Modelling the dynamics of Spain's electricity energy mix: evolution of generation shares over time

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Abstract

This report investigates the long-term evolution of Spain's electricity generation mix using a mathematical model based on replicator dynamics. Five main technologies—fossil fuels, nuclear, wind, solar, and hydroelectric power—are considered, and their shares are modelled as state variables constrained to a simplex[1]. The model incorporates effective growth rates determined by investment, technological progress, policy incentives, and resource availability. Qualitative analysis identifies conditions for equilibrium and stability, highlighting that, in generic scenarios, the technology with the highest effective growth rate dominates the market in the long term. Numerical simulations explore three scenarios: a baseline business-as-usual case, a renewable support scenario with enhanced policy incentives, and a nuclear phase-out scenario. Results indicate that solar and wind power increasingly dominate the energy mix, with solar energy achieving the largest share under most scenarios, consistent with recent trends in Spain's installed capacity.

[1]Here, the simplex refers to the set of vectors $x \in R^5$ such that $x_i \geq 0$ for all i and $\sum_{i=1}^{5} x_i = 1$. In this context, it represents all possible combinations of generation shares that sum to the total electricity output.

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1 Introduction

Spain's electricity generation mix has changed significantly over the last decade, mainly due to the rapid expansion of renewable energy sources and the gradual reduction of fossil fuel generation. In 2024, renewables such as wind, solar photovoltaic, and hydroelectric power accounted for approximately 56.8% of total electricity generation, representing a noticeable increase compared to previous years [1]. Provisional data for 2025 indicate that this trend continued, with renewable shares exceeding 60% in several months [2].

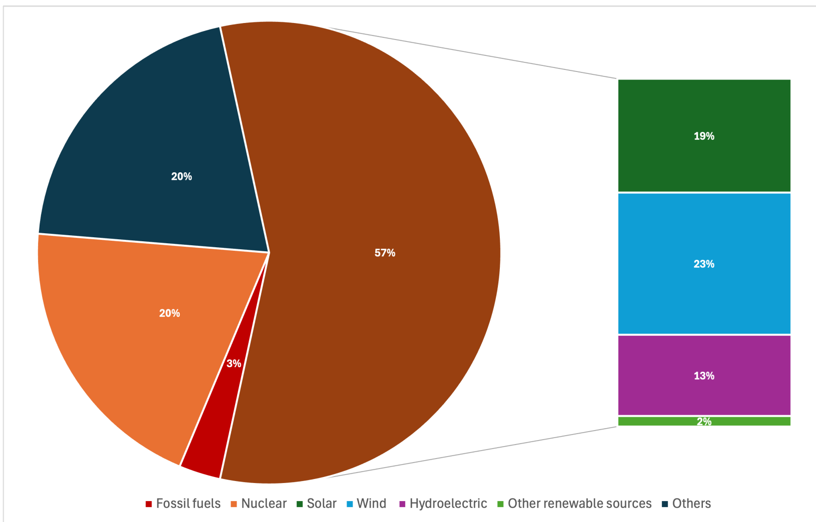

Figure 1: Spain's 2024 energy mix in electricity shares.

These developments make Spain a relevant case study for analysing how electricity generation systems evolve over time, especially under conditions of high renewable penetration. At the same time, the increasing share of variable renewable sources introduces challenges related to grid operation and system stability.

An example that illustrates these challenges is the large blackout that occurred on the 28$^{\text{th}}$ of April 2025, affecting Spain and some parts of Portugal. Although renewable generation was initially discussed as a possible contributing factor, later investigations indicated that the event was mainly caused by technical and planning issues in grid operation rather than by renewable output itself [3, 4]. Nevertheless, this event highlighted the importance of understanding how different technologies interact within a changing electricity mix.

Therefore, the problem addressed in this study is of particular interest due to the inherently dynamic nature of electricity generation systems and the increasing complexity introduced by the energy transition. The composition of an electricity energy mix is not static; instead, it evolves continuously in response to economic, technological, regulatory, and environmental factors. In the case of Spain, these dynamics are especially pronounced, given the rapid expansion of renewable generation, the gradual phase-out of certain fossil fuel technologies, and the growing relevance of energy security and grid stability considerations.

Lastly, my personal experience working in one of Spain's largest gas companies on renewable projects, including biomethane and hydrogen initiatives, has further motivated my interest in the dynamics of energy transitions. This background has underscored the importance of rigorous mathematical modelling to support strategic planning and to anticipate the impacts of regulatory and market changes on the energy system.

2 Mathematical model

2.1 Energy sources and state variables

We consider the evolution of the shares of five electricity generation technologies in Spain:

- Fossil fuels (coal and natural gas),
- Nuclear power,
- Wind power,
- Solar power,
- Hydroelectric power.

Let

$$x_F(t),\ x_N(t),\ x_W(t),\ x_S(t),\ x_H(t) \in [0,1]$$

denote the fraction of total electricity generation produced by each source at time t. The total electricity generation share must be 1:

$$x_F + x_N + x_W + x_S + x_H = 1 \quad \text{for all } t \geq 0.$$

2.2 Parameters

The dynamics of each energy source are governed by four distinct types of parameters:

- **Investment rates** $I_i \geq 0$: representing capital allocation, construction of new capacity, and replacement of existing infrastructure.
- **Technological improvement rates** $T_i \geq 0$: accounting for efficiency gains, cost reductions, and learning effects.
- **Policy incentive parameters** $P_i \in R$: capturing subsidies, carbon pricing, regulatory support, or penalties.

- **Resource availability factors** $R_i \in (0, 1]$: representing physical or geographical constraints, such as water availability for hydroelectric power or land and weather conditions for renewables.

The subscript $i \in \{F, N, W, S, H\}$ denotes the corresponding energy source.

2.3 Modelling assumptions

To keep the model simple and suitable for qualitative analysis, we adopt the following assumptions:

1. Electricity demand is assumed to be constant over the time horizon considered, so that different energy sources compete for a fixed total level of generation.
2. Changes in the electricity mix are assumed to occur gradually and can therefore be described using continuous-time dynamics.
3. Investment, technological progress, and policy incentives are modelled as factors that affect the growth or decline of each energy source independently.
4. Physical and geographical constraints are represented through resource availability factors that limit the effective growth of certain technologies.
5. Interactions between energy sources arise through competition for market share.
6. All model parameters are assumed to be constant in time, representing average conditions over a medium-term horizon.

2.4 Derivation of the model equations

For each energy source i, we introduce an effective growth rate defined as

$$g_i = I_i + T_i + P_i,$$

which combines the effects of investment, technological improvement, and policy incentives into a single parameter.

Resource availability is included by scaling the growth rate with a factor R_i. This accounts, in a simplified way, for physical or geographical constraints that limit the expansion of certain technologies, such as hydroelectric power.

To model competition between energy sources, we assume that the growth of each share is proportional to its current value and reduced by the overall occupation of the electricity mix. Under these assumptions, the evolution of the energy shares is described by the following system of Ordinary Differential Equations:

$$\frac{dx_F}{dt} = x_F \left(R_F g_F - \Phi(t) \right), \tag{1}$$

$$\frac{dx_N}{dt} = x_N \left(R_N g_N - \Phi(t) \right), \tag{2}$$

$$\frac{dx_W}{dt} = x_W \left(R_W g_W - \Phi(t) \right), \tag{3}$$

$$\frac{dx_S}{dt} = x_S \left(R_S g_S - \Phi(t) \right), \tag{4}$$

$$\frac{dx_H}{dt} = x_H \left(R_H g_H - \Phi(t) \right), \tag{5}$$

where $\Phi(t)$ represents the weighted average growth rate of the system and is defined below.

2.5 Relation to replicator dynamics and conservation laws

The system of equations (1)–(5) has the structure of a *replicator dynamical system*, a class of models commonly used in evolutionary game theory and population dynamics to describe competition among different types under a fixed total resource [5, 6, 7].

Canonical replicator equations. In their standard form, replicator equations describe the evolution of proportions

$$x_i(t) \geq 0, \qquad \sum_{i=1}^{n} x_i(t) = 1,$$

according to

$$\frac{dx_i}{dt} = x_i\big(f_i(x) - \bar{f}(x)\big), \qquad \bar{f}(x) = \sum_{j=1}^{n} x_j f_j(x), \tag{6}$$

where $f_i(x)$ represents the fitness or payoff of type i, and $\bar{f}(x)$ is the average fitness of the population. Types with above-average fitness increase their relative share, while those with below-average fitness decrease.

Identification with the energy mix model. In the present model, the "types" correspond to electricity generation technologies, and the variables $x_i(t)$ represent their shares in total electricity generation. The fitness values are assumed to be constant and are given by

$$f_i = R_i g_i = R_i(I_i + T_i + P_i).$$

With this choice, equations (1)–(5) can be written in the compact form

$$\frac{dx_i}{dt} = x_i\big(f_i - \Phi(t)\big), \qquad \Phi(t) = \sum_j x_j f_j,$$

which corresponds to a replicator system with constant fitness parameters.

Conservation law and invariant simplex. An important property of replicator systems is the conservation of the total sum of the state variables. Summing the right-hand side of the equations yields

$$\frac{d}{dt}\sum_i x_i = \sum_i x_i(f_i - \Phi) = \sum_i x_i f_i - \Phi \sum_i x_i = \Phi - \Phi = 0.$$

Therefore, if the initial condition satisfies $\sum_i x_i(0) = 1$, then

$$\sum_i x_i(t) = 1 \quad \text{for all } t \geq 0.$$

This implies that the dynamics are confined to the simplex of admissible energy mixes. In the present context, this reflects the assumption that total electricity generation is fixed and that different technologies compete for relative shares.

3 Qualitative analysis

Having defined the system of Ordinary Differential Equations, we now analyze its qualitative properties, focusing on equilibrium points, their stability, and the resulting long-term behaviour.

3.1 Equilibrium points

An equilibrium point x^* satisfies

$$\frac{dx_i}{dt} = 0 \quad \forall i,$$

which implies

$$x_i^*\left(R_i g_i - \Phi^*\right) = 0, \quad \Phi^* = \sum_j x_j^* R_j g_j.$$

For each energy source i, this condition implies that either

1. $x_i^* = 0$, meaning that the technology is absent from the energy mix, or
2. $R_i g_i = \Phi^*$, meaning that its effective growth rate equals the average growth rate of the system.

As a consequence, any equilibrium with more than one active technology must satisfy

$$R_i g_i = R_j g_j \quad \text{for all } i, j \text{ such that } x_i^*, x_j^* > 0.$$

This shows that coexistence equilibria exists only when the corresponding effective growth rates are exactly equal. In the generic case where the values $R_i g_i$ differ, the only equilibria are:

$$x_k^* = 1, \quad x_{i \neq k}^* = 0,$$

which correspond to the dominance of a single energy source.

3.2 Stability of equilibria

To study local stability, we linearize the system around an equilibrium point x^*. The Jacobian matrix $J = (\partial f_i / \partial x_j)$ has entries

$$\frac{\partial f_i}{\partial x_j} = \begin{cases} R_i g_i - \Phi^* - x_i^* R_i g_i, & i = j, \\ -x_i^* R_j g_j, & i \neq j. \end{cases}$$

We first consider $x_k^* = 1$. For $i \neq k$, small perturbations evolve according to

$$\frac{dx_i}{dt} \approx x_i (R_i g_i - R_k g_k).$$

If

$$R_k g_k > R_i g_i \quad \forall i \neq k,$$

then all perturbations decay exponentially, and the equilibrium is locally asymptotically stable.

Equilibria with multiple active technologies arise only when several values of $R_i g_i$ are equal. In this case, the Jacobian matrix would have zero eigenvalues, which implies neutral stability.

3.3 Long-time behaviour

The qualitative analysis leads to the following observations:

- For generic parameter values, solutions converge to a pure equilibrium corresponding to the dominance of the energy source with the largest effective growth rate $R_i g_i$.
- Coexistence of multiple technologies requires exact equality of effective growth rates which, in a real scenario, is pretty hard to have.

Interpretation. Within the limits of this simplified model, the qualitative analysis shows that small differences in effective growth rates determine which technology dominates the market in the long term. This provides a theoretical reference point for interpreting the numerical simulations presented in the next section.

4 Numerical simulations

Closed-form solutions of the system (6) are not available in general due to its nonlinear structure. Therefore, we define a series of numerical simulations in order to understand how the system we defined earlier might evolve when changing the parameters. The code used to obtain the results is available in a public GitHub repository [8].

4.1 Numerical method

The system is integrated using fourth-order Runge–Kutta (RK4) method.

4.1.1 Preservation of the simplex

The state variables are constrained to the simplex

$$\Delta = \left\{ x \in R^5 : x_i \geq 0,\ \sum_{i=1}^{5} x_i = 1 \right\}.$$

At the continuous level, the replicator structure guarantees that solutions starting in Δ remain in Δ for all times.

In numerical simulations, small violations of non-negativity or mass conservation may arise due to round-off and discretisation errors. To control these effects, the solution is corrected after each time step by enforcing

$$x_i \leftarrow \frac{\max(x_i, 0)}{\sum_j \max(x_j, 0)}.$$

4.2 Choice of initial conditions and renormalisation

The initial condition is chosen to represent the current composition of Spain's electricity generation mix in aggregated form. Approximate shares of the main technologies are given in Table 1.

Energy source	Share of electricity generation
Fossil fuels	3%
Nuclear	20%
Solar	19%
Wind	23%
Hydroelectric	13%
Other categories	22%

Table 1: Observed shares of electricity generation by energy source in Spain.

The model explicitly includes five technologies: fossil fuels, nuclear, solar, wind, and hydroelectric power. Other categories are not represented as separate variables. Therefore, to satisfy the conservation constraint of the replicator dynamics,

$$x_F(t) + x_N(t) + x_S(t) + x_W(t) + x_H(t) = 1,$$

the observed shares of the five included technologies are renormalised so that their sum equals one.

The combined observed share of the modelled sources is

$$0.03 + 0.20 + 0.19 + 0.23 + 0.13 = 0.78.$$

The initial condition is therefore defined as

$$x_i(0) = \frac{\text{observed share of source } i}{0.78}, \quad i \in \{F, N, S, W, H\}.$$

This yields the numerical values:

Energy source	Renormalised initial share $x_i(0)$
Fossil fuels	0.038
Nuclear	0.256
Solar	0.244
Wind	0.295
Hydroelectric	0.167

Table 2: Renormalised initial shares of the modelled electricity generation technologies in Spain.

4.3 Results

4.3.1 Baseline scenario: business-as-usual dynamics

We first consider the baseline scenario, which represents the evolution of Spain's electricity mix if we kept the same environmentally-aware mindset we have now in the future . The initial condition corresponds to the renormalised present-day energy shares, and the effective growth rates are chosen to reflect moderate renewable expansion, stable nuclear capacity, limited fossil-fuel growth, and fixed resource constraints.

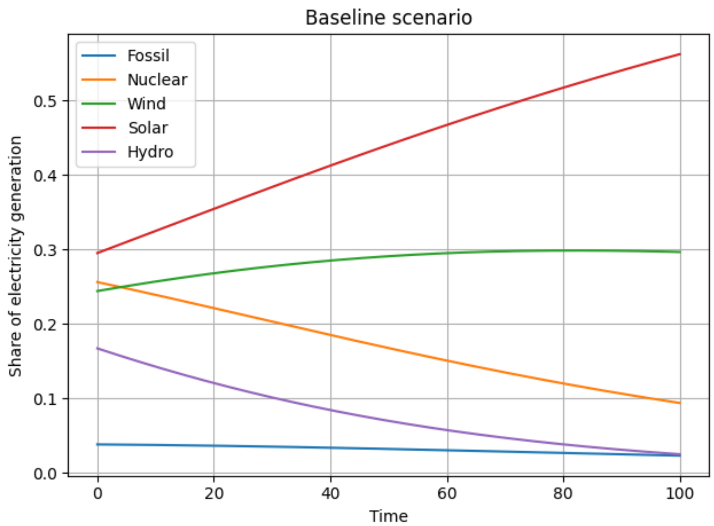

Figure 2: Baseline Scenario.

Figure 2 shows the time evolution of the market shares over a 100-year horizon. In this scenario, solar energy increases steadily and becomes the largest share of generation by the end of the simulation. By year 100, its share exceeds 50% of total electricity generation. This outcome aligns with recent developments in Spain's electricity system: in 2024, solar photovoltaic (PV) capacity became the single largest installed technology in Spain, surpassing wind power and accounting for nearly 25% of total installed power capacity [9].

Wind power also exhibits a positive growth trend, but at a slower pace than solar energy. Its market share increases during the first decades of the simulation and stabilises after approximately 60 years, remaining around 30%. This saturation reflects both its lower effective growth parameters relative to solar power and the presence of structural constraints limiting further expansion. In the Spanish context, this assumption is supported by recent evidence showing a slowdown in new wind capacity additions, linked to factors such as permitting delays, grid constraints, and increased project complexity as the most favourable sites have already been developed [10]. As a result, wind power grows initially but does not achieve long-term dominance within the fixed-share framework of the model.

Nuclear energy follows a decreasing trajectory, declining steadily from its initial share to slightly below 10% after 100 years. This decrease results from competition with faster-growing renewable technologies in the absence of strong positive growth drivers.

Fossil fuels remain at low market shares throughout the simulation, with a slight downward trend. Hydroelectric power also declines over time and converges to a similar share as fossil fuels by the end of the simulation. In the case of hydroelectric power, this behaviour is driven primarily by strong resource limitations, which restrict its ability to compete with expanding solar and wind generation.

Conclusion In the baseline scenario, the system converges towards an energy mix dominated by renewable sources, primarily solar and wind power. Nuclear energy, hydroelectric power, and fossil fuels all lose relative importance over time. The results are consistent with the qualitative analysis, which predicts convergence towards the technology with the highest effective growth rate.

4.3.2 Renewable support scenario

We next analyse a renewable support scenario, in which the effective growth rates of solar and wind power are increased relative to the baseline case, while fossil fuels receive reduced support. Resource availability factors and initial conditions are unchanged.

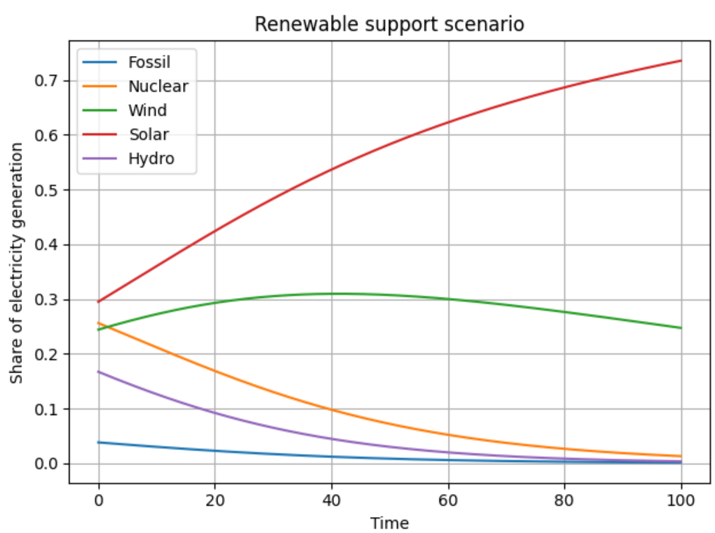

Figure 3: Renewable Support Scenario.

Figure 3 shows the resulting dynamics over a 100-year time horizon. Solar power grows rapidly and becomes strongly dominant, exceeding 70% of total electricity generation by the end of the simulation. This outcome reflects its substantially increased effective growth rate relative to all other technologies.

Wind power displays a non-monotonic evolution. Its share initially increases and reaches a maximum slightly above 30% after approximately 40 years. Subsequently, wind power loses market share and stabilises at around 25%. This behaviour results from competition within the fixed-share system: although wind power benefits from policy support, solar power's higher growth rate ultimately limits wind's long-term expansion.

Hydroelectric power declines throughout the simulation at a faster rate than in the baseline scenario. Increased competition from rapidly expanding renewables, combined with strong resource constraints, accelerates its relative decline. Nuclear energy follows a similar decreasing trend, maintaining a slightly higher share than hydroelectric power but remaining unable to compete with the supported renewable technologies.

Fossil fuels experience a more pronounced decline than in the baseline case. Their share decreases steadily over time and becomes marginal by the end of the simulation, reflecting both low effective growth rates and increased competitive pressure.

Conclusion Enhanced support for renewable technologies accelerates convergence towards a highly concentrated energy mix dominated by solar power. While both solar and wind initially benefit from increased growth rates, competition between them leads to the long-term dominance of a single technology.

4.3.3 Nuclear phase-out scenario

We finally consider a nuclear phase-out scenario, implemented by introducing a time-dependent effective growth rate for nuclear energy that becomes negative after $t = 40$ years. All other technologies evolve according to baseline or moderately enhanced growth rates. This scenario was motivated by the fact that, in 2023, the spanish government issued its plan to begin a nuclear phase-out so that, by 2035, all nuclear centrals would be shut down [11].

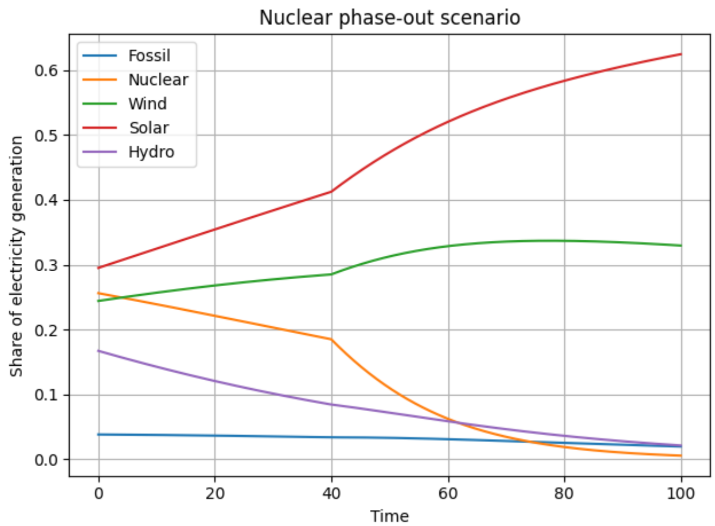

Figure 4: Nuclear Phase-out Scenario.

The results are shown in Figure 4. A clear change in curvature is visible at approximately $t = 40$ years in several trajectories, corresponding to the imposed policy shock.

Solar power increases steadily during the first 40 years and accelerates after the nuclear phase-out is introduced. By the end of the simulation, its share exceeds 60% of total electricity generation. This acceleration reflects the reallocation of market share from nuclear power towards the technology with the highest effective growth rate.

Wind power follows a similar but less pronounced pattern. Its share increases until approximately year 80, reaching around 33–34%, after which a slight decline occurs. The subsequent stabilisation reflects increasing competition from the rapidly expanding solar technology.

Nuclear energy shows the strongest response to the policy intervention. Prior to $t = 40$, its share decreases gradually. Once the effective growth rate becomes negative, the decline accelerates, driving nuclear power to a residual share of approximately 1% by the end of the simulation.

Fossil fuels and hydroelectric power both decrease throughout the simulation. Hydroelectric power declines more sharply, approaching a share of about 2% after 100 years, while fossil fuels decrease more slowly and retain a small but persistent presence.

Conclusion Introducing a negative growth rate for nuclear energy leads to its rapid decline and redistribution of market share towards renewable technologies, particularly solar power. The model predicts a structurally irreversible transition once the phase-out is implemented.

5 Limitations and directions for further work

5.1 Limitations

While the replicator-type model developed in this report captures essential aspects of Spain's long-term electricity market dynamics, several limitations should be acknowledged:

1. **Aggregation of technologies.** Our model restricts the system to five main energy sources, aggregating multiple fossil fuel types and excluding smaller renewable sources (e.g., biomass, geothermal). This simplification may overlook competition and substitution effects between other technologies.

2. **Time-invariant parameters.** Except for the nuclear phase-out scenario, all effective growth rates and resource availability factors are assumed constant over time. In reality, technological progress, investment flows, and policy incentives vary continuously and are influenced by economic cycles, political decisions, and market conditions.

3. **No storage or grid constraints.** The model does not account for operational limitations, electricity storage, transmission capacity, or demand fluctuations, which are critical in real electricity systems, especially for intermittent renewables such as wind and solar.

4. **Single-country focus.** The model considers only Spain and does not account for cross-border electricity trade, regional variations in renewable potential, or international policy influence, which can be important in an integrated European energy market.

5.2 Directions for further work

Future extensions could address these limitations by:

- Incorporating electricity demand dynamics and grid constraints to study operational feasibility and security of supply.

- Implementing feedback mechanisms where investment, policy, and technology evolve over time rather than being fixed parameters.

- Expanding the model to a multi-region framework to capture cross-border interactions and European energy market dynamics.

Despite these simplifications, the current model provides a clear and interpretable framework for understanding the qualitative effects of investment, technological improvement, policy, and resource availability on the long-term evolution of the Spanish electricity mix. It also serves as a foundation for more sophisticated and realistic models in future work.

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