or competencies mismatch) remains less common in the green H_2 and industrial transition context.

Finally, SD models aiming to inform policy decisions face ongoing scrutiny regarding empirical grounding and reproducibility. While many studies rely on plausible structural assumptions, fewer provide transparent parameter classification, documented data sources, calibration protocols, and multi-criteria validation beyond qualitative plausibility. In particular, KPI calibration against historical benchmarks, where possible, pattern-oriented validation (trend shape, turning points, delays), and systematic sensitivity analysis are not always consistently reported, despite being central to assessing robustness in feedback-rich systems. These gaps are especially relevant for emerging domains such as green H_2 industrialization, where the evidence base is still limited and policy discourse can easily outpace empirical validation.

2.2. Positioning on Gaps

Building on the above literature, this study positions SD as an exploratory decision-support tool for evaluating the socio-economic implications of green hydrogen industrialization at the regional level. The main value added lies in the coupled representation of three mechanisms that are rarely integrated simultaneously in existing SD applications: (1) an endogenous fiscal–public services loop linking economic activity to tax revenues and the capacity to sustain social services; (2) an education and competencies accumulation structure connecting public services and training capacity to labor competencies and productivity; and, pending the implementation of the model with a future broader configuration that contemplates social perception together with other elements useful for a broader interpretation of the issue, (3) social acceptance represented explicitly in a simplified version as an endogenous moderating stock that affects implementation speed, policy effectiveness, and delay amplification (Table A1).

In addition, to avoid one-sided interpretations driven by reinforcing feedbacks, the model systematically explores adverse scenarios (crowding-out of traditional sectors, short-term fiscal stress, and competencies mismatch) alongside baseline pathways. Model credibility is strengthened through transparent parameter classification, backcasting-based calibration against benchmark indicators, a validation strategy combining Root Mean Square Error (RMSE) with pattern-oriented trend checks, and systematic sensitivity analysis, complemented by scenario matrices, enabling a clearer assessment of robustness and conditionality of outcomes.

In this way, the authors' contribution builds on this stream by coupling fiscal capacity and public services, human capital dynamics, with the element of social acceptance as a contribution to the achievement of greater awareness for the public decision-maker.

2.3. Institutional Grounding of Causal Relationships in the Uruguayan Context

The causal relationships embedded in the System Dynamics (SD) model are not introduced as purely theoretical assumptions but are grounded in observable institutional and socio-economic dynamics specific to Uruguay.

First, the relationship between fiscal revenues and public services is consistent with Uruguay's institutional budgetary structure. Official data from the Ministry of Economy and Finance (MEF) and the Office of Planning and Budget (OPP) document the allocation of public revenues across functional expenditures, including education, health, and social services. Public social expenditure represents a significant and historically stable component of total public spending, supporting the representation of fiscal inflows translating into public service provision [46–50].

Second, the link between public investment in education and improvements in schooling indicators is supported by national statistical evidence. Data from the National Institute of Statistics (INE) and the National Institute for Educational Evaluation (INEEd) document measurable trends in years of schooling, enrollment rates, and learning outcomes associated with variations in public education expenditure [51]. While the model adopts a stylized exponential formulation to represent diminishing returns in educational attainment, the direction and structure of the relationship are consistent with Uruguay's historical educational development patterns.

Third, the connection between education, competencies, and productivity is supported by country-specific policy diagnostics and international institutional assessments focused on Uruguay. Reports by scholars [52,53] emphasize the role of human capital formation and workforce competencies as structural determinants of productivity and long-term growth in the Uruguayan economy. These findings provide empirical justification for modeling competencies as a driver of production efficiency.

Finally, the feedback mechanism linking productivity growth to fiscal capacity reflects Uruguay's tax structure, including corporate income taxation from the National Institute of Statistics (IRAE) [47] and labor-related fiscal revenues, which contribute directly to the public budget. As GDP and formal employment increase, fiscal returns expand correspondingly, reinforcing the capacity for public investment.

It is important to note that the SD model does not aim to replicate econometric causal estimates for Uruguay. Rather, it represents stylized but institutionally consistent dynamics, bounded and calibrated within ranges informed by national data and policy evidence. Sensitivity analyses are conducted to ensure that results remain robust under plausible variations in these relationships.

3. Methodology and Architecture

The methodological approach starts with the target definition and then works on the key performance indicators (KPI) and the variables to be identified, on their interactions, relationships and feedback loops, building CLD that can realistically represent the dynamics of the processes. To this, additional events or agents capable of generating delays, system instability or emerging factors can be added.

Model architecture proposes the possibility of hybrid simulation, allowing a further deepening of social behavior (Figure 1) at the individual level of agent-based modeling (ABM).

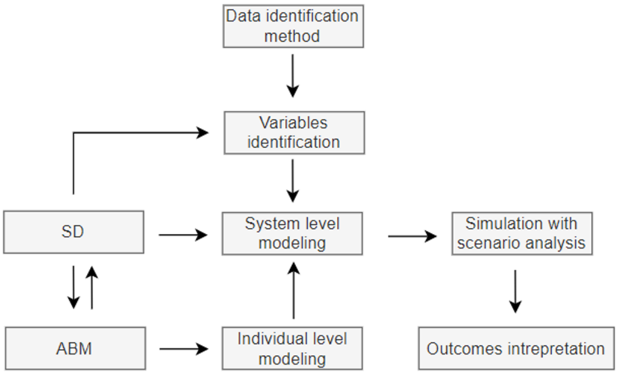

Figure 1. Model architecture.

SD is an M&S methodology for policy and strategy analysis, grounded in feedback systems theory. Over time, it has evolved into an autonomous field of application. Its capacity to represent and interpret a system's behavior and temporal variations [54] constitutes one of the main reasons for adopting SD in industrial design contexts, where feedback mechanisms are intrinsic to component interactions. In this framework, CLDs serve as effective tools for investigating the underlying causes of System Dynamics and for facilitating communication among variables.

The positive or negative nature of relationships within these diagrams is indicated by corresponding signs. In reinforcing loops, an increase in the source variable amplifies the effect variable, whereas in balancing loops, an increase in the source variable produces a reduction in the effect variable. These loops are essential instruments for visualizing and conveying the feedback structures of complex systems, together with their constituent components and behavioral dynamics.

As shown in Figure 2, which represents the first step of the case study model, the relationships between the components are the driving force behind its processes. For the model to be sustainable, these relationships must work in harmony with the initial inputs and the core assumptions. We find dependencies and identify mathematical relationships and formulations so that the link produces information and outputs that in turn can become an input for another relationship between elements. In CLD, balancing B allows the model to stabilize the effect variable regarding new revenues linked to the public services provided, while the two reinforcing R allow to strengthen traditional production and that of green H_2 [14,55].

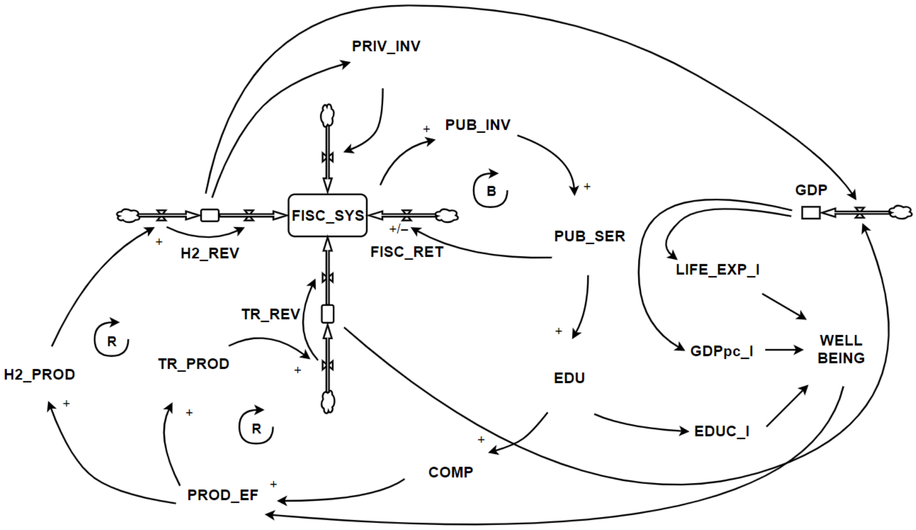

Figure 2. Causal loop diagram.

The model distinguishes between (a) *policy levers* that can be directly influenced by public intervention (e.g., training intensity and effectiveness, reinvestment share, fiscal parameters, regulatory delays, and engagement measures affecting social acceptance), (b) *state variables* describing the socio-economic system (education, competencies, acceptance, public services), and (c) *outcome indicators* used for policy evaluation (GDP per capita, employment, human development, inequality). This distinction enables a direct translation of model results into actionable policy instruments.

3.1. Contextual Grounding of Causal Feedbacks

The causal relationships represented in the model are not intended to describe universal or automatic development mechanisms. Instead, they reflect context-specific hypotheses grounded in the institutional, fiscal, and socio-economic characteristics of Uruguay.

Positive feedbacks linking fiscal revenues, public services, and human capital are not assumed to be automatic. Their strength is moderated by institutional capacity, policy implementation delays, and diminishing marginal returns, which are explicitly captured through elastic functional forms and time delays calibrated on Uruguayan public finance and education dynamics.

In particular, reinforcing feedbacks linking fiscal revenues, public services, education, labor competencies, and productivity are informed by the historically strong role of the Uruguayan state in education and social policy, as well as by the relative stability of its public finance and governance institutions. National statistical evidence indicates that public expenditure on education and social services has historically contributed to improvements in labor market outcomes and productivity, albeit with significant time lags and diminishing marginal returns, as represented in the following Equation (1) with the elasticity placed on the variability of education with respect to the public expenditure supporting it [28,46,47,56].

$$\Delta Education = \beta_E \log(1 + publicInvestment) \tag{1}$$

where elasticity is $\beta_E < 1$, supposing policy delay on 2–4 years for Education and 1–2 years for Productivity.

To avoid deterministic or overly optimistic dynamics, the model explicitly incorporates elastic functional forms, saturation effects, and policy implementation delays; feedback gains are calibrated below unity, and delays are introduced to represent administrative capacity constraints, institutional inertia, and the non-immediacy of social returns on public investment. Consequently, reinforcing loops should be interpreted as conditional and contingent mechanisms, whose effectiveness depends on governance quality, fiscal sustainability, and policy coherence over time, rather than as guaranteed or self-sustaining growth paths.

The link between economic activity and fiscal capacity is interpreted through Uruguay’s institutional channels: tax revenues are proxied through mechanisms consistent with corporate taxation [47] and social security contributions [56], while the translation of fiscal space into effective public services is mediated by budgeting and implementation capacity [46] and sectoral policy execution from the Ministry of Industry, Energy and Mining (MIEM) [28]; these institutional interfaces motivate the inclusion of explicit implementation delays and degressive yield elasticities, avoiding an expectable ‘revenue-to-services’ conversion and reflecting realistic constraints in policy execution.

The subject of the investigation is the impact evolution on the Paysandú population of 113,124 inhabitants distributed in an area of 13,967 km^2 almost entirely rural and with a medium-high unemployment rate [46,57], and on territory, environment and economy, and then extend it to other indicators; the conditions for measuring outputs such as well-being, Human Development Index, and growth of competencies and education are affected by the fiscal system. Once the elements relating to the aspects addressed have been defined, they become the subject of bibliographic investigation with the aim of studying their impact in terms of sustainability.

More concretely, Figure 3 outlines the relationships and model's process flow, identifying the quantitative outputs to be transformed, measured and evaluated. The loops are combined within a single analysis system followed by the creation of quantitative stock-flows to provide an overall picture of the impact of the project and observe trends between the desired KPIs.

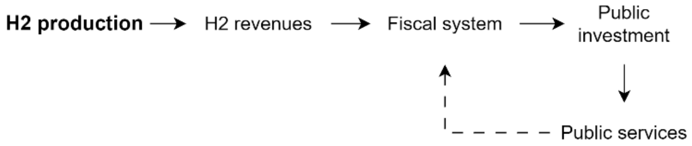

Figure 3. Subsystem CLD.

Initial parameters, the demand for green H_2 and traditional production are identified as initial variables taken from official sources and are crucial points for the operation of the various loops built into the model. Once the subsystems are verified, they connect together to run the model. Finally, in order to simplify the trends' projections some general assumptions have been introduced, considering the absence of idle capacity in production in a time frame of 30 years with technological updating [15,29,58–62].

3.2. Social Acceptance Focus

In the very first steps of the model, social acceptance was treated as an emergent outcome indirectly influenced by socio-economic variables (employment, income per capita, public services, education), rather than as an independent stock. The assumption was that improvements in these indicators increase the probability of social acceptance, consistent with empirical literature.

Nevertheless, given its relevance in the literature on large-scale energy and industrial infrastructure, social acceptance has been explicitly represented within the model structure rather than treated as an exogenous narrative condition. Social acceptance is modeled as an aggregate state variable capturing the overall level of public support or tolerance toward the green hydrogen project at the regional level, adding additional external stock and flow not to generate benefits directly, but to moderate the speed of investment, amplify or mitigate delays, and condition policy feasibility.

Equation (2) highlights the change in social acceptance over time

$$\frac{dA}{dt} = \gamma Information - \delta perceivedRisk \tag{2}$$

where acceptance A varies from 0 to 1, γ is a sensitivity coefficient and measures how effectively information translates into an increase in acceptance (effectiveness of information/engagement processes), and δ measures how much risk perception reduces acceptance (risk sensitivity of social acceptance); *A(t)* is a stock and affects the speed of investment (multiplier on investments) and the delay amplification when A < 0.5 (delays increase). Information is a synthetic indicator that represents the set of factors that increase acceptance because they improve understanding and trust, while *perceivedRisk* is the social perception of risk or criticality associated with the project (not necessarily the real technical risk). Since A is in [0,1], in implementation it is used as a constraint

$$A(t) = \{\min(1, \max\{0, A(t)\})\} \tag{3}$$

so that acceptance cannot exceed 1 or fall below 0.

It is a balanced dynamic with pro-acceptance pressures minus anti-acceptance pressures: if the term on the right is positive, then A increases and acceptance increases; if it is negative, A decreases and acceptance decreases, while if it is equal to zero, acceptance remains stable, all other things being equal.

Rather than directly generating economic or social benefits, social acceptance acts as a moderating mechanism, influencing the timing, effectiveness, and political feasibility of investments and public policies. Lower levels of acceptance increase implementation delays, reduce policy effectiveness, and constrain the activation of reinforcing feedbacks, while higher acceptance facilitates smoother project deployment and institutional coordination. This representation allows the model to capture how informational processes, perceived risks, and community engagement may condition socio-economic outcomes, without requiring a detailed agent-level modeling of individual attitudes.

Social acceptance does not create GDP directly, but it influences how quickly and how effectively investments are activated and implemented, whereas it enters as a multiplier of actual investment and a multiplier of implementation delays. Formally, it affects implementation delays through bounded multiplicative modifiers. Let us put $m_I(A) \in [0,\ 1]$ as scale effective investment activation, and $m_\tau(A) \geq 1$ a as scale implementation delays (coupling to investment and delays); we have, for instance

$$I_{eff}(t) = I_{plan}(t) \cdot m_I(A(t)),\ with\ m_I(A) = \min(1, \max(0, A)) \tag{4}$$

$$\tau_{eff}(t) = \tau_0 \cdot m_\tau(A(t)),\ \ with\ m_\tau(A) = 1 + k \cdot \max(0,\ 0.5 - A(t)) \tag{5}$$

where the first mechanism (acceptance leading to the activation of the investment) has in $I_{eff}(t)$ the planned investment (the one envisaged on the map), and in $\tau_{eff}(t)$ the investment that is actually activated in the system, with $m_I(A(t))$ which is the function that translates acceptance into ‘how much of the plane is realized’ (if $A < 0$ becomes 0, if $A > 1$ becomes 1, and if $0 \leq A \leq 1$ then $m_I(A) = A$; the second mechanism (acceptance leading to delays) means that if the acceptance is high ($\geq$0.5), then $0.5 - A \leq 0$, max(0, negative) = 0, then $m_\tau = 1$ with normal delay, while if the acceptance is low (<0.5), then $0.5 - A > 0$ and the delay increases proportionally to the distance from 0.5.

This ensures acceptance operates as an enabling/constraining mechanism rather than a direct source of economic benefits. In this formulation, social acceptance does not directly increase economic output; instead, it acts as an institutional feasibility filter that conditions both the speed and the effectiveness of policy implementation, and this avoids attributing intrinsic economic value to acceptance and instead models it as a constraint or enabler of planned investment.

3.3. Parameterization, Calibration, and Validation

Model parameters were defined according to a structured classification reflecting their function and degree of uncertainty within the system. Three main categories have been identified:

(1) structural parameters, defining the mathematical form of relationships between variables (e.g., elasticities linking public spending to education outcomes, education to competencies, and competencies to production efficiency);

(2) contextual parameters, derived from official Uruguayan statistical sources and international databases, including demographic trends, baseline education levels, GDP per capita, fiscal rates, and labor market indicators;

(3) exploratory parameters, governing feedback strength and time delays, introduced exploring alternative policy-relevant configurations rather than to reproduce historical values exactly.

Structural and context-specific parameters were initialized using publicly available data [28,46,47,56,57], while exploratory parameters were bounded within ranges reported in the empirical literature on human capital accumulation, public investment multipliers, and institutional dynamics [57,63–66] (Table A2).

The model calibration approach was conducted through a backcasting procedure over a historical reference period (2010–2022), with the objective of reproducing observed macro-level trends, as shown in Table A3, rather than point-wise values. Calibration focused on aligning simulated and observed trajectories for selected indicators, including population dynamics, average years of education, and GDP per capita, emphasizing growth rates, saturation behavior, and relative timing.

Benchmark time-series were used as calibration targets; parameters directly governing these dynamics (e.g., education effectiveness and delay, baseline growth terms, and fiscal feedback strength) were adjusted within literature-informed bounds to reproduce initial level, average slope, curvature/saturation where applicable, and the timing of short-term deviations (e.g., shocks). The calibration goal was trend reproduction rather than point-wise prediction.

Model validation follows a pattern-oriented approach consistent with established SD practice. Quantitative validation included RMSE computed on yearly values for each indicator

$$RMSE = \sqrt{\frac{1}{n}\sum\nolimits_{t=1}^{n}(y_t - \hat{y}_t)^2} \tag{6}$$

and complementary trend metrics (trend correlation of first differences, turning points, and lag-of-maximum-correlation) to evaluate timing and shape agreement between observed and simulated trajectories, where t is time index (years in our time window), n is number of yearly observations within the calibration window (for 2010–2022 included, n = 13), y_t is the observed value (benchmark) of the indicator (population, GDP per capita, education) at time t, and $\hat{y}_t$ is value simulated by the model at the same time t (simulated in a given year by the backcast).

In addition, pattern-oriented validation was conducted by comparing trend correlation of first differences, turning points, and lag-of-maximum-correlation between observed and simulated trajectories. Expert review was used as a secondary validation layer to assess causal plausibility, feedback signs, and order-of-magnitude consistency. In fact, qualitative validation was performed through expert judgment, assessing the plausibility of causal structures, feedback directions, and temporal dynamics; validation trend metrics (Figures A1 and A2) indicate that the model adequately reproduces stylized facts and long-term tendencies of the regional socio-economic system.

3.4. Reproducibility and Data Availability

To ensure reproducibility, model data and datasets are used for calibration, sensitivity analysis, and scenario simulations, including calibration series, baseline projections, and scenarios with 30-year horizons and adverse scenarios (Figures A3 and A4), along with tables of parameters used. A variable-mapping summary table (Table A4) links model exports to handwritten notation, allowing all reported results to be replicated independently.

4. Conceptual Framework and Results

The model was imagined with a general framework that contemplated the four areas of interest (environmental, productive, economic and social) interacting with each other through a series of relationships and dependencies that move its progress (Figure 4). In our case study, we focused on the functioning of the scenario linked to the fiscal system as the main driver of the evolution of the model's behavior, leaving its implementation and development on social, productive and environmental aspects to the future steps.

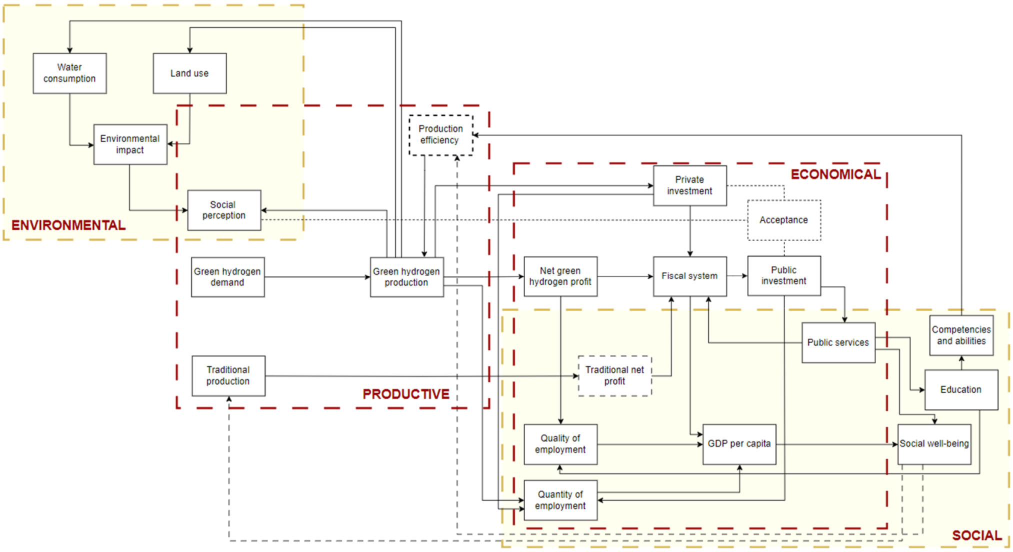

Figure 4. Overall project framework.

The feasibility is supported by the integration of the dynamic interactions shown in Figure 2. Specifically, Equation (7) governs the production revenue flows, while Equation (10) determines the private investment rate based on country risk and net profit, both feeding the central fiscal stock (Equation (8)).

The simulation outputs reported in this section are not forecasts, but they should be interpreted as conditional trajectories generated by the model structure under explicitly stated assumptions, parameter ranges, and scenario configurations. The purpose is to support policy learning by highlighting feedback-driven mechanisms, time delays, leverage points, and trade-offs, rather than predicting mere future values of socio-economic indicators.

4.1. Assumptions and Scenario Matrix

The model is configured to explore how a prospective green H_2 plant may affect regional socio-economic dynamics in Paysandú through fiscal capacity, public services, human capital accumulation, and productivity feedbacks. The analysis adopts a 30-year horizon and a stylized representation of production ramp-up. Baseline assumptions include (a) green H_2 production is primarily demand-driven and expands in phases, (b) no persistent idle capacity is assumed once the plant is operational, (c) feedback effects operate with explicit implementation delays, and (d) key relationships are saturating and bounded to avoid unrealistic exponential growth.

Table A5 summarizes assumptions on the baseline configuration and the adverse scenarios used to test robustness and downside risks (crowding-out, fiscal stress, competencies mismatch, and low acceptance), by indicating which parameters/levers are perturbed and the expected direction of effect.

4.2. Adverse and Limiting Scenarios

To avoid a one-sided interpretation driven by reinforcing feedbacks, we define a set of adverse and limiting scenarios that represent plausible risks associated with large-scale green hydrogen deployment in a peripheral territory. Each scenario modifies a small set of parameters or structural levers (Table A5) while keeping the remaining model structure unchanged, enabling an interpretable comparison of mechanisms and outcomes.

A first scenario considers potential crowding-out effects on traditional economic sectors, particularly agriculture and related activities, due to competition for skilled labor and wage pressures; under this configuration, net employment gains are reduced, and income growth becomes more uneven across sectors.

A second scenario addresses fiscal stress during the early investment phase, where substantial public expenditures precede delayed fiscal returns. In this case, short-term constraints on public services attenuate human capital accumulation and slow down the activation of reinforcing feedbacks.

A third scenario explicitly incorporates low social acceptance, resulting in increased implementation delays, reduced policy effectiveness, and weakened feedback mechanisms. Under such conditions, positive social outcomes are significantly delayed or partially offset.

These scenarios highlight that the benefits associated with green hydrogen industrialization are not automatic, but depend on governance capacity, fiscal sustainability, labor market coordination, and social legitimacy. In any case, in general results should be interpreted as conditional pathways rather than guaranteed outcomes, emphasizing trade-offs and risks alongside potential benefits.

Comparing baseline and adverse scenarios over the three-year horizon for the main outcome indicators (GDP per capita, employment index, years of education, inequality variables) and for the acceptance stock where applicable, the results show that positive socio-economic outcomes are not automatic and can be delayed or partially compensated when adverse conditions weaken fiscal capacity, they slow down the accumulation of human capital or limit implementation through low acceptance.

4.3. Social Growth Analysis

The aim is to verify whether the introduction of a new industrial production of H_2 and its derivatives, as e-methanol—understood as an important international strategic asset introducing added value to the country—through the construction of an energy self-sufficient and completely green plant, can create the conditions for a significant improvement in the social well-being and life expectations in the area concerned and increase—directly and indirectly—the ‘value chain’. Observing and interpreting how these elements affect social behavior and how the new system can directly and indirectly generate new forms of economies, raising social well-being, opens the prospect for further research.

The case study refers to a pilot green H_2 plant with the related services for green electricity necessary to support the operation of the plant, considering an area of the Department of Paysandú [28,67]. We place the indicators and elements identified linked to each other in order to verify their compatibility and functionality in relation to the objectives. Once set up, the relationships examined show links and limitations and can be described according to the dependencies and areas of intervention.

Assuming that the production of green H_2 is regulated by external demand—regulated by the market and by a set of geopolitical factors and which will expand gradually in phases, not through immediate large-scale implementation—the starting point concerns the production aspect linked to the economic one through the conversion of production into selling profit, followed by the fiscal system to which the income from the country’s traditional production also refers. Here the fiscal system works as a central pivot between public investments (to which one gives) and private investments (from which one receives) and acts as an entry flow for the investment incentive oriented towards generating public services, which feed the fiscal system itself; it is an output as a combination of the cost of production and the cost of sale, also affected by increasing in production through efficiency.

As reference parameters for the execution of the model, values derived from the authors' experience were set also in relation to the analysis of the compared statistical trend of population [56,57,68], data collected on site and assumptions resulting from experience, such as years of initial education (10.8) and maximum years of achievable education (15), minimum (60) and maximum production efficiency (90), initial (78), minimum (50), and maximum (82.87) life expectancy, and Gross Domestic Product (GDP) per capita (23,765).

If the public services promoted (as soon as they enter) feed the local development system increasing in turn the revenues in the fiscal system, as a feedback loop, it can be observed how both the contribution in terms of social welfare, composed of the educational component, life expectancy and wealth per capita are influenced. Then, the fiscal system affects indirectly the GDP from which the GDP per capita over time reveals the trend of the population and contributes to the understanding of social welfare, while, in consideration of the fact that 'feeling better, you work better', in turn the social welfare could also affect the production systems. Finally, production capacity, regulated by production efficiency, can vary in a range between min–max of actual production.

4.4. Case Study Outcomes

In the experimentation phase, we assume that market demand was taken for granted and without idle capacity, and that private investments will therefore be profitable, generating new fiscal revenues. The goal is to evaluate how the expansion of green H_2 production affects public investment. The study seeks to ensure that the region's traditional industrial and agricultural production does not minimize the real contribution of green H_2, so that its positive effect on public services, which are funded through the fiscal system, remains clearly visible and relevant.

For green H_2 production, the gross revenue comes from the sales cost forecast that the product may have over the next few years, which in turn is still very much influenced by the cost of production. Studies indicate possible paths and trends in technological evolution, for example through the development of efficient photocatalysts [69,70] or electrolysis [58,59], that could lead to a drastic reduction in the cost of production and a consequent downsizing of the selling price according to levelized cost of electricity (LCOE) [9,71].

In fact, as far as production cost is concerned, many efforts by researchers and scholars are aimed at the perspective of technological development, indicating how the research path can lead to innovative 'cost reduction' solutions on H_2 separation [58], as well as on cost reduction in intermediate process levels (stack, feeding), and that technological improvement, particularly in electrolysis, has followed the well-known dynamics of the learning by doing curve and the experience curve, where investment costs (CAPEX) and operating costs (OPEX) decrease with each doubling of cumulative installed capacity [72].

A decreasing scale has been set over a period of 30 years with the assumption that the cost of production will tend to decrease progressively according to the principle of the learning curve, and, to simplify, that during the same period the selling price Ps remains unchanged or increases with a slow progression discounted over time. For the production cost, we use a piecewise linear function, while for the selling price a decreasing exponential curve is set, imagining a maximum ceiling and discounting the sales value over time (Equation (7))

$$P_s(t) = P_{max} - (P_{max} - P_0)e^{-kt} \tag{7}$$

where P_{max} is the maximum sustainable price, P_0 is the initial price, and k is the rate of growth. Private investment and feedback from public services also flow into the stock of the fiscal system (Equation (8))

$$fiscalSystem(t) = \int_{t_0}^{t_n} \left(tax_{H2Prod} + tax_{tradProd} + tax_{privInv} + fiscalReturn\right)dt \tag{8}$$

where the terms below the integral are functions referring to the respective fiscal systems and variable over time, while *fiscalReturn* represents the taxation generated by new businesses, new jobs, new commercial establishments, which the presence of the plant has generated [63,73,74] according to Equation (9)

$$fiscalReturn = \rho \; publicServices \left(t - \tau_{delay}\right) \tag{9}$$

where ρ represents the feedback effect by public services as taxation on the activities generated, i.e., the share of public services that results in new fiscal revenues and τ_{delay} is the time delay in years to simulate a non-immediate effect, usually by shifting the application of fiscal feedback by at least one year. As public services increase, the ability to feed into the fiscal system also increases slightly, but the largest proportion remains dominant [12,74,75].

For public investment, assuming that incremental income (GDP from public services) is taxed on employment, consumption and profits, we can realistically more or less conservatively estimate a combined marginal fiscal rate such that the rate on additional public services generates new fiscal revenues [76].

To understand the part of public investment we refer to the data provided by the corporate income taxation IRAE to provide information relating to the distribution of population-oriented investment expenditures [47,77]; in this case, business as usual, we estimate that a minimal rate of the fiscal system is invested in public services, while to include private investment in the fiscal system we use Equation (10)

$$I_{priv} = P_{net} \; \alpha \left[1 - \left(r_f + r_s + r_c\right)\right] \tag{10}$$

where I_{priv} is the activated private investment, P_{net} is the net profit from the sale of green H_2, α is the correction rate ($0 \div 1$ value, considered as the share of profits that translates into private investments, such as reinvestment or the attraction of new capital), r_f is the risk rate as the sovereign bond yield, r_s is the discount rate, which reflects the cost, opportunity, and time preference of capital, and r_c is the country risk, which is a kind of country risk premium and reflects the country's Emerging Markets Bond Index (EMBI) and sovereign risk perception [49]; the term in square brackets represents a corrective factor of attractiveness, as the higher the rates or the risk, the lower the share of profits that actually generates investments.

Therefore, taxes arising from private investments with fiscal return of the State will be counted through the assigned fiscal value representing the effective fiscal rate on profits and capital [78]. This process therefore deserves further study with future research to refine the influence of feedback on the fiscal system.

4.5. Sensitivity Analysis

To assess the robustness of the model outcomes and to evaluate the influence of key assumptions, a systematic sensitivity analysis was conducted. Selected parameters governing education dynamics, feedback strength, investment behavior, and policy delays were perturbed individually within a range around their baseline values. The analysis focused on core outcome variables, including GDP per capita, average years of education, employment-related indicators, and public investment levels, over a time simulation horizon.

For each parameter p, shown in Table A6, two perturbed runs were performed, $p^{-} = 0.8p$ and $p^{+} = 1.2p$, holding all other parameters constant (one-at-a-time design). Sensitivity was quantified on endpoint values at year 30, and trajectory deviation over the full horizon using the normalized area difference. The main reported metric is the endpoint percent change relative to baseline

$$\Delta\%_Y = \left(\frac{Y_{30}^{var}}{Y_{30}^{base}} - 1 \right) \times 100 \tag{11}$$

A ±20% one-at-a-time analysis was performed on parameters governing education effectiveness (β_E), education delays (τ_E), fiscal feedback strength (α_F), reinvestment rate (α_I) as $\alpha_{I,eff} = \alpha_I \cdot (0.7 + 0.3A)$, and the productivity linkage from competencies, and the productivity linkage from competencies (β_P). Results were evaluated on GDP per capita, employment indicators, and average years of education over a 30-year horizon (Table A6). The system charts were used to rank parameter influence on endpoint outcomes, while spider plots assessed trajectory robustness. The analysis indicates that positive outcomes are conditional, with education effectiveness and fiscal feedback exerting the strongest influence, especially in the presence of policy delays.

Results indicate that model behavior is moderately sensitive to parameters governing education effectiveness and fiscal feedback strength, while remaining relatively robust to variations in reinvestment rates and short-term policy delays. In particular, positive social outcomes persist across a wide parameter range, although their magnitude and timing vary significantly.

Importantly, under high feedback gains and low delays, reinforcing loops may amplify growth trajectories, producing optimistic upper-bound scenarios. Conversely, reduced feedback strength or extended delays significantly attenuate social benefits, highlighting the conditional nature of positive outcomes and the critical role of institutional capacity and policy coherence.

4.6. Endogenous Reinforcing Dynamics and Methodological Implications

The model includes several endogenous reinforcing feedback loops linking economic output, fiscal revenues, public services, human capital, and productivity. While such structures are theoretically grounded and empirically observed in many development processes, they also introduce the risk of self-reinforcing dynamics that may amplify positive trajectories within the system. This risk is particularly relevant in exploratory SD models, where strong feedback gains combined with short delays may generate optimistic growth paths that are internally consistent but sensitive to underlying assumptions. Sensitivity analysis confirms that, under high feedback strength and low institutional delays, reinforcing loops can accelerate socio-economic outcomes beyond historically observed ranges.

For this reason, model outputs are not interpreted as forecasts, but as conditional trajectories illustrating how social and economic outcomes may evolve under specific structural and institutional configurations. The presence of reinforcing loops is therefore treated as an analytical feature to explore leverage points and potential policy risks, rather than as a guarantee of sustained growth, and reinforcing dynamics are interpreted as upper-bound scenarios rather than baseline expectations.

5. Discussion

Public services are the fuel to run the education and training system that allows to increase one’s experience, competence and abilities, and are proportionate to the fiscal system. Assuming a time frame between when the application of the service starts and when a result is obtained in education, the model allows us to better interpret the overall trend of the fiscal system and to compare the expected education with and without the new green H_2 production plant and how it increases as a function of the Public investment in Education.

Since the link between investment and output in years of education is supported by historical data and institutional practice, the use of an exponential function between public spending dedicated to education and years of schooling can be justified.

$$E(t) = E_{max} - (E_{max} - E_0)e^{-\varepsilon S_{pub}(t)} \tag{12}$$

Expression (12) is proposed as a goal-seeking solution for a process of limited exponential growth, which arises from the differential Equation (13)

$$\frac{dE}{dS_{pub}} = \varepsilon\,(E_{max} - E) \tag{13}$$

which describes how Education (E) approaches a maximum (E_{max}) with a rate proportional to the residual gap ($E_{max} - E$), based on the reasoning that as public services increase, the average years of schooling growth slow down as one approaches the maximum [68,79,80].

In this way, a stable and realistic evolution can be guaranteed, without infinite growth, making the variable sensitive to the cumulative level of public spending, but with diminishing returns, with the possibility of easily calibrating and modifying it for public policy scenarios. In reality, production cannot be continuous, and demand is assumed to be equal to maximum production capacity.

To visualize the relationship between Education and Competencies (C) we set a logistic curve to describe how variable grows with diminishing returns compared to an input (years of education)

$$C(E) = C_{min} + \left(\frac{C_{max} - C_{min}}{1 + e^{-k(E - E_m)}}\right) \tag{14}$$

where E_m is the midpoint, i.e., the years of education at the midpoint of the curve; in Equation (14), the midpoint represents the abscissa of the point (12.9) at which competencies have reached half of the gap between minimum and maximum.

Estimated midpoint indicates that, when the average schooling reaches the equivalent of the end of upper secondary school, competencies increase more rapidly [12,63,81]; the function represents diminishing returns well (after a certain point, more school adds fewer marginal competencies), as shown in Figure 5 (in the ordinate 'years in education') and in Figure 6 (in the ordinate '% of competencies').

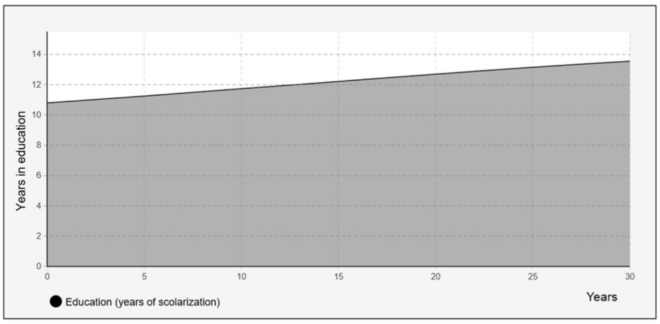

Figure 5. Education trend over time.

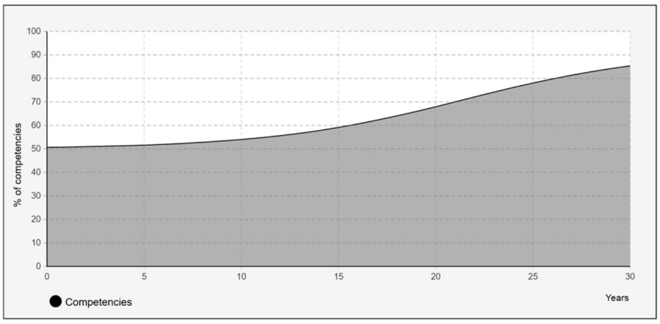

Figure 6. Competencies trend over time.

The loop closes with the relationship of Competencies with Production efficiency (E_p), which takes into account a simple and modular structure being able to isolate the competencies linear effect and the country-system effect represented by the Human Development Index (HDI). Production efficiency is expected to increase proportionally to the competencies of the workforce with the addition of any variable and increasing efficiency bonus with the increase in HDI, according to Equation (15)

$$E_p = E_{min} + (E_{max} - E_{min})\frac{C}{100} + \Delta_{HDI} \tag{15}$$

From an economic point of view, this relationship represents a direct link between human capital and industrial productivity and in the SD model the bonus captures contextual effects whereby a skilled workforce in a country with advanced infrastructure and institutions works more efficiently than one with the same competencies but in a less developed context [24,65,81]. The outcomes' consistency was tested with the forecast of the estimated trend without new production, moving on to an initial evaluation by the experts. In this regard, the trend of traditional production can be observed in the absence of a green H_2 production plant; this mini loop is a wild card for the fiscal system and GDP per capita, representing it as a starting point with a system that increases more slowly without affecting other outputs.

Among the quantitative results, for example, we obtain a different trend in GDP per capita with a 30-year projection with the new plant in operation (final index of 0.94 and a compound annual growth rate of 1.65%/year) and without (final index of 0.92 with a rate of 1.24%/year) compared to the current one highlighting that green H_2 adds about +0.4 percentage points of average annual rate, as well as an optimistic forecast of the growth index with investments in public services as a consequence of traditional production alone (0.868) or with the addition of green H_2 (0.901), also observing a positive trend in competencies rate of the workforce (86.97 vs. 63.42). These outcomes highlight how the model is able to represent scenarios on the impact of the new industrial project well, allowing the decision-maker to deepen the social dimension analysis and develop the necessary policies.

The model therefore proposes results that allow us to understand the impact it makes towards the aforementioned dimensions; in fact, through the CLDs' process and the stock and flow centered on the fiscal system, the relationships and interactions that animate the model act as determining factors for the trend of the economic dimension (higher revenues allow more investments, including in education), production (the growth of production is affected by greater efficiency and competence), environmental (the development of an industrial system oriented towards totally green energy, both as a source of income and as an output of sales and distribution), and social (a higher per capita income generates better local economies, increases the health system of the population and increases the potential for achieving greater local and national well-being), reducing the uncertainty of those who are responsible for making decisions on public policies and development of the territory.

Moving forward, it would therefore be worthwhile to open up the research to other indicators of social behavior such as years of education, quality of employment, environmental impact factors and perception, all key words that are already taken into account by the model, considering the performance of the economy and the growth of education as factors of uncertainty or limitation without a push factor that manages to combine public policies with those relating to conscious industrial development.

5.1. Comparison with SD Literature and Best Practices

SD is commonly used for policy learning in settings where outcomes emerge from feedbacks, delays and nonlinearities rather than from isolated cause–effect relations. Classical SD practice emphasizes transparency of model structure and assumptions, behavioral reproduction of reference modes, and robustness checks through sensitivity and scenario analysis as part of model credibility assessment. In line with these principles, the present model is designed as an exploratory decision-support tool, aimed at identifying leverage points and trade-offs rather than producing point forecasts.

Compared with related SD applications in the energy-transition domain, which often focus on technology diffusion and macro-economic outcomes under policy incentives, this study explicitly couples a fiscal-public services loop with human capital dynamics (education/competencies accumulation) and incorporates social acceptance as an endogenous moderating mechanism affecting implementation speed and delays. This configuration allows us to explore socio-economic pathways relevant to regional development and governance capacity, complementing more techno-economic hydrogen assessments.

Finally, the validation strategy follows a multi-criteria approach that combines quantitative fit (e.g., RMSE on benchmark indicators/KPIs) with pattern-oriented checks (trend reproduction and timing) and systematic uncertainty exploration (sensitivity and adverse scenarios). This approach aligns with established SD recommendations that model credibility should be assessed against the model purpose (policy learning) and the availability of empirical data, rather than solely through pointwise predictive accuracy.

5.2. Endogenous Optimism Risk and Interpretation Boundaries

A central methodological issue in SD models that include development-type mechanisms is the potential for endogenous optimism, i.e., self-reinforcing dynamics that can generate accelerating trajectories when feedback gains are high and delays are short. In this model, reinforcing loops connect economic output, fiscal revenues, public services, human capital accumulation and productivity. Although such structures are theoretically plausible, they may also amplify optimistic outcomes if parameter values implicitly assume strong institutional capacity, sustained fiscal space, and effective policy implementation over time.

For this reason, results are interpreted as conditional pathways. Sensitivity analysis indicates that parameters governing education effectiveness and fiscal feedback strength can materially shift long-run outcomes, while extended delays attenuate or postpone benefits. We therefore treat high-gain reinforcing dynamics as upper-bound pathways rather than baseline expectations, and we highlight the conditions under which the model may overstate benefits (e.g., low delays, high reinvestment effectiveness, high acceptance).

Importantly, incorporating adverse scenarios (crowding-out, fiscal stress, competencies mismatch and low acceptance) mitigates one-sided interpretations and helps identify policy vulnerabilities. The model thus supports decision-making by clarifying where optimistic dynamics originate and which institutional constraints can realistically limit or reverse them.

5.3. Limitations and External Validity

In light of the aforementioned considerations, several limitations must be recognized. First, the model is highly aggregated: it represents the Paysandú socio-economic system through average indicators (e.g., mean years of education, aggregate employment index, GDP per capita proxies). Consequently, it does not capture heterogeneity across municipalities, income groups, gender, or competencies categories, nor does it represent labor-market segmentation and wage distribution mechanisms explicitly. This limits the model's ability to assess distributional impacts beyond stylized proxies (e.g., an inequality pressure indicator).

Second, empirical grounding is constrained by data availability and by the emerging nature of green hydrogen industrialization. Although calibration and validation are conducted on selected historical indicators and complemented with pattern-oriented checks, several parameters remain partially uncertain and scenario-dependent; results therefore depend on assumed ranges for key feedback strengths and time delays.

Third, external validity is limited: the model is tailored to the institutional context and socio-economic structure of Uruguay and the Paysandú department. Transferring results to other countries or regions would require re-parameterization and potentially structural adaptation (e.g., different fiscal regimes, education effectiveness, labor mobility, or governance capacity). Future work should extend the framework by introducing higher-resolution representation of labor-market structure (competencies' categories and wage dynamics), explicit distributional modules, and/or hybrid approaches (e.g., coupling SD with agent-based components) where detailed micro-level mechanisms are essential.

Simulation outcomes are translated into decision-relevant levers by mapping each leverage point to a corresponding policy instrument and identifying the causal pathway through which it affects the evaluated outcomes. Table A7 summarizes the main levers, their model representation, and the expected direction of influence, while Tables A8 and A9 highlight the nomenclature and representation of the main equations in this manuscript. Importantly, the magnitude and timing of effects differ across scenarios: under fiscal stress, reinvestment policies yield delayed benefits; under competencies mismatch, training policies require coordination with industry; under low acceptance, engagement and risk mitigation policies become binding constraints.

The proposed model operates at the macro-regional aggregate level and relies on average indicators to represent social and economic dynamics. As such, it does not explicitly capture intra-regional heterogeneity, income distribution, social stratification, or labor market segmentation. This abstraction is a deliberate modeling choice, consistent with the SD paradigm, which prioritizes the analysis of structural feedbacks and long-term tendencies over distributional detail. However, this choice limits the model's ability to assess differentiated impacts across social groups, occupations, or geographic sub-areas. Consequently, the results should be interpreted as average structural tendencies, rather than as representative of individual or subgroup outcomes. The omission of heterogeneity may lead to an overestimation of aggregate benefits in contexts characterized by unequal access to education, competencies, or employment opportunities.

The model contains reinforcing endogenous loops linking GDP, fiscal revenues, public services, education, competencies, and productivity that could generate path-dependent and self-amplifying dynamics. To avoid artificial growth bias, the following stabilizing mechanisms were introduced: bounded functional forms, time delays in fiscal feedback, upper efficiency constraints, and diminishing returns in education. These mechanisms prevent unlimited expansion. The authors acknowledge that reinforcing structures may amplify initial advantages and therefore results should be interpreted as scenario-based projections rather than predictive certainties.

Future research may address this limitation through the integration of agent-based or hybrid modeling approaches, allowing a more granular representation of social diversity and labor market dynamics.

6. Conclusions

Expressing the complexity of human reactions in a social behavior requires an interdisciplinary approach that is well suited to the SD method, as demonstrated by the study applied to the Uruguayan case, showing the functionality of feedback, dependencies and trends that different scenarios can offer.

It is demonstrated that the new green H_2 industrial production is able to generate the opportunity for a change in terms of new professional competencies, which in turn allow greater efficiency in terms of production. On the other hand, a new entry of revenue into the fiscal system generates new prospects for private investments oriented towards the growth of the local economic fabric and for public investments dedicated to services for the population and for the growth of schooling and education. Finally, the development of an innovative and ecological product oriented towards progressive growth over the years makes it possible to guarantee an increase in GDP per capita, together with a better life expectancy and social well-being, orienting the country towards the goal of a higher HDI.

The study explored some potential socio-economic implications of the industrialization of green hydrogen through an exploratory model of SD applied to the regional context of Paysandú, Uruguay. By explicitly representing feedback mechanisms, institutional constraints, and social acceptance, the model provides a structured framework for examining how public investment, human capital development, and productivity may interact over time.

Operating at the macro-regional aggregate level and relying on average indicators to represent social and economic dynamics, the proposed model does not explicitly capture intra-regional heterogeneity, income distribution, social stratification or labor market segmentation, since this abstraction was a deliberate choice of modeling, consistent with the SD paradigm, to prioritize the analysis of structural feedbacks and long-term trends over distributional detail. Therefore, this choice limits the model's ability to assess differentiated impacts across social groups, occupations or geographical sub-areas and consequently the results should be interpreted as average structural trends, rather than as representative of individual or subgroup outcomes, leading to an overestimation of aggregate benefits in contexts characterized by unequal access to education, competencies or labor opportunities.

The model, which serves as a learning and decision support tool, helping policymakers to identify leverage points, trade-offs and risks in situations of uncertainty, deserves to be implemented in the economic, social, productive and environmental dimensions, orienting the study towards the aspects of the quantity and quality of employment, the social perception of the environmental impact generated by new production and the aspects of the economic repercussions that generate the process of improving well-being.

In fact, in light of the needs of the public decision-maker to outline rules and incentives for the promotion of the territory towards new industrial policies, it may be important to expand information on social evolution thanks to a new investment that concerns natural resources linked to sustainability, human resources conditioned by the growth of training and competencies, the economic aspects that can affect the development of new investments and public services, which in turn can increase life expectancy and develop the social dimension.

The results suggest that positive social outcomes are possible but conditional; strengthening dynamics can only support human capital accumulation and income growth if supported by governance capacity, fiscal coherence, labor market coordination and social legitimacy. Conversely, adverse conditions, such as fiscal stress, crowding effects, or poor social acceptance, can delay or significantly reduce benefits. However, these first results—although limited by the above—demonstrate the versatility of the method and the usefulness of this innovative approach, highlighting the possibility of assessing the impact on industrial intervention from a social and economic point of view and in terms of sustainability and green energy sources.

Given data constraints and the exploratory aim, model credibility is supported through transparent parameter documentation, trend-based calibration, pattern-oriented validation, and systematic sensitivity/scenario analysis, rather than through point forecasting accuracy.

Future research could overcome this limitation through the integration of agent-based or hybrid modeling approaches, to have a more detailed representation of social diversity and labor market dynamics, which open up a perspective of interest from the point of view of sustainability and impact as a useful element and tool to support decision-making. Thus, through robust implementation that may also include the possibility of hybrid or agent-based approaches to better capture heterogeneity and distributional effects, from a strategic engineering perspective the model can contemplate future applications to support public decision-making.

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Abbreviations

H_2	Hydrogen
M&S	Modeling and Simulation
SD	System Dynamics
KPI	Key Performance Indicator
CLD	Causal Diagram Loop
GDP	Gross Domestic Product
LCOE	Levelized Cost of Electricity
INE	Instituto Nacional de Estadística
INEEd	Instituto Nacional de Evaluación Educativa
IRAE	Impuesto a las Rentas de las Actividades Económicas
EMBI	Emerging Markets Bond Index
HDI	Human Development Index
HSC	Hydrogen Supply Chain
CAPEX	Capital Expenditure
MEF	Ministerio de Economía y Finanzas
MIEM	Ministerio de Industria, Energía y Minería
OPEX	Operating Expenditure

OPP	Oficina de Planeamiento y Presupuesto
S-LCA	Social Life Cycle Assessment
RMSE	Root Mean Square Error
TVET	Technical and Vocational Education and Training

Appendix A

Table A1. Literature comparison (symbols' legenda: ✓ = explicitly present; ◐= partial/indirect; — = not explicitly addressed in the model).

Reference	Domain	SD Mechanisms	Validation Approach	Policy Levers Examples
[25]	Public investment/project feasibility (SD and ABM)	Fiscal ✓/Education —/Acceptance —	Empirical benchmarking and dynamic feasibility; mixed-method validation (specific)	Public investment design; project appraisal levers; policy packages
[26]	Sustainable development (systems perspective)	Fiscal ◐/Education ◐/Acceptance ◐	Qualitative SD validation; insight-driven exploration (conceptual)	Broad sustainability policy levers (portfolio/interactions)
[29]	Energy transition/green hydrogen scaling (export scenarios)	Fiscal ◐/Education —/Acceptance —	SD long-term scenario simulation; explicitly SD (in abstract)	Capacity expansion trajectories; enabling conditions for GH2 scaling
[44]	Energy transition (power system policy)	Fiscal ✓/Education —/Acceptance —	Historical fit; Theil statistics (historical data calibration)	Incentives, capacity payments, regulatory actions (market design)
[45]	Energy transition (green hydrogen industry)	Fiscal ✓/Education —/Acceptance —	Model validation; scenario simulation (policy scenarios)	Subsidy type/intensity/duration, income tax rate, electricity price support
[43]	Energy transition (socio-political feasibility/governance)	Fiscal ◐/Education —/Acceptance ✓	Calibrated to historical data; exogenous uncertainty analysis	Governance and planning, policy implementation intensity, 'political capital' management
[41]	Acceptance/behavior in climate mitigation (building renovation)	Fiscal ◐/Education —/Acceptance ✓	Behavioral pattern exploration (further investigations needed)	Subsidies, certification systems, training of experts; intensity pulses vs. long low-intensity policies
[62]	Regional development/infrastructure socio-economic impacts	Fiscal ◐/Education —/Acceptance ◐	SD-based CBA; sensitivity analysis over time	Infrastructure investment options; timing/phasing of investment
[42]	Energy transition (SD review and social aspects)	Fiscal ◐/Education ◐/Acceptance ◐	Review of how SD models incorporate social aspects (meta-validation)	Identifies categories of social-policy integration in SD energy models

Table A2. Systematic sensitivity analysis parameters.

Type	Indicators	Sources
Structural	education elasticity, delays	[28,46,47,56]
Contextual	GDPpc, fiscal rates	[46,57]
Exploratory	feedback strength	scenario

Table A3. Parameters' registry.

Symbol	Model/Dataset	Baseline	Unit	Range/Scenario	Source Class	Equation/Section
β_E	Education	0.17	1/year	±20% one-at-a-time	Structural (lit. and calib.)	Equation (6), Section 5
τ_E	Education delay	3.0	year	±20% one-at-a-time	Structural (assump. and lit.)	Equation (6), Section 5
α_F	Fiscal feedback rate	0.08	–	±20% one-at-a-time	Exploratory (scenario)	Equation (3), Section 4.3
α_I	Reinvestment rate	0.35	–	±20% one-at-a-time	Exploratory (policy lever)	Equation (4), Section 4.3

Table A3. *Cont.*

Symbol	Model/Dataset	Baseline	Unit	Range/Scenario	Source Class	Equation/Section
β_P	Productivity by Compentencies	0.60	–	±20% one-at-a-time	Structural (lit. and assump.)	Equation (7), Section 5
γ	Information	0.20	1/year	±20% (robustness)	Structural (acceptance lit.)	Equation (2), Section 3.2
δ	Perceived risk	0.22	1/year	±20% (robustness)	Structural (acceptance lit.)	Equation (2), Section 3.2
r_disc	Discount rate	MC	%	uncertainty (MC)	Context/Exploratory	Investment appraisal
Risk	Country risk	MC	index	uncertainty (MC)	Context/Exploratory	Investment activation
τ_reg	Delay time	MC	year	low acceptance scenario	Exploratory (scenario)	Delay modifier
r_ret	Fiscal return	MC	%	uncertainty (MC)	Context/Exploratory	Profitability
Shock_P	Shock production	MC	–	uncertainty (MC)	Exploratory	Production trajectory

Table A4. Variable mapping.

Variable	Data	Unit	Notes
GDP per capita	GDPpc (time-series)/GDP (MC endpoint)	USD/person/year	Calibration; scenarios and sensitivity
Employment	EmploymentIndex	index (baseline = 1)	Scenarios and sensitivity; interpretable as relative employment
Education	EducationYears	year	Calibration; scenarios and sensitivity
Social acceptance	Acceptance	0–1	Endogenous stock, affecting investment speed and delays
Well-being	Human Index	index	MC endpoint/composite indicator
H_2 output	H_2 Production	ton/year	Plant output; scenarios
Inequality	InequalityVariable	index	Adverse scenarios (crowding-out, mismatch)

Table A5. Scenario matrix.

Scenario	Mechanism	Model Implementation (Parameter/Levers)	Expected Effect
Fiscal stress (short-term)	Upfront fiscal pressure reduces capacity to expand public services temporarily	Temporary reduction in effective public services/reinvestment effectiveness; slower fiscal return	Delayed education and productivity gains; lower GDPpc in early years
Competencies mismatch	Competencies accumulation translates weakly into productivity due to mismatch	Reduce competencies → productivity linkage β_P (or equivalent) during early years	Education increases but weaker GDPpc/employment response
Low acceptance	Low legitimacy increases delays and reduces investment activation/policy feasibility	Lower initial acceptance A(0); increase delay amplification when $A < 0.5$; reduce investment activation	Slower ramp-up; delayed benefits; potentially lower endpoints

Table A6. Sensitivity parameters and perturbation design.

Parameter	Baseline	Perturbations	Primary Pathway	Main Outputs Affected	Meaning
β_E (education effectiveness)	0.17	0.8×, 1.2×	E(t) accumulation speed	EducationYears, GDPpc, EmploymentIndex	education effectiveness/elasticity, spending
τ_E (education delay)	3.0 years	0.8×, 1.2×	Delay amplification	EducationYears, GDPpc	education delay
α_F (fiscal feedback rate)	0.08	0.8×, 1.2×	GDP→Fiscal syst. → Services loop gain	GDPpc, Human Index	fiscal feedback strength

Table A6. *Cont.*

Parameter	Baseline	Perturbations	Primary Pathway	Main Outputs Affected	Meaning
α_I (reinvestment rate)	0.35	0.8×, 1.2×	Investment → Services → Competencies	GDPpc, EmploymentIndex	reinvestment rate
β_P (competencies→ productivity)	0.60	0.8×, 1.2×	Competencies translation into output	GDPpc, EmploymentIndex	productivity linkage, competencies vs. efficiency

Table A7. Policy implications.

Lever	Model Variable(s)	Policy Instrument	Primary Outcome(s)	Expected Effect	Key Risk/Trade-Off
Training capacity	β_E, EducationYears	TVET programs, curricula, funding	employment, GDPpc	↑ competenciess → ↑ productivity	delay τ_E, mismatch
Regulatory speed	timeDelay	permitting reform, strike	GDPpc, employment	↓ delay → earlier benefits	legitimacy/ acceptance
Reinvestment rules	α_I	local fund, revenue earmarking	Human Index, education	↑ public services	fiscal constraints
Acceptance building	Information, perceivedRisk, A(t)	engagement, monitoring, safety	all	↑ feasibility and speed	costs, credibility
Fiscal incentives	fiscalRate	fiscal relief, IRAE, fiscal tools	investment, labor	↑ investment	fiscal stress

Table A8. Main Parameters and Variables Terminologies.

Symbol	Definition	Dimensions/Units
Variables		
$E(t)$	*Education level (average years of education)*	Years
$C(E)$	*Competence level*	Adimensional (0–100 or normalized)
$A(t)$	*Social Acceptance*	Adimensional (0 to 1)
I_{eff}	*Effective Investment (adjusted by acceptance)*	Currency (USD)/Time
$I_{plant}(t)$	*Planned Investment*	Currency (USD)/Time
I_{priv}	*Private Investment*	Currency (USD)/Time
$P_s(t)$	*Selling price (H_2 or energy)*	Currency (USD)/Energy unit
P_{net}	*Net Profit*	Currency (USD)
E_p	*Production Efficiency*	Adimensional/Percentage
$S_{pub}(t)$	*Accumulated public investment in education*	Currency (USD)
$fiscalSystem$	*Fiscal System Stock (budget)*	Currency (USD)
$fiscalReturn$	*Fiscal Return (tax collection from services)*	Currency (USD)/Time
Parameters		
E_{max}	*Theoretical maximum education level*	Years
E_0	*Initial education level*	Years
C_{max}/C_{min}	*Upper and lower competence limits*	Adimensional
ε	*Public investment efficiency rate*	1/Currency (USD)
γ	*Information influence coefficient*	1/Time
δ	*Perceived risk impact coefficient*	1/Time
τ_0	*Baseline implementation delay*	Time (Years/Months)
τ_{delay}	*Fiscal return delay time*	Time (Years)
β_E	*Public expenditure elasticity*	1/Currency (USD)
ρ	*Public services feedback rate*	Adimensional
k	*Growth or decay constant*	1/Time
r_f, r_s, r_c	*Risk rates (financial, social, country)*	Adimensional (Decimal rate)
y	*Public services to tax multiplier*	Adimensional
α	*Investment propensity factor*	Adimensional

Table A9. Main equations' system focus.

Equation	Variables	Description
$P_s(t) = P_{max} - (P_{max} - P_0)e^{(-kt)}$		**selling price**
	P_{max}	*maximum sustainable price*
	P_0	*initial price*
	k	*rate of growth*
$fiscalSystem(t) = \int_{t_0}^{t_n} \left(tax_{H2Prod} + tax_{tradProd} + tax_{privInv} + fiscalReturn\right) dt$		**fiscal system**
	$taxH_2Prod$	*taxation generated by new production*
	$taxtradProd$	*taxation generated by traditional production*
	$taxprivInv$	*taxation generated by private investment*
	$fiscalReturn$	*taxation generated by new businesses, new jobs, new commercial establishments*
$fiscalReturn = \rho\ publicServices\left(t - \tau_{delay}\right)$		**fiscal return by public services**
	ρ	*feedback effect by public services as taxation on the activities generated*
	t	*time in years*
	τ_{delay}	*time delay in years to simulate a non-immediate effect*
$I_{priv} = P_{net}\ \alpha \left[1 - \left(r_f + r_s + r_c\right)\right]$		**private investment**
	P_{net}	*net profit from the sale of green hydrogen*
	α	*correction rate*
	r_f	*risk rate*
	r_s	*discount rate*
	r_c	*country risk*
$E(t) = E_{max} - (E_{max} - E_0)e^{-\varepsilon S_{pub}(t)}$		**education**
	E_{max}	*maximum education*
	E_0	*initial education*
	S_{pub}	*public spending in education*
	ε	*education sensitivity to public spending (on public services)*
$\frac{dE}{dS_{pub}} = \varepsilon\,(E_{max} - E)$		**differential equation in education on public services**
	E_{max}	*maximum education*
	$E_{max} - E$	*residual gap in education*
	S_{pub}	*public spending in education*
	ε	*education sensitivity*
$C(E) = C_{min} + \left(\frac{C_{max} - C_{min}}{1 + e^{-k(E - E_m)}}\right)$		**competencies vs education**
	C_{max}	*maximun competencies*
	C_{min}	*minimum competencies*
	E	*education*
	E_m	*midpoint in education*
	k	*slope coefficient*
$E_p = E_{min} + (E_{max} - E_{min})\frac{C}{100} + \Delta_{HDI}$		**production efficiency**
	E_{min}	*maximum education*
	E_{max}	*minimum education*
	C	*competencies*
	HDI	*Human Development Index*
	Δ_{HDI}	*efficiency bonus (+0.01, +0.02, +0.03) if HDI exceeds over 0.85, 0.90, 0.95*
$\frac{dA}{dt} = \gamma Information - \delta perceivedRisk$		**social acceptance**
	γ	*information translation sensitivity*
	δ	*social acceptance risk sensitivity*

Appendix B

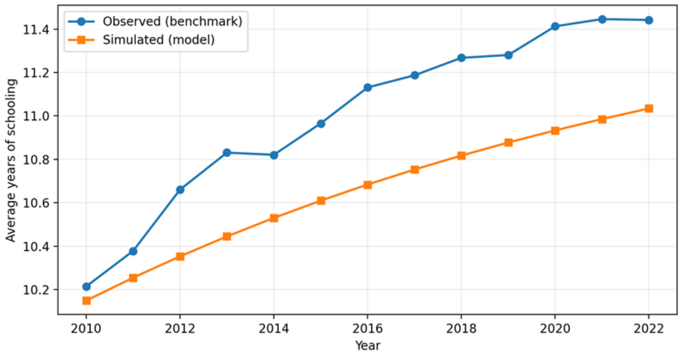

Figure A1. Education.

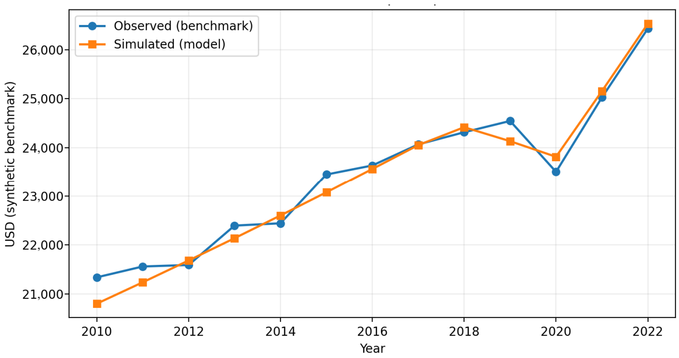

Figure A2. GDPpc.

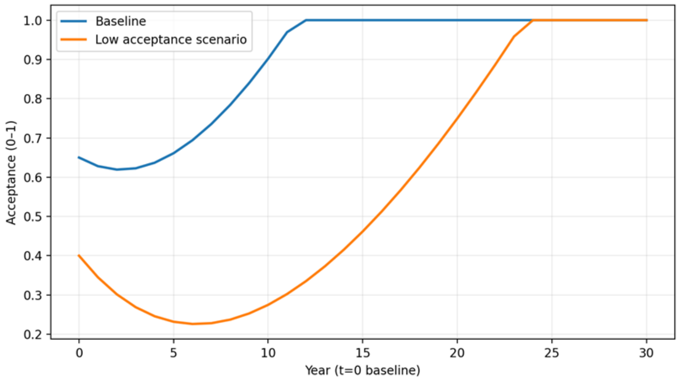

Figure A3. Acceptance scenario.

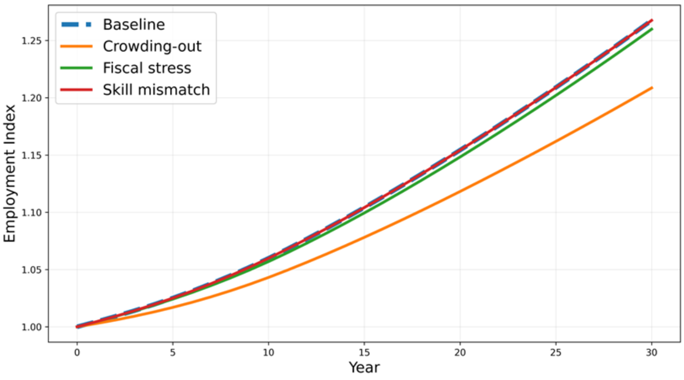

Figure A4. Employment scenario.

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