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GUSTAVO ONOFRE ANDREÃO

ENERGY TRANSITIONS' POLICY MIXES

MIX DE POLÍTICAS EM TRANSIÇÕES ENERGÉTICAS

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GUSTAVO ONOFRE ANDREÃO

ENERGY TRANSITIONS' POLICY MIXES

Prof. Dr. José Maria Ferreira Jardim da Silveira – orientador
Prof. Dr. Miguel Vazquez Martinez – coorientador

Defendida em 14/12/2023

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"En fin, que acaba el decimocuarto asalto con Rocky Balboa [màs o menos] en pie." Tese do Miguel, pág 8 (2011)

Resumo

A mudança climática é um fenômeno diretamente ligado ao aumento das emissões de gases de efeito estufa causadas pelo homem. Como sociedade, devemos agir e desenvolver meios para mitigar a mudança climática e seus efeitos. O setor energético é um dos principais emissores de gases de efeito estufa em todo o mundo. Os sistemas elétricos são uma parte relevante do setor de energia. Uma maneira de mitigar a mudança climática é a transição para mixes de eletricidade de baixo carbono por meio do aumento da participação de fontes renováveis e do declínio da geração de eletricidade a partir de combustíveis fósseis. Essa solução está sendo tentada tanto por países desenvolvidos (por exemplo, países da União Europeia) quanto por países em desenvolvimento. Esta tese se concentra nas transições energéticas para sistemas de baixo carbono em países em desenvolvimento usando combinações de políticas com enfoque em setores elétricos. Nesse sentido, pretendemos analisar com mais profundidade os efeitos das restrições financeiras desses países em desenvolvimento sobre os processos de transição, bem como analisar os efeitos das interações entre políticas nesse contexto. Do ponto de vista metodológico, partimos do arcabouço "Institutional Analysis and Development" (IAD) de Ostrom. A estrutura IAD foca nas interações e resultados dos agentes em uma situação delimitada por múltiplas regras. Essas interações ocorrem em um modelo de simulação computacional denominada Technology, Finance and Energy (TeFE), ou seja, usamos um modelo baseado em agentes para simular as interações. Esses agentes simulados são: produtores de tecnologia, responsáveis pela produção de ativos de geração de eletricidade; fornecedores de energia, que adquirem esses ativos para produzir eletricidade; um formulador de políticas energéticas, responsável pelo mecanismo de leilão; um formulador de políticas tecnológicas, responsável por incentivar os produtores de tecnologia; e um banco de desenvolvimento, responsável pelo financiamento da aquisição de ativos de geração de eletricidade por produtores de energia com taxas de juros subsidiadas. Os agentes na estrutura IAD também são capazes de avaliar resultados e se adaptar. Em nossa análise, os agentes seguem a heurística "Satisficing" de Simon. As interações ocorrem em um contexto no qual a dependência do caminho, custos irrecuperáveis e inovação estão presentes, o que destaca a relevância da adoção de tecnologia. Os resultados do modelo mostram que um mix de políticas no qual várias políticas são combinadas leva a transições energéticas que são entendidas como melhores por formuladores de políticas e entidades privadas, ou seja, transições energéticas que geram maiores lucros e alcançam melhor os objetivos de política. Além disso, mixes de políticas com múltiplas políticas alcançam esse status mais rapidamente do que cenários com apenas uma política em vigor. Dessa forma, em economias em desenvolvimento, a combinação de políticas por meio de mixes de políticas produz efeitos não triviais tanto no nível quanto na velocidade das transições energéticas.

Palavras chave: Modelos baseados em agents, política energética, política tecnológica, financiamento público, complexidade.

Abstract

Climate change is a phenomenon directly linked to man-made increases in greenhouse gases emissions. We as a society must take action and develop means to mitigate climate change and its effects. The energy sector is one of the top emitters of greenhouse gases worldwide. Electricity systems are a relevant portion of the energy sector. One way to mitigate climate change is to transition to low-carbon electricity mixes through the increase of renewables and decline of fossil-fuel electricity generation. Such solution is being attempted by both developed (e.g. EU countries) and developing countries. This thesis focuses on energy transitions towards low-carbon electricity systems in developing countries using mixes of policies. As such, we aim to further analyze the effects of financial constraints of such developing countries on transition processes, as well as to analyze the effects of policy interactions in such context. From a methodological standpoint we start from Ostrom's Institutional Analysis Development (IAD) Framework. The IAD framework focuses on the interactions and outcomes of agents in a situation that is bounded by multiple rules. Such interactions occur in a computational simulation named Technology, Finance and Energy model (TeFE), i.e., we use an agent based model to simulate interactions between agents. Such simulated agents are: technology producers, responsible for producing electricity generation assets; energy providers, that acquire such assets in order to produce electricity; an energy policy maker, responsible for the auction mechanism; a technology policy maker, responsible for giving incentives to technology producers; and a development bank, responsible for financing the acquisition of electricity generation assets by energy producers with subsidized interest rates. Agents in the IAD framework are also able to evaluate outcomes and adapt. In our analysis, agents follow Simon's satisficing heuristic. Interactions occur in a context in which path dependence, sunk costs and innovation are present, which highlights the relevance of technology adoption. The results from model show that a policy mix in which multiple policies are combined leads to energy transitions that are understood as better by both policy makers and private entities, i.e., energy transitions that yield higher profits and better achieve policy goals. Moreover, policy mixes with multiple policies achieve such status faster than scenarios with just one policy in place. As such, in non-central economies, combination of policies through policy mixes produce non-trivial effects regarding both the level and speed of energy transitions

Keywords: Agent-based model, energy policy, technology policy, public financing, complexity

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IBGE	Instituto Brasileiro de Geografia e Estatística
BNDES	Banco Nacional de Desenvolvimento Econômico e Social
KfW	Kreditanstalt für Wiederaufbau

List of Abbreviations and Acronyms

CAPEX	Capital expenditure
CC	Commercialization Chamber
CE	council entity
DBB	Development Bank
EP	Energy producer
EPM	Energy Policy Maker
GHG	Greenhouse gas
IAD	Institutional Analysis and Development
kW	kilowatt
kWh	kilowatt hour
MW	megawatt
MWh	megawatt hour
NIE	New Institutional Economics
NPV	Net present value
O&M	Operation and management
ODD	Overview, Design and Details
OIE	Old Institutional Economics
OPEX	Operational expenditure
PPA	Power Purchase Agreement
R&D	Research and Development
RBV	Resource-based view
RES	Renewable Energy Sources
RES-E	Renewable Energy Sources for electricity production
SES	Social-Ecological System

TCE	Transaction Costs Econonomics
TP	Technology Provider
TPM	Technology Policy Maker

Contents

Introduction

Change is inherent to most social and biological systems. Change is also inherent to economic systems, especially in relation to energy: for example, coal and oil prompted two industrial revolutions. Since at least the first industrial revolution, the manners in which energy is supplied, transported and consumed are crucial for determining how economic systems are shaped. Widespread use of electricity only increased the relevance of how energy is supplied and consumed, and especially of how energy is transported: in the case of electricity, transportation occurs through permanent physical network connections between supplier and consumer. Such physical network prompted a centralized industry. Nevertheless, new regulations in the 1990's prompted yet more changes to this network industry. In terms of regulation, the role of a single class of actor, i.e. the policy maker, is emphasized by how much policy makers shape electricity systems. Nevertheless, despite how large the role that policy makers play in the industry, they still need to coordinate with other players such as energy producers, technology manufacturers and banks for example.

Policy then affects electricity systems. In this sense, there is a clear connection between desired result and the policymaking activity, in other words, between what the policy maker wants and what the policy maker is doing to achieve it. We thus go back to the coordination problem: policy makers give incentives to attempt to steer change towards desired results.

Policy in this sense is more than mere rhetoric, focusing on policy instruments that are used by the policy maker to attempt to reach closer to certain policy goals. At first, in the context of mitigating climate change, a single policy with a single goal was attempted: carbon tax aimed at reducing emissions. However, it quickly became clear that a single policy would have significant problems to prompt an energy transition towards low-carbon electricity systems. Such understanding became even clearer when analyzing underdeveloped and in-development economies. As such, energy policy began to be used with more policy instruments: auctions, feed-in tariffs, quotas, etc. Moreover, more policies began to be used: technology policy focusing on incentivizing R&D in renewable sources, industrial policy focused on local content, financing policy focused on guarantees and specially lending with special traits (below market interest rates, more ammortization time, etc.) done by development banks[1] and even multilateral banks.

Since we have more than one policy maker, we must analyze how those three policies intertwine and affect each other. In order to do so, we focus on the policy mix. Nevertheless, policy makers do policies in order to achieve certain goals, i.e., policy making has a function behind it. In other words, policy makers affect energy transitions and may attempt to steer that change towards a certain goal. In that sense, the function behind a policy maker's actions may be to prompt technology development, to prompt the development of the economy, or even to prompt the change towards renewables. Those functions then connect with system results, respectively with technology development (innovation and imitation), internalization of industrial chains, and expansion of renewable capacity. The division between functions and results is because policy makers do not control results but control their functions. In other words, despite the relevance of policy makers, they do not control private agents, thus not controlling results.

In order to analyze policy mixes in energy transitions and the importance of reducing policy mixes' incongruities through coordination, we then develop a three part toolbox. The first part of the toolbox, developed in chapter 1, delves into the theoretical aspects of it. We gather relevant topics in institutional and evolutionary economics, arguing that one cannot analyze those topics in a *ceteris-paribus* manner, thus advocating for co-evolution. In that sense, we then argue that complexity is a relevant addition in order to make the analysis more suitable to transitions.

Then we delve into the empirical aspects of the toolbox in chapter 2. We reiterate the importance of energy and electricity in relation to climate change, thus advocating for change in terms of energy transitions to low-carbon electricity systems. Following that reasoning, we then do an overview of topics related to three policies: energy, technology and financing policies. Lastly, we advocate for the use of policy mixes and delve into how policy mixes may have incongruities.

[1]Brazil even has the very interesting case of having a national development bank (BNDES) and a regional development bank (Banco do Nordeste) competing for projects.

After that we reach the final part of the toolbox: the agent-based model (ABM). In chapter 3 we present the methodology behind the Technology, Financing and Energy agent based model (TeFE). It is an ABM that emphasizes interactions, feedbacks and adaptation while attempting to simulate a electricity mix with a focus on simplicity. In order to streamline the chapter, we follow the ODD protocol to an extent.

Lastly, we present model results and discuss them. We focus our analysis on system elements related to the transition, e.g. adoption of renewables. Those elements are analyzed in terms of their absolute values and, specially, of three vectors: speed, acceleration and growth. Moreover, the vectors use three different time scales: short-term variation (month-on-month), mid-term (year-on-year), and long-term (four years variation). All those comparisons are then made in relation to nine different scenarios: a baseline scenario without any policy; three scenarios with either auctions, cash-flow incentives to technology providers or public financing; one scenario with a policy mix comprised of all three policies used; and four scenarios with that policy mix and a simple coordination rule for policy makers using four different thresholds (low, low intermediate, high intermediate and high).

Chapter 1

Theoretical toolbox: literature review of selected topics

This chapter has four main sections besides an introduction and a conclusion. We first review topics that are related to evolutionary economics, then we review topics related to institutional economics. Afterwards, we present some topics on the co-evolution between institutions and technology and, lastly, we review some topics on the complexity approach to economics.

In this chapter we present a synthesis of pertinent literature review for our proposed analysis. In other words, we expose the theoretical toolbox that we shall use in this thesis. We are analyzing how to change tangible assets in order to mitigate climate change. As such, we start by analyzing technical change. Nevertheless, technology does not change by itself, being inserted into an economic system wrapped around institutions. Therefore, we then present some topics on institutional economics, focusing on Ostrom (2005) Institutional Analysis and Development (IAD) framework. Among those topics, we focus on rules and rule-changing behavior, thus also analyzing some topics on decision-making by actors in the economic system. From that, we get the big picture that rules and technology do not change in a vacuum, as they are constantly changing and their evolution affects one another: co-evolution. Therefore, we dwell on the topic of co-evolution of technology and institutions. Nevertheless, the topic of co-evolution is very broad, thus needing some additional topics in order to be streamlined. As such, we then present some topics on the complexity approach to economics that, although broadens the analysis, provides clearer paths and methods for analyzing the matter of change: networks, agent-based models, risk & opportunity versus costs & benefits, and so on. After that section we then conclude this chapter, attempting to wrap up the subjects as one cohesive theoretical toolbox[1] that will provides us with the means to analyze our case studies.

1.1 Topics related to evolutionary economics

Schumpeter (2008, 1997) criticized mainstream economics of the time for its lack of emphasis on technology and for its emphasis on equilibrium. Those criticisms took the form of creative destruction: the possibility of innovation clashes with the possibility of a single, stable and convergent equilibrium. Inspired by Schumpeter's works, more authors followed its research on innovation, technology and non-equilibrium.

Resource-based view (RBV), against the notion of profit maximization inherent to mainstream[2] economics (although absent from some major neoclassical economists, as Marshall (COMIM, 2000)), Possas (1999) shows some criticisms to that postulate. The reality is inherently more complicated than modeled: the computational and rational skills for one to maximize profit would be high, imposing limits to such notion (MARCH, 1991; SIMON, 1979, 1959). Thus, firms would tend to seek satisfactory profit levels rather than optimal. Furthermore, firms are composed of a coalition of different individuals with possibly different and clashing agendas, hence producing a variety of goals for the firm that depend on quantitative and qualitative aspects of such coalition (PONDÉ, 2002).

Nevertheless, it is possible to theorize upon firm objectives, as Penrose demonstrates. Firms tends to seek higher levels of profit and/or growth, with most other possible objectives being somewhat related to such goals (POSSAS, 1999). The Penrosian approach and the view of the firm in the RBV framework put emphasis on firms' abilities to "read" markets and technologies, creating business models to seize new opportunities. Hence, innovation is key for firms. Within the RBV, a firm's competitive advantage stems from its ability to use its available tangible and intangible resources[3]: valuable, rare, inimitable and non-substitutable abilities (TEECE, 2009; TEECE; AUGIER, 2009).

[1]As we are not exactly focused on expanding on the mathematics and statistics, most of the practical (or modeling) toolbox to be use is quite standardized and therefore we will not develop too much of that.

[2]We are aware of the differences between orthodox, neoclassical and mainstream, as stated by Dequech (2007). We however refrain from differentiating among the former notions, as their differentiation is not central to our arguments.

[3]Teece, Pisano, and Shuen (1997) within the Dynamic capabilities theory, foregoes the term "resource" in favor of the term "firm-specific asset".

Within RBV, routines appear as central units of analysis. Routines may be understood as collections or sets of institutions that pave the way for certain behaviors under certain circumstances (POSSAS, 1999). Routines appear as explicit repetitions of coordinated actions (TEECE; PISANO; SHUEN, 1997). Routines store and reproduce knowledge, especially tacit knowledge (LANGLOIS, 1995). Routines thus appear as a necessity in uncertain environments.

Dequech (2011) clarifies the concept of uncertainty, differentiating it from simple probabilistic risk. The author differentiates between procedural and fundamental uncertainties, within the concept of substantive uncertainty, i.e., when one cannot produce accurate probabilistic distributions in relation to all possible events. Procedural uncertainty occurs when agents do not have the processing power (information, cognition) to acquire and process the needed information to undertake decisions without uncalculated risks and rewards. Fundamental uncertainty however, happens when agents are, regardless of their abilities to acquire and process information, unable to know *ex-ante* the best decisions regarding any situation. Within fundamental uncertainty, agents' decisions influence the ex-post results of their decisions, e.g., innovation is a source of uncertainty that cannot be previewed in any form and influences all decisions within the system. Innovations are therefore closely related to fundamental uncertainty.

In relation to innovations, Freeman and Perez (1988) elaborate a taxonomy of innovations[4]:

- **Incremental innovations:** occur continuously in any industry, due to inventions and improvements or as a result of learn-by-doing and learn-by-using processes
- **Radical innovations:** occur discontinuously, they are disruptive innovations that arise from certain R&D activities. They are unevenly distributed within a sector
- **Changes of "technology systems":** far-reaching changes in technology, affecting a variety of branches and giving rise to new sectors. They are composed of a constellation of radical and incremental innovations in bursts together with organizational and managerial innovations.

[4]While discussing Keynes' work and its analysis of investment, especially of the psychology behind investment decisions, the authors discuss the existence of "true uncertainty" or "fundamental uncertainty" in Dequech (2011) terms, which would prohibit the formation of correct expectations about future events (FREEMAN; PEREZ, 1988).

- **Changes in "techno-economics paradigm" or technological revolutions:** They are essentially changes of technology systems that become so far-reaching that they encapsulate the economy as a whole.

A number of clusters of radical, incremental, organizational, managerial and behavioral innovations composes technological revolutions. It is a meta-paradigm, having a strong pervasive effect on the economy, affecting significant institutional arrangements and the institutional environment of an economy or of the world. In that sense:

> ... It is evident that we view Schumpeter's long cycles and 'creative gales of destruction' as a succession of 'techno-economic paradigms' associated with a characteristic institutional framework, which, however, only emerges after a painful process of structural change (FREEMAN; PEREZ, 1988, p. 47).

Therefore, innovations affect not only the technical progress of an economy, but also the institutional bases of a society. Innovation is thus an evolutionary process. In relation to neo-Schumpeterian authors, since Nelson and Winter (2004) and Dosi and Nelson (1994) there has been a surge in the use of biology notions and concepts, specially evolution. Concepts of "selection" and "survival" were already relevant for Nelson and Winter (2004), which depicted the importance of innovation and technical progress for the economic growth.

Arthur (2015b) expands on the concept that the economy is an expression of its technologies:

> This way of thinking carries consequences. It means that the economy emerges — wells up — from its technologies. It means that the economy does more than readjust as its technologies change, it continually forms and reforms as its technologies change. And it means that the character of the economy—its form and structure —change as its technologies change. [...] The economy in this way emerges from its technologies. [...] Technology creates the structure of the economy, and the economy mediates the creation of novel technology (and therefore its own creation) Arthur (2015b, p. 136–137).

According to Dosi and Nelson (1994), one may find evolutionary arguments in Marx, classical political economy authors, neoclassical economists, old institutional economy authors as well as in Schumpeter's writings. Regarding a more formal and decisive evolutionary approach, the authors underline that evolutionary theories aim to: first, explain a system's dynamics; and second, to permit randomness and variation in otherwise static systems. As such, "[e]volutionary models in the social domain involve some processes of imperfect (mistake-ridden) **learning and discovery**, on the one hand,

and some selection mechanism, on the other" (DOSI; NELSON, 1994, 154–155, emphasis on the original). Selection mechanisms make the fitness of agents' endogenous to the model, linking units of selection to observable traits, e.g., a company's cash-flow may be linked to its economic performance.

Lastly, interactions enable the adaptation of agents to the environment. It makes variety and heterogeneous agents endogenous to the system. Rationality and uncertainty are traits that are relevant for the interactions of agents and to the possibility of idiosyncratic behavior among agents. In light of this and following Schumpeter (2008), the perfect rationality and the sovereignty of the markets in neoclassical economics are challenged by Dosi and Nelson (1994). As such, they are favorable of approaches closer to reality, such as Simon (1959, 1979) bounded rationality, as well as to fundamental or procedural uncertainty in Dequech (2011) terminology. The bounded rationality of agents may be extended to policy makers, that produce mental models expecting to artificially select certain traits within environmental selection[5] (ARTHUR, 1994).

In light of this, both Arthur (1989) and David and Greenstein (1990) provide models for analyzing selection of technology given certain traits, i.e., models for analyzing if certain technologies can become standards of an industry, entering lock-in. The authors emphasize the role of path dependency on the economy, i.e., the fact that past events influence future events: the non-ergodicity of economic systems. David and Greenstein (1990) specifically analyze the importance of sponsored technologies, emphasizing the role of networks and network externalities for standard competition in industries[6].

Malerba and Orsenigo (1997) understand that the knowledge opportunities, appropriation and accumulation are crucial for the identification of technological regimes within economies. In a similar fashion, Dosi and Nelson (2010) undertake an extensive review of knowledge and information in relation to innovation.

Technology stands as man-made method for achieving a certain end. It involves knowledge, processes and artifacts. Technology shares some common traits with information, given the fact that the use of both is non-rival, they are indivisible goods, and they have increasing returns to use. Nevertheless, technological knowledge necessarily involves tacit knowledge of difficult codification. Technological knowledge may be

[5]For more on the matter, we recommend Mitchell and Woodman (2010) for their analysis of selection of locked-out technologies through policy-maker actions.

[6]See (KATZ; SHAPIRO, 1994) for more.

decomposed into two categories: **(i)** its characteristics, i.e., if it is decomposable, readily available and so on; and **(ii)** sources, i.e., is it generated exclusively within the firm, exclusively outside it or in a network of firm and other entities. Technologies are recipes, routines and artifacts. Technology as recipes are input-output procedures, whereas technology as routines stand as patterns of problem-solving behaviors, and finally technology as artifacts stand as product designs Dosi and Nelson (2010).

Given the importance of knowledge for technology, learning is a central process for the technical progress. Firms are units capable of learning, sharing knowledge and producing goods and services, while also being units capable of innovative behavior. In this sense, heterogeneity is endogenous to the economy, as companies have different knowledge assets, use them in different ways, and acquire, process and accumulate knowledge in different manners. There is heterogeneity in innovative, diffusion, adaptive and imitation capacities, being such heterogeneities persistent over time (DOSI; NELSON, 2010). There is also heterogeneity in the innovative capacity (FREEMAN; PEREZ, 1988; SCHUMPETER, 2008).

1.2 Topics related to institutional economics

Cavalcante (2018) states that there exists discontinuities and similarities between Old Institutional Economics (OIE) and New Institutional Economics (NIE)[7]. The author analyses institutions in three dimensions: mental models, rules of the game, and organizations[8]. The author understands that institutions structure human interaction, by being rules of the game, and also mold conceptions of reality, by being mental models. We focus on institutions as rules of the game, following North (1992)

The central unit of analysis for NEI are transactions. Coase (1937), dissatisfied by the mainstream approach to both firms and law systems, understood that not only production costs must be analyzed in order to minimize costs and maximize profit, but that transaction costs must also be considered. After all, the existence of the firm is not justified by mainstream economics, on the contrary, the disembodied input-output equations represented by firms are single entities, being price-taking firms (TIGRE, 2005).

[7]OIE and NIE are nomenclatures stated by (POTTS, 2007).

[8]The author also considers big players as institutions, however we refrain from such terminology, preferring the term “organization”.

Table 1.1: Relation between traits and governance structure. Source: Williamson (1981)

Traits / Governance Structure	**Market**	**Hierarchy**
Incentives	strong	weak
Control and Authority	weak	strong

Transaction costs are thus the costs of accessing the market according to Coase (1937), justifying the emergence of firms.

When considering transaction costs into the economic analysis, the allocative and distributive efficiency may not coincide, thus violating welfare theorems. In this sense, transaction costs are crucial for the economic analysis, in the sense that they significantly change the efficiency criteria of otherwise "efficient" allocations in neoclassical terms (COASE, 1960). The economic analysis then must consider both the production and transaction costs for a reasonable analysis (COASE, 2008).

In that sense, Tadelis and Williamson (2012) show how the Transaction Costs Economics (TCE) are a relevant methodology for analyzing the effects of economic organization over economic value. There exists two polar opposites in a spectrum of governance structures: hierarchy and market. Perfect market is an abstract construct in which the sole source of communication between agents is price, whereas perfect hierarchy is another abstract construct in which there exists full control over all firm's activities. Essentially, markets buy while hierarchies make. Nevertheless, the authors point towards the importance of governance structures in between both polar opposites: "[t]he upshot is [...] the combined use of markets and hierarchies" (TADELIS; WILLIAMSON, 2012, p. 8). Table 1.1 depicts the strengths of both polar opposites. Control is strong in hierarchy due to the endogenous existence of an interface coordinator that exercises authority over decisions, correcting disturbances and stopping incoordination. Nevertheless, the presence of an interface coordinator is costly and it mainly stops agents from having incentives to coordinate: coordination is not incentivized, rather enforced.

However, one may criticize the sole use of TCE given the fact that it still uses the maximization behavior, updated in order to minimize transaction costs (CASTELLI; CONCEIÇÃO, 2016; HIRATUKA, 1997; VAZQUEZ, 2018). In order to go beyond that criticism, one may go beyond TCE within institutional economics.

Taking a step back from TCE, one may change the focus of the analysis from the transaction itself, i.e., from the passage of a certain good from one interface to another

(TADELIS; WILLIAMSON, 2012), to the broader concept of institutions. There exists a variety of notions and definitions for the term: before Coase, Veblen (1898), Veblen (1899, 1999) and Commons (1931) defined institutional economics. They, alongside other authors encompassed the OIE stream. For Commons (1931), institutions embody frameworks of laws and habits, as well as the behaviors of individuals, being necessarily dynamic. Institutions both encompass and become rules. For Veblen (1898), Veblen (1999) and Veblen (1994), institutions are norms, habits and laws that are created and sustained within communities. They are shared understandings between members of a network.

Hodgson (2004) understands that Veblen stood as an author poised to apply Darwinian principles to its analysis of socio-economic institutions. In light of this, Veblen analysed the emergence and evolution of institutions in socio-economic life, focusing on their dynamics and mutability. This is clearly understood by Veblen (1898), in which the author criticizes the theories and specifically the redutionistic method of neoclassical economics. According to the author, it is clear that economics must strive to be an evolutionary science. Veblen (1898) goes against the "discovery" of natural laws, and elucidates the communal factor of institutions:

> The economic life history of the individual is a cumulative process of adaptation of means to ends that cumulatively change as the process goes on, both the agent and his environment being at any point the outcome of the past process. [...] What is true of the individual in this respect is true of the group in which he lives. All economic change is a change in the economic community, – a change in the community's methods of turning material things to account. The change is always in the last resort a change in habits of thought. This is true even of changes in the mechanical processes of industry. [...] The notion of a legitimate trend in a course of events is an extra-evolutionary preconception, and lies outside the scope of an inquiry into the causal sequence in any process. **The evolutionary point of view, therefore, leaves no place for a formulation of natural laws in terms of definitive normality, whether in economics or in any other branch of inquiry. [...] From what has been said it appears that an evolutionary economics must be the theory of a process of cultural growth as determined by the economic interest, a theory of a cumulative sequence of economic institutions stated in terms of the process itself** (VEBLEN, 1898, 891–893, our emphasis).

Therefore, according to Veblen (1898), "economics", or to be more specific neoclassical economics of the turn of 19th to 20th century, is not an evolutionary science due to the acceptance of hedonistic value theory, i.e., the utility-value theory of Bentham (2007) and Mill (1998). In this sense, neoclassical economists are unable to understand the importance of anthropology, psychology, political and social sciences, as well as Darwinian biology.

Veblen (1898) states that neoclassical economics suffers from three major problems: animism, taxonomy and hedonism. Veblen suggests, based on the analysis of instincts by modern psychologists, that institutions are habits of though. Furthermore, as those habits of though are shared understandings of any community, they evolve with said community, therefore also encompassing rules. Institutions are therefore ways of thinking about things and ways of doing said things. Cavalcante (2018) states that most of OIE accepts Hodgson's reconstitutive downward causation: "The patterns of behavior that may become rules are not absolute restrictions to human action, but they are temporally seem as constraining in the sense that individuals cannot voluntary and instantly alter crystallized habits of thought" (CAVALCANTE, 2018, p. 4–5).

Commons (1931), having in the idea that scarcity leads to conflict, possesses a different idea of institution: it is a collective action in relation to individual action, regarding what one must, can and cannot do. It has a similar tone the understanding of Crawford and Ostrom (1995) understanding of institutions of rules and related sanctions or benefits regarding what one can, cannot or may do given certain situation. Commons (1931) emphasizes transactions and, more importantly, property rights.

According to Ostrom (2011), there are three levels of specificity that the study of institutions depend on.

- **Frameworks:** the most general form of theoretical analysis. It identifies elements and the general relationships among these. From this, it provides a general set of variables to be used to analyzed the instutitonal arrangements. Frameworks provide the metatheoretical language for comparing theories by identifying universal elements that need to be included for any theory in the topic to be relevant, without addressing the relations among them. These elements help generate questions.

- **Theories:** define which are the relevant elements and in which forms do they interact with each other, regarding the shape and the strength of interactions and elements. Assumptions are a part of theory, being necessary to (1) diagnose an specific phenomenon; (2) explain its processes; (3) and predict outcomes; Multiple theories are compatible with one framework;

- **Models:** make precise assumptions about a limited number of variables and parameters to predict outcomes by using a particular theory. Agent-based models fall into this category. Multiple models are compatible with most theories

The importance of learning in a complex environment is highlighted by the institutional approach. Within that approach, Ostrom (2005) develops upon the Institutional Analysis and Development (IAD) framework[9]. A way to use the IAD framework (figure 1.1) is as a multi-tier conceptual map. That framework identifies the action situations and the resulting patterns of interactions and outcomes, and then evaluates them. The analysis is not static, encompassing a multitude of feedbacks that provides dynamics for the framework. The framework, given its emphasis on feedbacks, dynamics and rules, is appropriate for the analysis of coevolution.

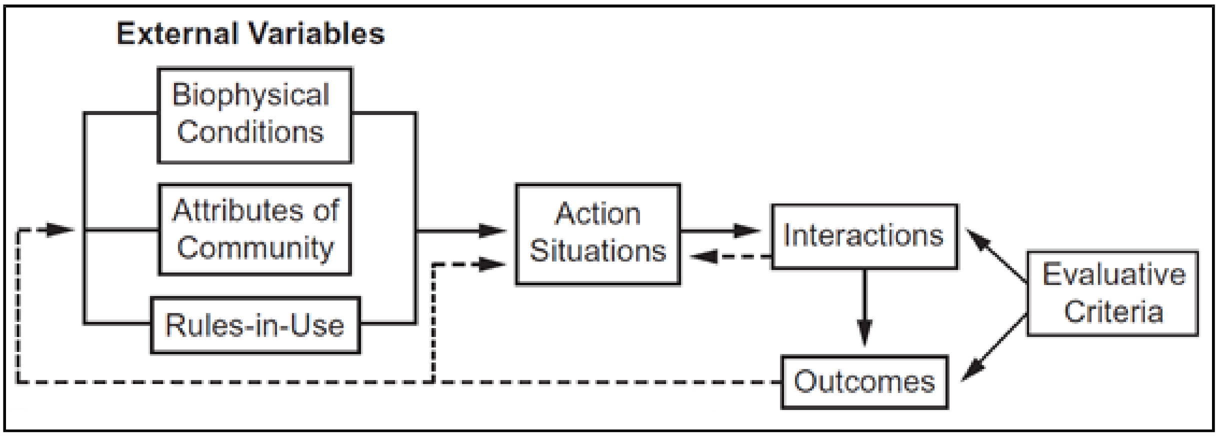

Figure 1.1: A framework for institutional analysis. Source: Ostrom (2011, p. 10)

The external variables encompass the biophysical conditions, attributes of community and rules-in-use. By "external", Ostrom (2005) is not referring to the usual economic notion of "external", i.e., outside of the model, not being affected by it, essentially static, given. The use of "external" is less rigid, especially in regards to rules-of-use. External variables encompass characteristics of the system as whole, of its agents and of their interactions. The external variables represent the state of those characteristics in a given moment, in spite of variables changing every round of the framework. As such, the external variables are not necessarily static, as the framework may imbue them with dynamics. Out of the three external variables, we focus on the rules in the next subection.

[9] Ostrom (2011) draws upon conclusions of previous studies (OSTROM, 2005, 2008). It also introduces the Social-Ecological System (SES) framework. Nevertheless, our choice is for the IAD framework due to its methodological simplicity.

The external variables determine the relative positions of agents in the action situation. Regarding those positions, interactions take place and, out of the latter, outcomes emerge. The outcomes then influence the external variables as well as the action situation. The interactions also present feedbacks with the action situation.

North (1990) states the relevance of path dependence, i.e., how the past shapes the future. Furthermore, institutions are the "rules of the game" of socio-economic life (NORTH, 2008). By negating the ergodicity of neoclassical economics, that statement in turn points towards the fact that institutions are endogenous to every society, being specific to certain socio-economic systems, when analyzing in a more macro level: "... economic institutions, and institutions more broadly, are endogenous; they are, at least in part, determined by society, or a segment of it." (ACEMOGLU; JOHNSON; ROBINSON, 2005, p. 2). For Hodgson (2005, p. 2): "[i]nstitutions are durable systems of established and embedded social rules that structure social interactions". In this sense, some rules are codifiable, whereas some imply tacit knowledge, in a similar fashion as to technology and routines (DOSI; NELSON, 2010).

In relation to the transaction costs of NEI, Hodgson (2005) understands that rules are embedded into governance structure, thus transactions in markets, hierarchies or anything in between happen due to institutions. Given the endogenous character of institutions, governance structures acquire a more evolutionary and dynamic facet, against the static analysis of NEI (VAZQUEZ, 2018). In a similar fashion, preferences and choice must also be considered endogenous characteristics of a socio-economic system (BOWLES, 1998). In relation to economic development, institution-building or rule-making goes beyond governmental decree, encompassing self-organising mechanisms (HODGSON, 2005).

Potts (2007) also highlight the importance of institutions as rules:

> Institutions are the coordinating mechanisms that compose the economic system, and are at once a rule population, a rule system, and a rule process. Institutions, in this view, are neither essentially subjective nor objective, but process-structures of operational social knowledge – i.e., functioning rules for coordinating the economic actions of people with respect to each other and the material environment (POTTS, 2007, p. 343)

Institutions are thus the building blocks of value creation by providing the rules (structures and processes) for coordination, transaction and production processes. In relation to rules, the focus of the author is on the generic rules. Those can be divided into subject rules and object rules. Subject rules are rules of cognition and behavior of micro agents, for example, rationality, habits and preferences are subject rules. Object rules however focus on organizing objects, be they people or material objects (POTTS, 2007). Object rules that organize people are social technologies, whereas object rules that organize material objects are physical technologies to use Nelson (2008) and Nelson (2002) terms.

Nevertheless, the most relevant statement about rules is that rules as institutions are intrinsically related to knowledge: the "[i]nstitutional economic analysis, in turn, is a generic analysis of rules, as **units of knowledge**" (POTTS, 2007, 344, our emphasis). Furthermore, knowledge directly affects the value-system of an economy, as new knowledge may or may not become new institutions or change the existing ones, i.e., information becomes a decisive variable in analyzing rules, and in consequence institutions and thus in the analysis of socio-economic systems[10] (POTTS, 2007). The relation between knowledge and rules as decisive for the evolution of socio-economic systems is a concept similar as to Dosi and Nelson (2010) , in the sense that knowledge is a key factor for technology and for routines. Data is unorganized or dispersed bits of information (both codified and tacit); information is organized or categorized data; and knowledge is the assimilation of information, involving how to use it (HESS; OSTROM, 2007).

Within institutional economics, North (2008) understands that institutions are essentially "rules of the game", being "the game" the social-economic life (in all its spheres of existence, including competition between firms), being "rules" both formal and informal codes of conduct and norms (encompassing routines), and being "the players" organizations in any level (from individuals to firms, to countries and to the world as a whole). Rules are shared understandings among the involved actors (agents, e.g. firms) about what actions (or states) are required, prohibited or permitted alongside the correlated benefits or sanctions (CRAWFORD; OSTROM, 1995). They are the result of implicit and/or explicit efforts to achieve order. Stability is important regarding rule-ordered actions and it depends upon the shared meaning assigned to those rules: if actors interpret the rule differently, the resulting order will be weaker than if not (OSTROM, 2011). Rules in this sense are similar to codes of conduct: by setting the "rules of the game", the players have more information about the game itself, reducing uncertainties.

[10]Further references on the topic are Punzo, Rocha, and Ruiz (2015), Hess and Ostrom (2010) and Hayek (1986).

Daniels (2008) further corroborates the importance of regularity for interactions, although the author addresses the topic of when regularity becomes rigidity.

Revisions in rules, common when the evaluative criteria is based on efficiency, alter behavior and in consequence the allocation of resources, dynamically affecting the whole system, which in turn may, through feedbacks, promote another revision in rules. That dynamic of revisions in particular leads to the emergence of co-evolution within the IAD framework. Rules, therefore are not necessarily static (OSTROM, 2005). The analysis of change within the action situation also corroborate the importance of co-evolution in the IAD framework.

Given asymmetries of information and bounded rationality, revisions of rules become important for the elaboration of evaluative criteria. Learning (a dynamic process of interaction) is relevant for the decision process of policy-makers regarding maintenance or revision of their evaluative criteria. Agents (including policy-makers) learn from their mistakes and past actions, correcting their behavior (given their information and behavioral limitations) in order to produce more efficient results, even if the criterion of efficiency is subjective. Given the dynamics of the IAD framework, learning becomes crucial for the analysis. The dynamics and feedbacks of the framework implies in coevolution of learning processes: all agents can learn from the interactions, successes and mistakes, improving upon their behaviors in order to achieve better results. The dynamic of rules and evaluative criteria guide the co-evolution between agents' behaviors and rules (VAZQUEZ; HALLACK, 2018).

The focus of the analysis is the action situation, of which its internal structure is depicted in figure 1.2. Rules are directly related to the interior of the action situation. Action situations are defined as "... the social spaces where individuals interact, exchange goods and services, solve problems, dominate one another, or fight ..." (OSTROM, 2011, p. 11). Inside the action situation, an agent makes assumptions four clusters of variables:

1. **resources**;
2. **valuation**;
3. ways to obtain, process and use **knowledge**;
4. **decision-making processes**.

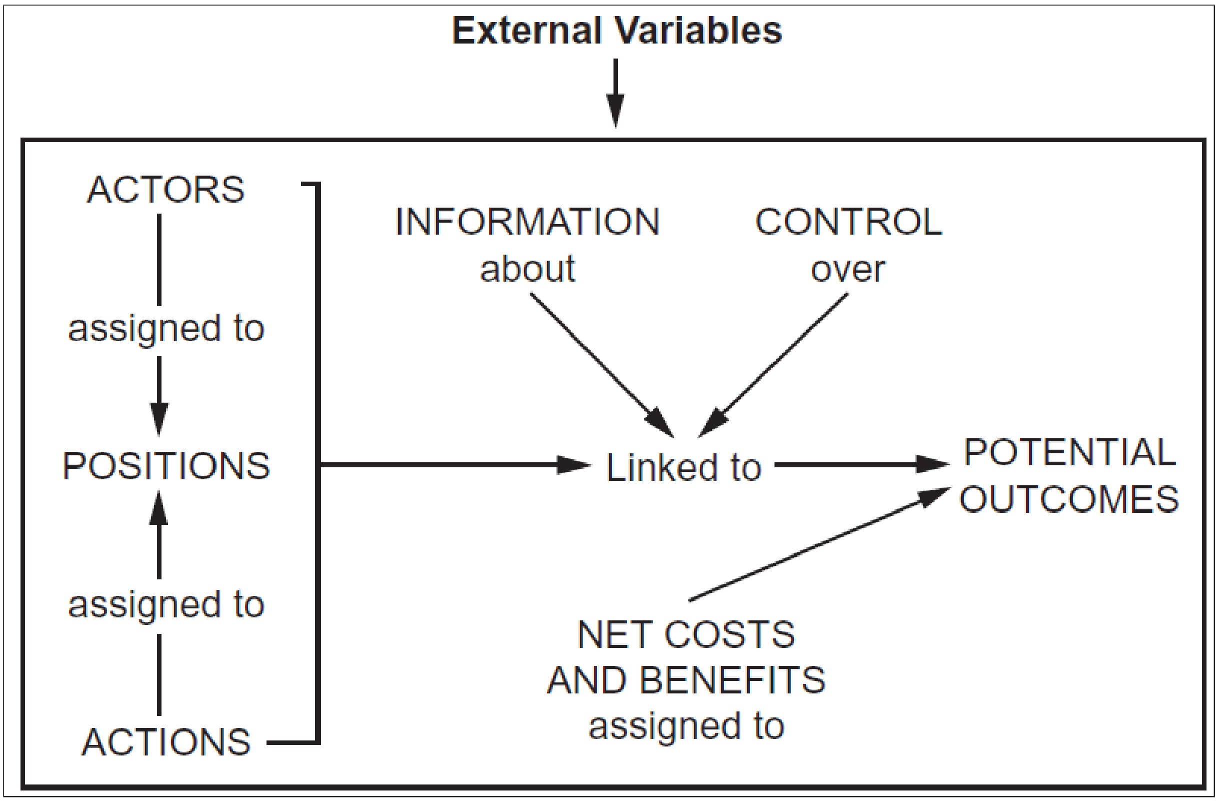

Figure 1.2: The internal structure of an action situation. Source: Ostrom (2011, p. 10)

The analysis of the action situation can be further analyzed in two ways. First by inquiring about the factors that affect the **structure** of the situation, and second by exploring the **change** over time of outcomes, perceptions and strategies. Within the action situation framework we find seven variables:

- **The actors:** who does what?
- **The positions:** where do they stand regarding power and strategies? Are there hierarchies and differences in actors?
- **The allowable actions:** what can they do, cannot do or should do?
- **The potential:** what can happen? What cannot happen? The potential depends on the problem, because actions are not always streamlined and modular (BALDWIN; CLARK, 2002; GLACHANT; PEREZ, 2007);
- **The level of control over choice:** level of independence, autonomy and randomness of decision
- **The available information:** how much do they know? Is information commonly, readily and/or freely available? Do they interpret information the same?

- **The costs and benefits of actions and outcomes:** how do their actions and the actions of other, given the others variables, affect them and the others, and how do they all evaluate this?

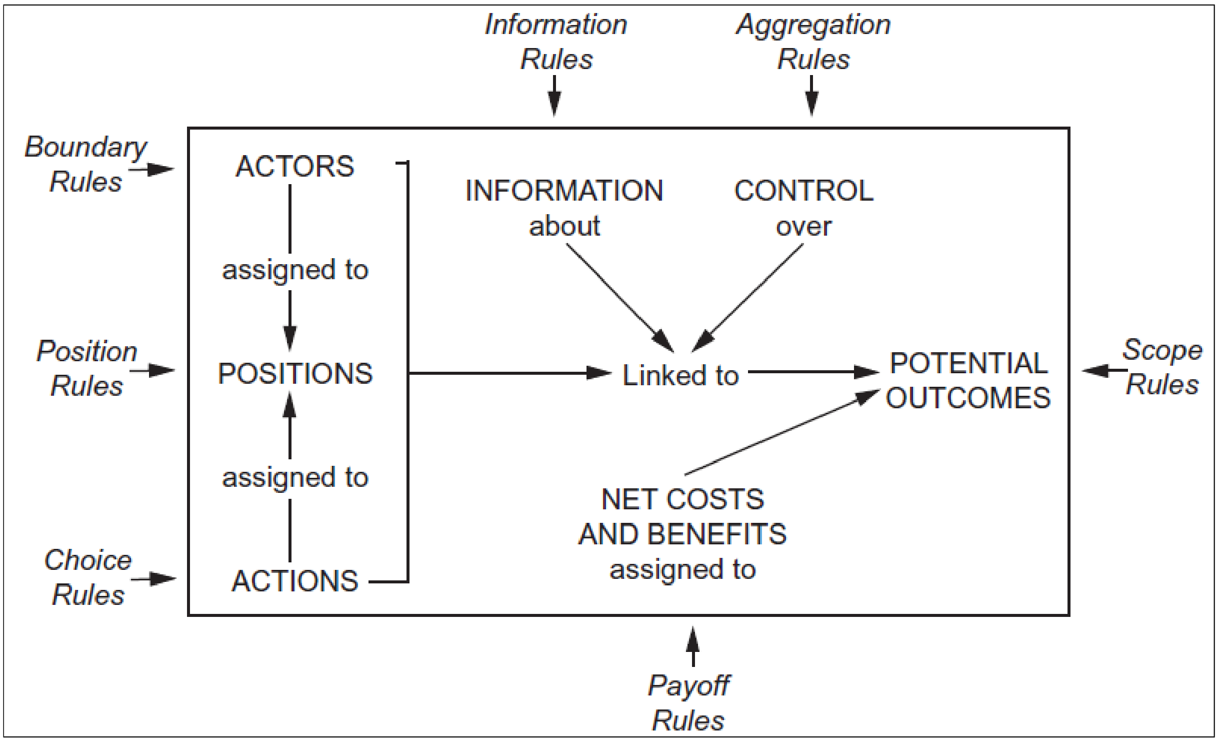

Figure 1.3: Rules as exogenous variables directly affecting the elements of an action situation. Source: Ostrom (2011, p. 20)

Figure 1.3 shows how rules (as external variables) affect the elements inside an action situation more precisely than external variables (taken as a group) affected it (as depicted in figure 1.2). Ostrom (2011) pointed out seven types of rules that affect the structure of an action situation:

1. **Boundary rules:** directly affect the actors, their attributes and resources in the acts of entering, staying and leaving the interactions;

2. **Position rules:** Establish the possible positions to actors;

3. **Choice rules:** assign sets of actions (permitted, required or prohibited) to actors in certain positions (determine the decision tree faced by actors);

4. **Scope rules:** establish the potential outcomes and the actions related to them;

5. **Aggregation rules:** determine the level of control that an actor in certain position exercises in the selection of an action;

6. **Information rules:** determine the level of knowledge-contingent information related to actions and outcomes;

7. **Payoff rules:** affect the net benefits and costs assigned to combinations of actions and outcomes, therefore determining the incentives and deterrents for actions.

The last element to be analyzed is the evaluative criteria. Sustainability[11] and economic efficiency are prominent forms of evaluating outcomes. More specifically, economic efficiency is determined by the magnitude of net benefits of a specific allocation of resources, being central for studies in which the estimation of benefits and costs or rates of return to investment are important[12] (OSTROM, 2011).

Policy-makers are one of the main agents responsible for evaluating outcomes through efficiency criteria. As a policy-maker or a rule-maker is an agent embedded into the complex and ever changing context, rules are emergent context-specific properties of dynamic interactions between policy-makers and other agents (OSTROM, 2005). According to Arthur (1994), policy-makers interpret reality through simplified and limited models, adapting as necessary. That corroborates the use of a subjective measurement of efficiency, defined by the simplified and limited interpretation of reality that a policy-maker could induct from reality.

March (1991) reiterates the importance of knowledge for organizations while also advocating for two different behavior types for organizations: **exploitation**, i.e., the "... refinement and extension of existing competences, technologies and paradigms" (MARCH, 1991, p. 85) focused on positive, proximate and predictable returns; and **exploration**, i.e., "... experimentation with new alternative" (MARCH, 1991, p. 85) focused on returns that may be uncertain, distant and even negative at times. Firms allocate resources between the two processes according to explicit and implicit choices. Explicit choices are related to profit over cost in relation to risk equations, whereas implicit choices are more related to organizational forms and customs, such as routines, rules of thumb and heuristics. The author also states that the "distance" between learning and the returns for exploration is greater than that distance for exploitation. In that sense, the processes of learning and realizing the returns is deeply affected by networks as well as by the costs and benefits, or, to use Sharpe et al. (2020) and Mercure, Sharpe, et al.

[11] In regard to sustainability, we recommend Janssen and Ostrom (2006).
[12] As in the analysis of infrastructure projects (GATTI, 2013).

(2020) nomenclature, risks and opportunities[13]. Tsai and Jhang (2010) reiterate the fact that exploitation focuses on short-term production and selection, whereas exploration focuses on long-term risk taking and innovation, as well as search and discovery. Those two opposite behaviors lead to homophily and preferential attachment, and, respectively, to convergence and variation processes that occur concomitantly with selection processes by firms, markets and policies.

Sharpe et al. (2020) and Mercure, Sharpe, et al. (2020) risk-opportunity analysis may be compared to Ostrom (2005) rule change calculus: in it, the incentive to change from one rule or one institution to the other is given by the difference in the perceived or estimated benefit of the current set of rules and of a new set of rules, following equation 1.1.

$$\Gamma_i = R_{new} - R_{old} \tag{1.1}$$

In that equation, Γ_i is the incentive to change of a certain agent i and R_j is the perceived benefit of a certain set of rules j. One may then update the equation from benefits to opportunities and insert a term reflecting risks (equation 1.2). In that new equation, now an inequality equation that reflects a situation in which there are incentives to change, ρ reflects the perceived risks by the agent i in changing from the current set of rules to an j set of rules.

$$R_{new} > R_{old} + \rho_{i,j} \tag{1.2}$$

As such, there are three ways to influence the incentives for agents to change: by increasing the perceived opportunities of a new set of rules; by reducing the perceived opportunities of an old set of rules; and by reducing the perceived risk of such change. All three may occur at the same time: there is no need for only one phenomenon to occur.

[13]The authors argument in favor of risk and opportunity over costs and benefits partially due to the complex context of most current economic analyses.

1.3 Topics related to the co-evolution between institutions and technology

Technical progress and institutional change are significant processes in the economic analysis of society. Neo-Schumpeterian and institutionalists focused respectively on the technical and institutional aspects of the socioeconomic change. Nevertheless, technology and institutions do not exist in a vacuum and are essentially integrated and related. Therefore, there exists a need to go beyond evolutionary institutional analysis and beyond evolutionary technological analysis, analyzing co-evolutionary processes of technical-institutional change. Langlois and Foss (1999) also suggest that economics must go beyond the *ceteris paribus* argument when analyzing costs.

Nelson (1994, 2001) highlights the interaction between technical and institutional changes, i.e., between the evolution of both technology and institutions in a given system. Nelson (2002) states his case for evolutionary and institutional economics joining forces:

- Both share a central behavioral premise that understands that habits of action and thought are main causes for human action and interaction
- Both reject the instrumentalism methodology o Friedman (1981) that, although humans do not maximize their utilities, they act "as if". For both streams, maximization is rejected.

Nevertheless, evolutionary economics focus on technology with institutions being underlined as "exogenous variables", whereas institutional economics focus on institutions and largely takes technology and innovation as given (HIRATUKA, 1997; VAZQUEZ, 2018). In order to understand how both streams could join forces, Nelson (2002, p. 20) highlights the importance of routines within firm: "[t]he performance of that firm or organization will be determined by the routines it possesses and the routines possessed by other firms and economic units with which the firm interacts. . . ".

In this sense, routines may be understood as "programs" or "general algorithms"[14] (FRENKEN, 2006) involving two different aspects:

- **Physical technology:** a recipe regarding any division of labor;

[14]In this regard, Vazquez (2018) emphasizes the importance of "algorithmic rationality".

- **Social technology:** a division of labor in conjunction with means for coordination.

Regarding the latter: "... social technologies are what many scholars have in mind when they use the terms 'institutions.'" (NELSON, 2002, p. 22). Social technologies (institutions) would then define and be defined by the different stratus of "rules of the game" (CRAWFORD; OSTROM, 1995; NORTH, 2008). Furthermore, routines are important methods for reducing uncertainties in environments where there exists procedural uncertainty (DEQUECH, 2011; TEECE; PISANO; SHUEN, 1997). Nelson (2002) then states:

> Within this formulation, new "institutions" and social technologies come into the picture as changes in the modes of interaction-new modes of organizing work, new kinds of markets, new laws, new forms of collective action – that are called for as the new technologies are brought into economic use. In turn, the institutional structure at any time has a profound effect on, and reflects, the technologies that are in use, and which are being developed (NELSON, 2002, p. 23).

There exists an "obvious interdependence" between social and physical technologies, i.e., between institutions and technology or between institutional and technological changes. The co-evolution between institutions and technologies is thus the "... driving force behind economic growth" (NELSON, 2002, p. 27). However, co-evolution is not a smooth process: "[a]t best, resulting incoherencies between institutions and technology can be a driver for further innovation and reform. At worst, incoherencies lead to undesirable trade-off s in performance criteria and outright systemic failures" (FINGER et al., 2013, p. 103–104). In light of the possible disharmonies in the technical-institutional co-evolutionary processes, uncertainties and creative destruction (SCHUMPETER, 2008) are present, and hence path dependence and change are in this case the norm. Neo-Schumpeterian and institutional economics both analyze structural processes of non-ergodic change:

> Each one of those two [neo-Schumpeterian and neo-institutional economics] has its own key-factor of social-economic change that works as a type of 'gene' that carries in it the characteristics that clash in the process of evolutionary selection. In neo-Schumpeterian theory, this key-element is the technical change and firms' routines, whereas in the institutional school that gene are institutions and individual habits (CASTELLI; CONCEIÇÃO, 2016, p. 861).

Darwinian evolutionary ideals in neo-Schumpeterian economics focus on competition, being evolution a cumulative facet of economic change processes. Cumulativeness is also relevant for institutional economics, nevertheless, neo-institutional economics focuses on social norms, habits, laws and codes of behaviour, i.e., institutions; more precisely, neo-institutional economics focus on institutional change, inertia and resistance to change (CASTELLI; CONCEIÇÃO, 2016).

Technical change must be considered into the economic analysis (CASTELLI; CONCEIÇÃO, 2016). Furthermore, one cannot only incorporate exogenous technical change (*à la* Solow) or incorporate technical change only as an element that reduces costs. Technology must be considered as a paradigmatic event, intertwining itself with society, its social norms, social habits and laws (FREEMAN; PEREZ, 1988). Technology is relevant for the decision process of agents, including rule-definition processes.

Technical progress may be the principal force behind economic growth, nevertheless, technology does not exist in a vacuum and it needs to be, to a certain degree, designed and operate by people (CASTELLI; CONCEIÇÃO, 2016). Thus, there is an institutional dimension to the technical change process that needs to be analyzed. Nelson (2002, 1994) understands that the co-evolution of institutions and technology is central to the economic analysis. In a similar fashion, the notion of technology in Arthur (2015b) also encompasses the institutions that co-exist and co-evolve with technology. In this sense:

> Under favorable conditions, the Schumpeterian bandwagons roll and business confidence improves, leading to an atmosphere of 'boom' in which, although there are still risks and uncertainties attached to all investment decisions, animal spirits rise. Such favorable conditions include complementarities between innovations and the emergence of an appropriate infrastructure as well as some degree of political stability and institutions which do not hinder too much the diffusion of new technologies (FREEMAN; PEREZ, 1988, p. 43)

In fact, when one considers that there exists interdependency between different "landscapes", i.e., between the institutional and technology dimensions, and there exists evolution in the landscapes, one cannot understand adaptation as response to signals or as response to conflicts. Adaptation as response to signals is related to perfect rationality and perfect to asymmetric information, being equilibrium a feasible option: agents adapt responding to changing signals, e.g., agents change their preferences given price or quantity shocks. Adaptation as response to conflict is related to TCE, given the fact that agents may rely on different governance structure to reduce transaction costs and consequently conflicts (VAZQUEZ, 2018).

Given co-evolution, one must understand adaptation as a learning process, in which agents learn in an uncertain environment and each learning process affects the

Table 1.2: Relationship between action situations and institutional and technological levels. Source: Vazquez (2018)

Situation type	**Institutional level**	**Technological level**
Operational -level situations	Resource Allocation	Operation Management
Collective -choice situations	Governance	Routines
Constitutional -level situations	Institutional environment	Technological trajectory
Metaconstitutional -level situations	Embeddedness	Technological paradigm

agent, the other agents and the landscapes. As such, co-evolution is related to complex adaptive systems and to the complexity approach to economics (VAZQUEZ, 2018). In this sense, the IAD framework is also relevant by being a multi-layer framework, capable of complementing and integrating the analysis of institutions and of technologies.

Table 1.2 depicts that relationship between technology and institutions at multi-levels. There essentially exists level-shifting strategies, i.e., by affecting a certain technical or institutional variable, one is also affecting the others. For example, a change in the technological trajectory significantly affects the variables at the technological level of lower levels (operation management and routines), but it also affects the institutional environment in terms of feedbacks and thus the other variables at the institutional level (resource allocation and governance). As such, "[c]onsequently, agents deciding at a lower level (e.g. collective choice situations) may engage in level-shifting strategies to change the rules at the higher level (e.g. constitutional-level situations)" (VAZQUEZ, 2018, p. 18).

1.4 Topics related to the complexity approach to economics

Complexity science is a mutidisciplinary field of research, rooting itself in dynamical-systems theory and chaos theory (BALE; VARGA; FOXON, 2015). Complexity studies interactions of complex entities and their consequences, analyzing pattern-like structures called "phenomena". Complex entities are: interdependent, connected, adaptive and diverse entities. Phenomena emerge from interactions, not being part of the system as a whole and neither of the agents (often called "elements" in broader terms). Essentially, it studies how change emerges, propagates itself, survives and ends[15] (ARTHUR, 2013, 2015a).

Complexity draws elements from both newer and older mathematical methods: chaos theory, statistics, probability theory, etc. "Complex" is no synonym to "complicated", as the latter depends on the heterogeneity of the object of study whereas the first is directly related to the number of objects and relations within a system (MITTELTRASS, 2012). The complexity approach to economics[16] applies the complexity to the economic analysis. It does not require equilibrium as a precondition (both in the short-run and the long-run). It focuses on the interactions among agents within their context. In this point of view, both actions and strategies constantly co-evolve. That gives importance to time, as structures are constantly being created and adapting. Phenomena (an important topic for the matter), invisible to standard equilibrium analysis rises in importance, as the analysis broadens to a meso-layer between micro (individual agents) and macro (all agents and the context). Phenomena are characterized by patterns. This approach focuses on the formation of patterns and how they affect its causes, i.e., how novelties emerge and how its emergence affects what it emerged from (ARTHUR, 2013, 2015a).

To assume that agents can seize better positions is to implicitly assume nonequilibirum, as novels reactions may change the outcome. One can understand that equilibrium analysis[17] is a special case of nonequilibrium analysis in economics, therefore, this approach, when applied to economics, analyses it in a more general way (ARTHUR, 2013,

[15] "Or, to put it another way, complexity studies the propagation of change through interconnected behavior" (ARTHUR, 2013, p. 11).

[16] Arthur (2013, 2015a) prefers the term "Complexity Economics", however, we refrain from the term because we understand that it is still a broad, although powerful, point of view applicable to economics. We do not understand that there is already a solidified school of thought associated with the applications of complexity to economics (then validating the use of the term). The term "complexity approach to economics" seems more true to the fact that this is an extremely broad approach, yet to undergo the time, effort and debates to solidify it as "complexity economics". To put it in more methodological terms (in accordance with Lakatos), the construction of a "complexity economics" heuristics is still underdeveloped when in comparison with other "types of economics" (e.g. behavioral economics). For an analysis of Lakatos, methodology and philosophy of science, we recommend Blaug (1992) and Cavalcante (2007, 2015).

[17] "Like many economists I admire the beauty of the neoclassical [equilibrium] economy; but for me the construct is too pure, too brittle — too bled of reality. It lives in a Platonic world of order, stasis, knowableness, and perfection. Absent from it is the ambiguous, the messy, the real" (ARTHUR, 2013, p. 2). Furthermore, "[w]here equilibrium economics emphasizes order, determinacy, deduction, and stasis, this new framework [complexity] emphasizes contingency, indeterminacy, sense-making, and openness to change" (ARTHUR, 2013, p. 19).

2015a). According to Arthur (2013, 2015a), nonequilibrium endogenously arises in the economy due to:

- **Knightian Uncertainty:** In most cases, agents are not capable of putting realistic probability distributions over future events. "Not-knowingness" is a common feature among market agents. There is no general "optimal" move (e.g. maximization). Moreover, "Uncertainty engenders further uncertainty" (ARTHUR, 2013, p. 4). Behavioral economics[18] demonstrates how this uncertainty shapes the decision making process of individuals and firms.

- **Technological innovation[19]:** In regards to this topic, the author follows an evolutionary approach: innovation is unpredictable, comes in bursts, and is a powerful motor of the economic activity .

Under these two circumstances, the analysis deviates significantly from standard equilibrium economics. Agents lie in an ever-evolving context, having to adapt and learn, while responding to problems faced and molding its own environment as part of this process:

> The overall view we end up with is one of creative formation: of new elements forming from existing elements, new structure forming from existing structure, formation itself proceeding from earlier formation. This is very much a complexity view. (ARTHUR, 2013, p. 17).

In relation to phenomena, Arthur (2013, 2015a) understands that they are:

- **Spontaneous**;

- **Temporal:** emerging or happening within time (in comparison with equilibrium which is a timeless state);

- **Meso-level:** neither at the micro level (individual) or macro (all agents);

[18]Although we do not delve deeper into the topic, we recommend Tversky and Kahneman (1981), Camerer, Loewenstein, and Rabin (2004) and Kahneman (2003). Furthermore, the books by Loewenstein and Elster (1992), Thaler and Sunstein (2009) and Thaler (1992) stand as suggested further readings on the topic.

[19]Arthur (2013, 2015a) definition of technology encompasses both machinery and processes as well as the institutions (organizations, law) related: they are means to human purposes.

- **Phase transitory:** they change from phases **without the possibility of going back** (it may become similar to a previous phase, however, it will be a new phase, not a throw-back to the previous one).

Moreover, the author understands that economical phenomena share three characteristics:

- **Self-reinforcing changes in prices:** price, as an economic signal, change (at least in part) due to endogenous factors;
- **Clustered volatility:** Periods of low and high activity are randomly interspersed;
- **Sudden percolation:** events suddenly are transmitted through the network [20].

Without a single, convergent and stable equilibrium, one has to study the emergence and the propagation of change. Complexity, without limiting the term, can be understood as the study of these two processes (ARTHUR, 2013, 2015a).

Moreover, Elsner, Heinrich, and Schwardt (2015) understand that complex phenomena are: **(1)** unpredictable; **(2)** robust, as to some degree they extent their existence in time; **(3)** happen in large events; **(4)** emergent properties; **(5)** novel, as they are not necessarily constrict to certain expected outcomes; **(6)** fractal, as complexity must be a property in all scales of analysis.

In that sense, Robert and Yoguel (2016) advocate that path dependence, positive feedbacks, micro-heterogeneity, emergent properties, self-organizing systems, habits and routines, innovation (novelty) and cumulative causation were all mentioned in economics at some point in its history. The authors divide in two the development of complexity topics in economic thinking (figure 1.4). The authors are more concerned with information and knowledge and how they develop and evolve over time tended to focus on the flux of information, especially through self-organizing networks, coordination and

[20]"An event occurring at one node will cause a cascade of events: often this cascade or avalanche propagates to affect only one or two further elements, occasionally it affects more, and more rarely it affects many. The mathematical theory of this—which is very much part of complexity theory—shows that propagations of events causing further events show characteristic properties such as power laws (caused by many and frequent small propagations, few and infrequent large ones), heavy tailed probability distributions (lengthy propagations though rare appear more frequently than normal distributions would predict, and long correlations (events can and do propagate for long distances and times)" (ARTHUR, 2013, p. 11).

innovation. On the other hand, authors that focused on economic change tended to shift their attention towards feedbacks and divergence[21].

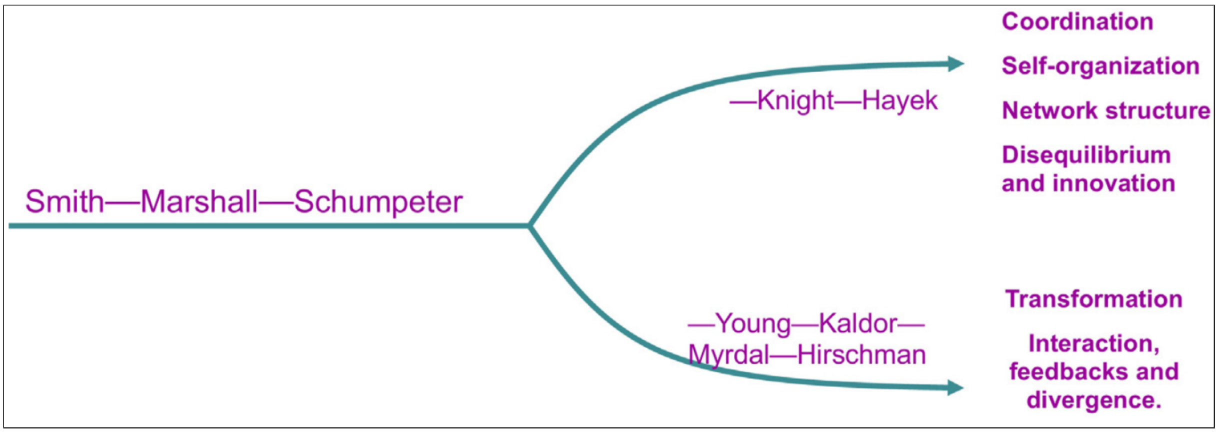

Figure 1.4: Two alternative paths of complexity in economic thinking. Source: Robert and Yoguel (2016, p. 8)

Restraining economical phenomena to negative feedbacks (e.g. diminishing returns), quickly causes systems to converge to equilibrium. Positive feedbacks may cause non-equilibrium, however, **only** allowing positive feedbacks gives way to **explosive** non-equilibrium, making it difficult to analyze patterns and behaviors. The presence of both positive and negative feedbacks acting together are a defining property of complex systems, coexisting in a delicate manner. Multiple-attractors, lock-ins and path-dependency are properties derived from this combination (ARTHUR, 2013, 2015a).

An important consequence of complexity is that the context changes according to agents and agents change according to context, configuring a dancing landscape (MUELLER, 2016). Understanding landscapes as graphical representations of situations, it can represent an economic problem in three dimensions involving: two sets of inputs (allocated to the x-axis and y-axis) and a set of outputs[22] (allocated to z-axis).

The concept of **dancing landscape** is well understood when in comparison with the concept of **rugged landscape**. The latter can represent severely difficult prob-

[21]The authors are actually concerned with possible policies that use knowledge from complexity topics. In that sense they advocate that "Regardless of the economic dynamic that has arisen from the complexity perspective, it reveals emergent properties that are the consequence of simultaneous bottom-up and top-down processes. In other words, the evolutionary dynamic is built through individual actions, but they are also affected by macro and meso structural conditions, including institutions, which limit their behaviors, choices, and possibilities for learning. In this sense, the complexity approach is coherent with regulatory recommendations in which both types of intervention are justified" Robert and Yoguel (2016, p. 13).

[22]It is important to notice that the inputs and outputs do not need to be single numbers (e.g. labour and capital), as they can be vector representations of n sets of variables (e.g. labor could be divided into skilled and non-skilled, and capital could be divided into natural, social and technological capital).

lems, resulting in a very complicated and intricate 3D representation. However, rugged landscapes are fixed, so behaviors do not need to go beyond maximization (even without perfect information), i.e., one can, given time, analyze **all** of the landscape and correctly find the best answer. The former, nevertheless, does not allow that. Dancing landscapes can actually be very simple and straight-forward (or very complicated), however, change is a characteristic of this type. It is not known: if there is going to be change; when the change is going to happen; to how much degree the problem will change; who will it affect; and if it will endure[23] (MUELLER, 2016).

One cannot, given any amount of time, **completely** analyze a dancing landscape and correctly find the best answer. A maximization behavior would, in this case, be unrealistic, providing unsatisfactory results (MUELLER, 2016). In this sense, we use **algorithmic rationality**: agents induct behavioral algorithms from the environment, adapting as they go[24].

Arthur, Durlauf, and Lane (2015) then relates networks to complex structures. According to the authors, adaptive non-linear networks are systems[25] with the following characteristics[26]:

- **Dispersed interaction:** heterogeneous and dispersed agents interact, and from such interactions macro patterns emerge
- **No global controller:** There is no global entity that controls actions (e.g. Walrasian Auctioner), with control happening through competition and cooperation mechanisms;
- **Cross-cutting hierarchical organization:** the economy has a multitude of organizational levels where interactions take place. Units at lower levels serve as building blocks for higher levels, nevertheless there may be cross-hierarchical organizations;
- **Continual adaptation:** behaviors constantly adapt;
- **Perpetual novelty:** changes may lead to other changes;

[23]Similar to uncertainty, which is unquantifiable. We recommend Langlois and Cosgel (1993) as further reading.
[24]Simon (1959), Arthur (1994) and Elsner, Heinrich, and Schwardt (2015).
[25]Potts (2000) expands the concept of systems as topographical hyperstructures
[26]Comim (2000) agrees on those characteristics.

- **Out-of-equilibrium dynamics:** there is no optimal equilibrium for the economy, as improvements are always possible and frequently occur.

Kirman (1997) states that, regarding relations among agents, economists must aim for models between no connections and full connectivity: the first is related to general equilibrium whereas the latter is related to game theory according to author. According to him "... the most interesting problem in this context [models with interactions between agents], is to model how the links between individuals develop and hence how market structure itself evolves" (KIRMAN, 1997, p. 496). Thus, Kirman (1997) is advocating for an analysis of how networks evolve.

Another important aspect of the complexity approach to economics is that, complexity as a field of science, does not lie inside economics. It is common to place complexity among more hard science fields (e.g. physics). However, it is also a matter of analysis in philosophy and methodology.

In conclusion, in this chapter we aimed to present the theoretical toolbox to be used in this thesis. Our focus was to connect subjects to one another as well as to connect those subjects to the main theme of this thesis: transitions towards low-carbon economies. As such, we first presented topics regarding technology, mainly those proper to evolutionary economics. For a transition to occur, we need to change the energy mix which involves changing the technology used. In that sense, technical change is key both in relation to innovation and to diffusion. Financing is a key aspect for infrastructure projects, thus including energy projects. Moreover, public financing is especially relevant for infrastructure projects in developing countries. Given the locked-in status of carbon-intensive technologies, policies aimed at both reducing such lock-in and the locked-out status of low-carbon technologies are key to the transition process.

Moving from technology itself to technology policy, the role of institutions becomes clear and thus the analysis of institutional economics (summarized in table 1.3) becomes key. As such, we analyze Ostrom (2005) IAD framework in order to build a methodological basis for this thesis. The IAD framework emphasizes the role of rules: prescriptions of actions that should, should not or can be taken alongside their respective consequences. In that sense, we can understand policies as rules and therefore as institutions.

Table 1.3: Differences between mainstream and institutional economics. Source: Own elaboration

Mainstream economics	**Institutional economics**
Atomised agents in reductionism analysis	Holism
Homo economicus	Humans are guided by habits and routines that can mutate
Individual agents	Embeddedness
Equilibrium	Path dependence cumulative causality
Fixed well-behaved preferences	Dynamic preferences
Exogenous technology	Endogenous technology
Symmetry of power	Asymmetry of power

Table 1.4: Differences between mainstream and evolutionary neo-Schumpeterian economics. Source: Own elaboration based on Castelli and Conceição (2016)

Mainstream economics	**Evolutionary economics**
Substantive rationality	Bounded rationality
Maximizing behavior	Routines, heuristics
Equilibrium analysis	Dynamics, feedbacks and path dependence
Atomized agents	Interactions (networks)
Homogenous goods (price competition)	Heterogeneous goods (Product competition)
Market as the center of analysis	Firm as the center of analysis

Both institutions and technology play a role in the commonplace economic, the more on transition processes. One could take institutions as given and analyze technical change, or on the contrary take technology as given and analyze institutional change, nevertheless, by analyzing both changes in conjunction, one allows unique conclusions to be had. In that sense we argue in favor of co-evolution between institutions and technology.

In order to base such co-evolutionary framework we have to go deeper into the IAD framework in relation to its level-shifting strategies, which combines both bottom-up and top-down cause and effect. Level-shifting strategies also allow us to combine changes from one specific level to another, in our case from institutions to technology and vice-versa.

Analyzing co-evolution, complexity appears as a possible way to structure how we approach change. In that sense, it broadens the analysis to simulation models and network analysis. In the next chapter we shall review case studies of transitions, focusing on practical or empirical traits. Such review is based on the theoretical framework developed in this current chapter.

Chapter 2

Empirical toolbox: policy mixes for transitions towards low-carbon energy systems

In this chapter we present a synthesis of pertinent empirical topics for our proposed analysis.

2.1 Climate change and the role of energy

Climate change is a global phenomenon which encompasses the increase in average global temperatures above historic averages. Climate change is a consequence of human action, being a direct consequence of the increase of greenhouse gases (GHG) since the first industrial revolution. In this regard, the use of fossil fuels is responsible for a large part of such emissions, with transportation and production of electricity as the top emitters of GHG globally (IPCC, 2022b,a).

Transportation, as well as heating, steel industries and other sectors are very relevant, both in terms of percentage of global GDP and in terms of percentage of GHG emitted. This thesis focuses on electricity production and means to reduce its emission of GHG. For the other industries, as well as for electricity production, solutions were proposed since the start of the second half of the 20th century. One solution is to reduce emissions by reducing the size of those industries. This solution is normally related to degrowth theories. There is a serious debate around degrowth theories and we will not delve into such debate. Another solution is to reduce emissions by capturing the GHG emitted. Carbon capture and storage (CCS) is a proposed solution that has yet to be used in large scale. Another solution is to change from fossil fuels to biofuels that may reduce or mitigate the emissions. The increase in use of biofuels and the expected increase in hydrogen are solutions that are related to this route. This solution nevertheless is still limited to transportation regarding biofuels, and regarding hydrogen, is a solution that is still being developed. Another solution to most sectors is to electrify them. The increase in use of electric vehicles as well the substitution of fossil heating to electric heating are solutions that go this route. This solution nevertheless depends on the electric mix: if the mix expands towards fossil fuels such solution may not pertinent.

2.2 Electricity systems and the role of renewables

One solution to mitigating climate change, this one more relevant to us, is to change the electric sector from fossil fuels to renewable fuels. The change from fossil to nuclear could also be interpreted as a solution, since it would produce electricity without emitting GHG, nevertheless we refrain from analyzing nuclear power plants due to a multitude of reasons: nuclear power plants take long periods to be planned and constructed, ensuring a steady flux of uranium may be a significant problem, there are significant safety concerns, and, given its costs and risks, nuclear power plants are not an option for most of countries in the world. In that sense, we prioritize renewable electricity sources (RES-E) instead of nuclear due to a multitude of reasons: they are significantly less costly than nuclear, they do not have the same magnitude of safety concerns, their fuels normally have zero to very low costs, and they seem to be a solution that may be widespread throughout the world easily than nuclear power plants.

Production of electricity from renewable sources is not something new: hydro power plants are used since the beginning of the use of the alternate current, wind power plants were relatively common for off-grid farms, and solar power plants are directly linked to the increase in use of satellites since the 1950's. Nevertheless, there has been a boom in the use of new renewables[1] in producing electricity since the 1990's (PINTO JUNIOR, 2007). This is due to a multitude of reasons, on the supply side there are the

[1]Mainly solar and wind farms.

falling trends in costs of generating and even in the costs of storing electricity (HELM; HEPBURN, 2019). Joskow (2008) reflects on the changes in the electricity industry since the 1980's. Mejdalani (2022) depicts the evolution of the electricity industry, from its infancy until its current days, focusing on the lock-in of fossil fuels and on the rise of renewables. Manhães (2021) analyzes another network industry, telecommunications, that shares some interesting similarities and differences to electricity industries.

The deployment of solar and wind power plants has grown rapidly and steadily since the 1990's all throughout the world. Solar and wind, in terms of reserves, have the largest and most well distributed in the world (PEREZ; PEREZ, 2015). Solar and wind, as well as hydro without dams, have significant problems with intermittence, a problem that traditional fossil and nuclear power plants do not have in their everyday operation[2]. Intermittence of new renewables is a well studied phenomenon in systems with high penetration of new renewables, nevertheless, it is not that big of a hassle for most systems that it begins to impact such electric mixes. Such impact is not that big specially because of regulation and industry standards. Helm and Hepburn (2019) understand that digitalisation and electrification are connected: demand for more electric energy goes hand in hand with more demand for digitalisation. Moreover, the authors identify a deeper connection between electrification and renewable energy production in the sense that digitalisation may even feedback renewable electricity generation by curbing intermittency.

2.3 Topics on energy industries: sources and transformation technologies

A common division of energy sources is between primary energy sources, secondary energy sources and transformation processes. In simple terms, primary energy sources are harnessed from nature and used in their original extracted form, whereas secondary energy sources need to be produced from those primary sources, thus leading into transformation processes (PINTO JUNIOR, 2007). Examples of a primary energy

[2]Fossil power plants may experience fossil shortage and nuclear power plants may experience difficulties in receiving refined uranium, nevertheless such events are not routine in terms of actually receiving the fuels in the power plant. Shortage not due to physical lack of fuel but due to price surges is more common, nevertheless is also not part of everyday operation: owners of solar power plants, for example, know that, everyday, they will stop producing for around 12 hours during the night.

Table 2.1: Specific traits of emerging and mature technologies. Source: Own elaboration based on Winskel et al. (2014)

TRAIT	Emerging technology fields	Mature industries
Design variety or consensus	High variety, low consensus	Low variety, high consensus
Organizations	Distributed	Concentrated
Majority of innovations	Radical	Incremental
Scale and modularity	Smaller scale and high modularity	Larger scale and less modularity
Learning or technology transfer	Important mechanism for innovation in energy technology fields, there are significant barriers in specific cases	
Niche or mainstream markets	Normally form niche markets at first	More capable of capturing mainstream markets
Policy and regulatory context	Inconclusive	
Financing	Importance of public financing	More private financing
System integration	Renewables have significant more barriers to integrate into fossil and nuclear dominated sectors	Tends to have easier system integration

source, a secondary energy source and a transformation process are respectively solar energy, electricity and the production of electricity out of solar energy.

Energy industries form around the extraction of primary energy sources, the transformation of such sources into secondary energy sources, and the supply of both types of energy sources. Demand for both types of energy sources can be source-specific (e.g. telecommunications can only run on electricity) or not (e.g. heating can be done via natural gas or electricity).

We now discuss electricity generation technologies. Electricity is a secondary energy source[3] as such, its characteristics depend on the characteristics of the source used to produce electricity. We shall analyze the following technology characteristics:

[3]Electricity can be found in the nature but it currently cannot be extracted, e.g. lightning.

if it is green; if the production process is intermittent or not; its lump investment (in MW terms)[4]; its building time; its lifetime; its capacity-factor; if its transportation is economically feasible or not[5]; as well as its CAPEX and OPEX[6].

Thermal power plants produce electricity by burning fuel to produce steam in order to power steam turbines that in turn power generators[7]. Thermal plants need fuel to burn in order to generate steam. The most common fuels encompass: coal, fuel oil, biomass[8] and natural gas. Biomass-fueled thermal plants use renewable sources and thus normally the emitted GHG are offset in the life-cycle of the biomass source. Thermal plants that use fuel oil are being decommissioned throughout the world, due to: high emissions and overall better efficiency of other options. Coal thermal plants emit lots of GHG and their use is always scheduled to be reduced throughout the world. Natural gas thermal power plants in turn are normally considered the cleanest of all those options, besides biomass power plants, and thus are quite often considered to be the best non-renewable power plants to be used. In that regard, it is common for electricity mixes to consider the use of natural gas thermal power plants for more 25-50 years at least. Given this, we focus our analysis on natural gas thermal power plants.

Transportation costs of parts of the thermal power plants are normally expensive, due to their size. Their lump investment is normally also quite large. CAPEX is also quite high. OPEX of thermal plants is high, especially because of the fuel costs. Thermal power plants take some years to be built. Thermal plants have high capacity factors, especially because they can operate without much effects of seasonality, climate or period of the day.

Wind power plants use wind energy to generate electricity. Wind energy turns large fans connected to generators. Wind power plants, also called wind farms, are in-

[4]Rosenberg (2000) stated the relevance of lump investment in industrial machinery in Charles Babbage works from the 19^{th} century

[5]We are basically discussing the technology's transportation costs: is it desirable to manufacture that technology close to the actual power plant spot or is it feasible to concentrate manufacturing at a location that may be far away from the power plant? In other words, is transportation a strategic hindrance that must be acquainted for or not?

[6]We stress the fact that we attempt to extract positive fuel costs from OPEX, as we aim to separate O&M costs from fuel costs.

[7]This is the broad process, however there are several developments (e.g. combined-cycle). Moreover, nuclear power plants follow the same principle of turning water into steam, however they are not part of our analysis for multiple reasons regarding the nuclear source: it is non-renewable; and although green there are serious issues regarding nuclear waste and security of supply chains and nuclear enrichment. We refrain from more analysis on the topic of the nuclear source and nuclear power plants.

[8]In Brazil it is quite common to have thermal power plants that use sugarcane biomass.

termittent, not producing electricity when winds are too weak or too strong. There are two main designs for wind power plants: horizontal turbine and vertical turbine. Horizontal turbine is the dominant design in which the turbine sits atop a tower and spins horizontally. Vertical turbines are more common for smaller deployments, nevertheless their commercial uses are still experimental.

Wind turbines' parts are somewhat transportable but at high costs, thus industries that are positioned closer to areas in which wind energy is growing have significant advantages. The lump investment for wind power plants are visible, being each wind turbine a lump of investment. Building time for wind power plants is around one year. Their lifetime is around 20 years. Capacity factor is smaller than the capacity factor for thermal power plants, specially due to sazonality, depending heavily on the site in which the power plant is installed. CAPEX is still high but lower than the CAPEX of thermal plants. OPEX is much lower than the CAPEX of thermal plants due to wind having no cost, being comprised almost exclusively of maintenance costs.

Solar panels use solar energy to chemically release electrons from the elements that compose those panels, thus not using generators. Solar panels can be made out of a multitude of materials such as thin film panels and, the more common silicon panels. Solar panels need structures to secure them in place (frames) and also inverters to convert the variable generation from direct current to alternate current, allowing the use on common devices.

Solar panels are transportable. Moreover, both solar and wind sources do not use heat to produce steam in order to power steam turbines, which diminishes energy conversion and thus conversion losses (HELM; HEPBURN, 2019). The lump investment for solar is the smallest one, since individual panels are relatively light and encompass small capacities (normally between W and kW). Similarly, solar power plants also share the lowest CAPEX and OPEX. Solar power plants can be built relatively fast and they normally can last for up to twenty years.

The technology is therefore available, so why have all countries not moved away from fossil fuels to renewables regarding electricity production? Besides the technical problems of having a 100% electricity mix comprised of intermittent renewables, we focus on two hindrances to that: the perceived risks of renewables and renewables being more costly than fossils. We shall show how policies may tackle such hindrances.

2.4 The role of technical change in transition process

Technical change and innovation have several impacts on how me harness and use energy, including how we produce and consume electricity. One obvious impact is that innovation allows us to found new ways to harness already used sources, e.g., from hydro wheels to hydro turbines. Another impact is that innovation allows us to found new sources to produce electricity with, e.g., solar panels.

Another important aspect of innovation is that it allows us to found more efficient ways to produce electricity from technologies already used. Such increases may derive from lowering costs, from developing new equipment for power plants or even from seemingly unrelated innovations[9].

In this sense, technical change can lead to more efficient equipment and thus to more competitive renewable power plants. Through innovation it is possible to reduce costs of producing electricity from renewables, which in turn affects the perceived risks of using such renewable sources.

Innovation is not certain, although it is quite often related to higher R&D expenditures and sustained R&D structures: stable expenditures, consistency in the staff, high quality equipment, etc. In this regard, one broad type of policy associated with technical change and innovation is technology policy, specially in the form of giving direct incentives to innovative firms to perform R&D activities.

Regarding renewable energy generation, there are three main drivers in today's industry: rapid technology change; new market players; and increased customer expectations regarding efficiency and clean energy. These opens the possibility to a future "tipping point", where companies will have to decide whether to continue on its former ways or to look for new (clean and renewable) ways (GROUP, 2015).

Schmidt and Sewerin (2017) analyze the relation between institutions and technology in the transition towards a low carbon economy. The authors emphasize the role of politics and policy for the transition to occur. On figure 2.1, Schmidt and Sewerin (2017) display the relations between politics, policy and technological change in terms of the disciplines involved. They argue that the nexus from policy to technology change is

[9] Widespread use of sensors in wind turbines, better forecasting techniques, more data availability for investors to decide where to install power plants, etc.

well studied, whereas the other way around not so much. We argue that co-evolution fills this gap [10].

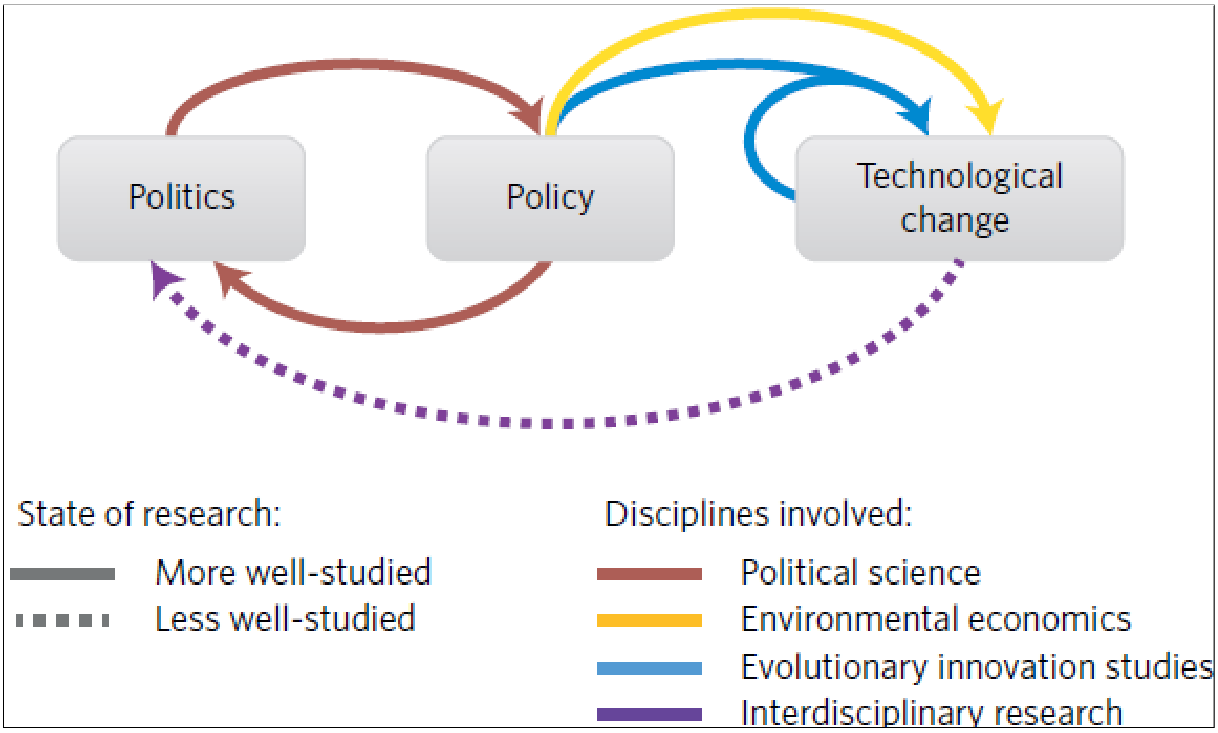

Figure 2.1: Interplay of politics, policy, technology change and climate change. Source: Schmidt and Sewerin (2017, p. 2)

2.5 The role of public finance in transition process

Regarding this topic, "[i]n innovation, the State not only 'crowds in' business investment but also 'dynamizes it in' – creating the vision, the mission and the plan" (MAZZUCATO, 2015, p. 4)[11]. In relation to new industries (e.g. renewables), nudging is not enough, State and public entities need to support venture capitalists and technology entrepreneurs with long-term support frameworks. Hence, State and private actors need to work together in cohesion in order to sustain innovative behavior[12] (MAZZUCATO, 2015).

[10]The authors argue that the relation between policy and politics is analyzed through political science. We do not delve into those matters.

[11]This section draws elements from Vazquez, Hallack, et al. (2018).

[12]Mazzucato (2015) states that cohesion of policies and private-public-partnerships are coherent with the Keynesian view over investment. Indeed, Keynes advocated that public policies need to be coherent and need to investment-inducing in order to sustain growth and thus full-employment (CARDIM DE CARVALHO, 1997)

Projects to deploy power plants are often considered infrastructure projects. Infrastructure projects are long-term investments with at least two different phases: (i) the construction phase, when most capital expenditures are made and almost no cash flow is generated; and (ii) the operation phase, when little capital expenditures are made and cash flow is generated[13].

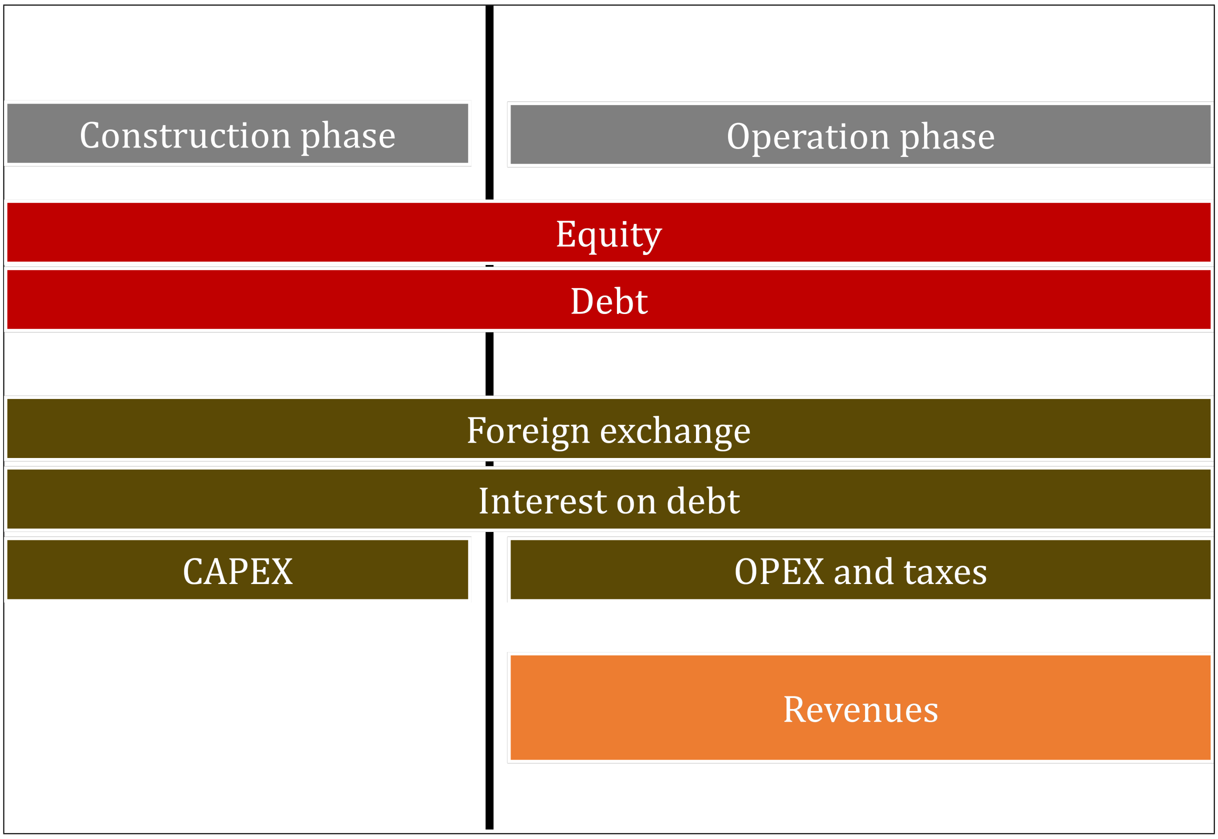

Figure 2.2: Schematic representation of a generic infrastructure project.
Source: Vazquez (2018)

Figure 2.2 describes an elementary infrastructure project. First (in grey) the project is split between two phases: construction and operation. Second, we represent (in red) the financing source: equity and debt. Third we represent (in green) the costs associated to the project that must be financed: the foreign exchange[14], the interest that must be paid on debt, CAPEX (considering the costs of the construction phase) and OPEX (considering the costs of the operational phase). Lastly, we represent the revenue.

Following the logic of Figure 2.2 we group the mechanisms to promote investment in RES projects under two broad headers: **(1)** financial instruments and **(2)**

[13] Slightly more detailed schemes may be designed (e.g. including phases where part of the infrastructure is built and some cash is generated). For instance, some turbines of a power plant might be ready and able to sell energy before the total completion phase.

[14] Especially important to Latin American and Caribbean (LAC) countries.

Category	Instrument	Project Finance	Corporate Finance
Debt	**Bonds**	Project bonds Green Bonds	Corporate Bonds Green Bonds
	Loans	Syndicated Loans Direct Lending (to project)	Direct lending (to corporate) Syndicated loans Securitised loans
	Hybrid	Subordinated Debt Mezzanine Finance	Subordinated loans Convertible bonds
Equity	**Listed**	Yieldcos	Listed Stocks
	Unlisted	Direct investment in Project (SPV) Equity	Direct investment in corporate equity

Table 2.2: Basic financing instruments for infrastructure. Source: Own elaboration based on OECD (2015a,b).

"revenue-enhancing" instruments, including dimensions related to contract design. Regardless of considering an equity or debt investor, infrastructure is a special asset with long-lived assets, low technological risk and high entry barriers. As such, they are normally strongly regulated assets with predictable and stable revenue streams.

An important distinction when defining promotion mechanisms is whether the market design assumes project finance, as in LAC countries, or corporate finance, as in the EU or the US. Project finance builds on the idea that financing does not depend on creditworthiness of sponsors, only on the ability of the project to repay debt and remunerate capital (GATTI, 2013), i.e., the financing of one economic unit previously defined (WEBER; ALFEN; STAUB-BISANG, 2016). Project finance tends to allow a higher level of debt when cash flows are more stable.

Corporate finance is more traditional. Firms in charge of the investment issue shares or borrow in capital markets to obtain the required funding. Such firms will often have a portfolio of projects.

In another scheme, OECD (2015a) also considers the differences between debt and equity instruments (Table 2.2). Bonds and loans are the two main financing instruments for infrastructure projects. Debt markets are structured to form long-maturity products coherent with the long lives of infrastructure projects. Moreover, those instruments may benefit from players with a preference for long-term investments, e.g. pension funds. Consequently, a large portion of the project is typically financed through debt instruments, predominantly loans.

A relevant part of debt instruments is subordinated debt and, in general, instruments both for project and corporate finance that have characteristics between debt

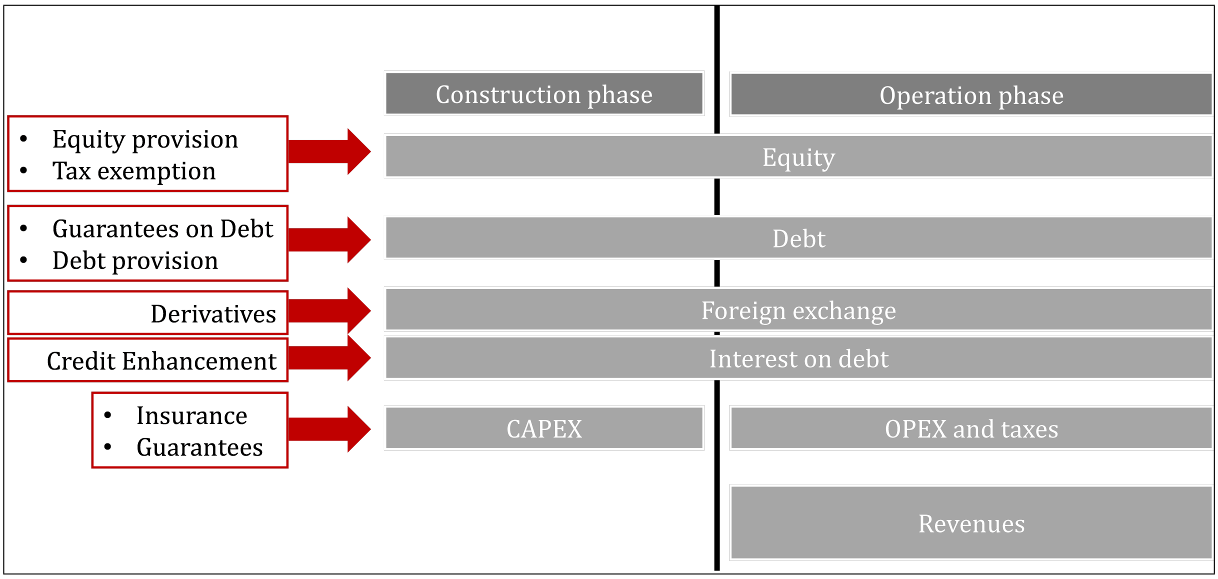

Figure 2.3: Schematic representation of potential financial instruments to mitigate risks. Source: Vazquez, Hallack, et al. (2018)

and equity (OECD, 2015a). Subordinated debt can be seen as an instrument designed to absorb credit loss before senior debt, increasing the quality of the latter.

Finally, equity finance may be seen as the risk capital of the project, usually required to begin the project or refinance it. Listed shares would be traded in public markets whereas unlisted shares would provide direct control of the project. One may place project equity finance closer to debt instruments regarding the fact that the risk over return ratio of infrastructure projects may be lower. In any case, we understand equity investment as receiving residual claims on cash flows, thus being the highest risk investments.

Finance plays an important role in technical change. Schumpeter (1997) already recognized the importance of finance for innovation. In his "Theory of Economic Development", capitalists and bankers have to interact in order for innovation to emerge. Mazzucato and Perez (2014) also advocate for the importance of finance and its link to innovation. Innovation is an uncertain process, being cumulative and path-dependent. However, in the context of financialization and shareholder-value maximization behavior of post-1990's, finance became risk-averse:

> However, major innovations can take 15-20 years to fully develop, which means, that this particular financing model only works for gadgets that ride on existing technology, rather than the big waves of the future. Thus secular stagnation is a result of this financialization, not an excuse for it (MAZZUCATO; PEREZ, 2014, p. 7).

In this sense, Mazzucato (2015) state the importance of the State in relation to public financing[15] and the importance of supporting new technological paradigms, such as the green paradigm.

2.6 The role of energy policy in transition process

Energy policy directly affects the revenues of firms that produce electricity. Energy policy can be conducted in several different ways: through carbon taxes, through various types of feed-in tariffs, through quotas and certificates, through auctions, etc (HELD et al., 2014). Figure 2.4 depicts several instrument that affect revenue for firms. Carbon tax directly affects OPEX and taxes. Feed-in tariffs can be considered a sort of grant. Quotas and certificates may fit into the market design instruments. Auctions, especially when combined with tenders and PPAs combine revenue stabilization (tenders and PPAs) with market design, since auctioned power plants normally have a certain period to enter the mix, then they have to provide a certain amount of MWh.

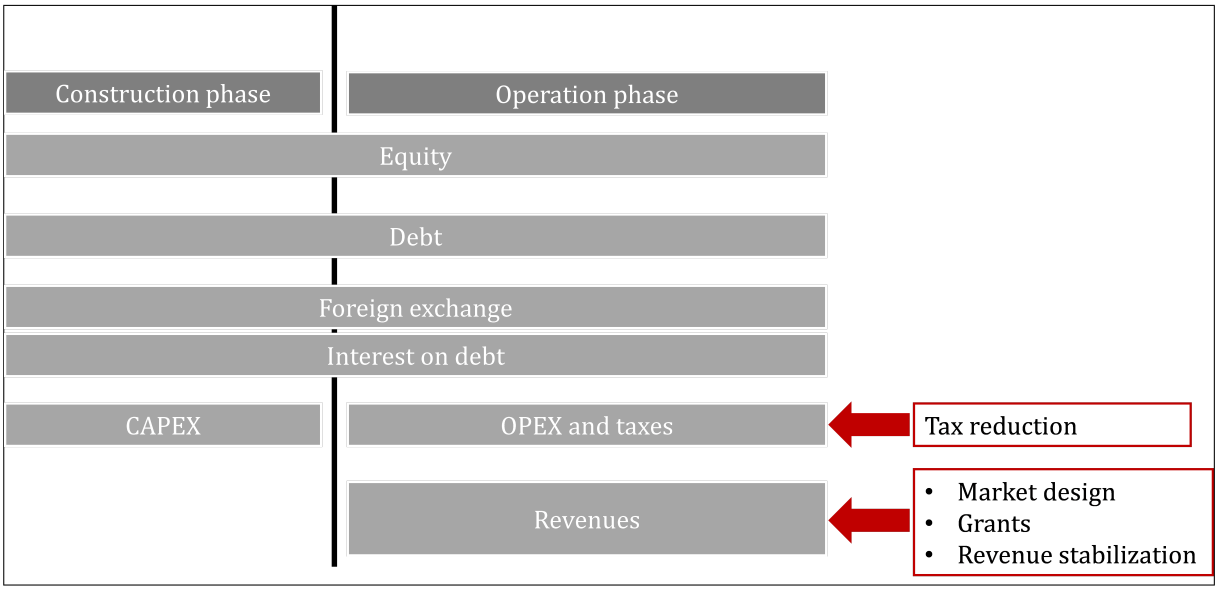

Figure 2.4: Schematic representation of revenue-enhancing instruments to mitigate risks. Source: Vazquez, Hallack, et al. (2018)

We focus on auctions. Auctions can be used in energy markets in a series of ways: determining which firm may have access to certain oil or gas fields; determining which plant project to use for a certain power plant[16]; and to determine which plants

[15]Mazzucato and Penna (2015, 2016) emphasize the role of public development banks such as the german KfW and the Brazilian BNDES.
[16]Normally a large power plant, such as a hydro or nuclear plant.

will be awarded power purchase agreements, etc. We focus on the last type, in which normally the auction has a certain capacity that it wants to contract, sometimes limiting competition to certain sources, e.g., solar plants. The auctioneer, normally the State or some regulatory entity, then proceeds to contract power plants, from cheapest to most expensive, until either the maximum expansion is reached or the maximum price is reached. Auction-contracted plants then are awarded long-term PPAs and are obliged to produce certain amounts of electricity and also to start providing electricity in the next three to five years.

Tran (2014) understands that sustainability transitions rely on diffusion of innovations (both technological and behavioral) on both physical (energy systems) and virtual networks. As such, transitions are viewed by the authors as a '... subclass of diffusion phenomenon...' (TRAN, 2014, p. 8).

Köhler et al. (2018) identify six processes that tend to perpetuate existing systems and thus need to be addressed in order for transitions to happen: knowledge and capabilities; the technical and institutional frameworks; economies of scale and markets; the social-political aspects of the system as it is; the interlinked clusters of technologies used; and everyday practices and lifestyle.

Transitions gather a series of characteristics, such as reshaping the network of relations between agents in the system and being polycentric, i.e., neither centralized nor decentralized in their chain of decisions. Moreover, transitions have dynamics that are not of constant velocity, typically starting slow due to path dependence and then picking up speed. Transitions are open-ended and are uncertain by nature, and they both are triggered by agents and emerge endogeounsly from the system (KÖHLER et al., 2018).

2.7 Policy mixes for energy transitions

Policy mixes[17] involve "... complex arrangements of multiple goals and means which, in many cases, have developed incrementally over many years" (KERN; HOWLETT, 2009, p. 395)[18]. Policy mixes analyze synergies and tensions from different policies in a system (NYKAMP, 2020). In economics, policy mix refers back to post-great depression

[17] (ROGGE; REICHARDT, 2016) provides different definitions and comparisons.
[18] This section is inspired by Furtado and Andreão (2023) section on policy mixes.

macroeconomics[19] to describe the interplay between fiscal and monetary policies (TOBIN, 2001; REYNOLDS, 2001–2002). Evolutionary economists in turn focused on innovation policy mix analyses.

The current generation[20] of studies related to policy mixes (2000s-) suggested modeling as a methodological tool, and proposed four steps for policy mixes (HOWLETT; RAYNER, 2007):

1. Assess a wide range of available policy instruments;
2. Focus on instruments that have synergies;
3. Use different instruments, such as self-regulation and incentives;
4. Consider information instruments.

In short, policy mixes assess (a) which instruments can be mixed; and (b) how they integrate (HOWLETT; RAYNER, 2007). Policy mixes research focus on avoiding inconsistency of instruments and incoherence of goals (ROGGE; REICHARDT, 2016; KERN; HOWLETT, 2009; FLANAGAN; UYARRA; LARANJA, 2011; MAGRO; WILSON, 2013; NYKAMP, 2020). Policy mixes that are both consistent and coherent are congruent: the goal for any policy mix and its processes.

Consistency "... captures how well the elements of the policy mix are aligned with each other, thereby contributing to the achievement of policy objectives" (ROGGE; REICHARDT, 2016, p. 1626) and break into: consistency between strategies, between instruments, and between strategies and instruments.

Coherence[21] refers to the "... synergistic and systematic policy making and implementation processes contributing – either directly or indirectly – towards the achievement of policy objectives" (ROGGE; REICHARDT, 2016, p. 1626). Coherence applies to different policy fields, the capabilities of policymakers, and the effects of policies.

Rogge and Reichardt (2016) adds credibility, comprehensiveness, and different dimensions (policy field, governance and geography) to the concept of congruity. Perfect congruity is less tangible as analysis broadens, and optimal policy mix is harder to pinpoint[22]. Cunningham et al. (2020) corroborates the difficulty to evaluate policy mixes

[19](FLANAGAN; UYARRA; LARANJA, 2011; CUNNINGHAM et al., 2020) attribute the origin to 1960s Keynesians.

[20]Howlett and Rayner (2007) explicits the three generations of studies regarding policy mixes.

[21]see also (NYKAMP, 2020).

[22]In line with (ARTHUR, 1994; DEQUECH, 2011)

and describes how it requires large amounts of quantitative and qualitative data. Nykamp (2020) emphasizes the dynamics of policymaking and states that tensions between different implementation processes may cause incongruity. Clearly, the more dimensions a policymaker has in mind during policy elaboration, implementation and assessment, the harder it is for the analyst to compare different policy mixes.

Howlett and Rayner (2007) provides a taxonomy for situations with multiple goals and instruments (table 2.3). An optimal arrangement occurs when there are no conflicts among goals and among instruments. Otherwise, it fails. An optimal arrangement have low tensions and high synergies among the policy mix (NYKAMP, 2020).

Goal mixes	**Instrument mixes**	
	Consistent	**Inconsistent**
Coherent	optimal	ineffective
Incoherent	misdirected	failed

Table 2.3: Typology of policy mix arrangements based on the relationship between goals and means. Source: (HOWLETT; RAYNER, 2007, p. 8)

Intermediate cases happen when either goals or instruments have conflicts among them. Conflicting goals lead to misdirected arrangements, whereas conflicting instruments lead to ineffectiveness. Misdirected arrangements may work properly but will likely fail objectives. Moreover, synergies between instruments are insufficient given incoherent goals. Ineffective arrangements may fail in spite of having coherent objectives. Inconsistent policy mixes hardly reach coherent goals. As an example, according to Helm and Hepburn (2019) the Spanish policy regime for renewables is a clear example of the need for policy consistency.

Nykamp (2020) argues that inconsistency and incoherence may be unknown during implementation and become problematic when received by other agents of the system. It is not trivial to know beforehand which policy mixes may be congruous. Uncertainty is the reason why "ex-ante" best policies are unknown (DEQUECH, 2011; ARTHUR, 1994).

(CUNNINGHAM et al., 2020) provides a comparative taxonomy of a policy mix: rationales (or goals); domains; instruments; and actors[23]. Rationales support and shape the policymaking process (forward-looking), and determine how to assess results (backward-looking). These backward and forward looking reasoning justify policy imple-

[23]We use the taxonomy of (MAGRO; WILSON, 2013) due to its simplicity.

mentation. Whereas policies have theories behind them, reasoning is provided retrospectively (FLANAGAN; UYARRA; LARANJA, 2011).

Actors are the principals of policy (in game theory terms) (FLANAGAN; UYARRA; LARANJA, 2011; CUNNINGHAM et al., 2020). The authors coined the term "policy subsystem" as the collective of agencies, regulators and other actors that shape policy. From an institutional standpoint, agents and rules' recipients shape the rules. Actors implement, assess and review such rules (NORTH, 1992; CRAWFORD; OSTROM, 1995).

Domains reflect types of policy, such as public financing or energy policy. Different instruments may arise from domains. Energy policy, for example, may combine auctions and a carbon tax to achieve a certain goal. Moreover, different instruments from different domains may also be combined: auctions and public financing for example (HELD et al., 2014; HOCHSTETLER; KOSTKA, 2015). In sum, policy mixes are the emergence of the Rationale-Domain-Instrument-Actor combination, through the dynamics of the policymaking process (ROGGE; REICHARDT, 2016).

Instruments are the means that implement the policies. There is fundamental uncertainty about which aspect of a certain instrument is responsible for which outcome (FLANAGAN; UYARRA; LARANJA, 2011). Especially so with policy mixes which include interactions, dynamic development, and learning (ARTHUR, 1994). As such, it is difficult to pinpoint which instrument within each domain of policy generates an outcome, given the interplay between the policy itself and the system characteristics'.

Following (ARTHUR, 1994), policy elaboration and assessment are subjective. However, they should be evidence-based. As such, policymakers should use a wide range of indicators to assess the impacts of their policies, especially if they want to achieve transparency[24].

Constantini, Crespi, and Palma (2015) analyzes congruity beyond national borders in OECD countries, using traditional econometric regressions. The authors find that similitude between policy mixes of neighboring or cooperating countries leads to better achievement of policy goals. In terms of applicability, (CUNNINGHAM et al., 2020) analyses a wide range of policy mixes. (NYKAMP, 2020; MAGRO; WILSON,

[24]See Cardim de Carvalho (1997).

2013; CONSTANTINI; CRESPI; PALMA, 2015; HOWLETT; RAYNER, 2007; KERN; HOWLETT, 2009) provide single case studies.

2.8 Operationalizing infrastructure industries: models for electricity industries

In light of this, one must then decide how to analyze policy mixes and if and how should models of policy mixes be operationalized. There are a multitude of options: analyzing policy mixes through the use of indicators, through the use of interviews, through the use of models, etc. Regarding the use of models, one way further subdivide it into models: using statistics, using econometrics; using partial equilibrium, using general equilibrium, using agent-based models, etc. Vazquez (2011) depicts several examples of models for analyzing electricity mixes and electricity markets. The EMMA model is a partial equilibrium model for several European countries (RUHNAU et al., 2022). There are also several DSGE focused on electricity mixes (SUN; XU; ZHENG, 2023; SCHREINER; MADLENER, 2022). Nevertheless, there is a growing number of agent-based models for electricity systems, such as the Schumpeter meeting Keynes (DOSI; FAGIOLO; ROVENTINI, 2010), including the DSK model (LAMPERTI et al., 2018). One ABM uses Ostrom (2005) to analyze electricity mixes (IYCHETTIRA; HAKVOORT; LINARES, 2017) The E3ME-FTT model is also a relevant model regarding this object of study (MERCURE; POLLITT, et al., 2018).

Köhler et al. (2018) states that there are six key modeling features for a simulation that tackles transitions:

- Capability of representing non-linear behavior;
- Capability of representing qualitatively different system states;
- Capability of representing changes in social values and norms;
- Capability of representing diversity and heterogeneity;
- Capability of representing dynamics at and across different scales;
- Capability of incorporating open processes and uncertainties or contingencies.

According to Foxon et al. (2013), complexity economics can address the key environmental questions regarding transitions:

- what incentive mix is needed to promote more sustainability among consumers and firms?
- how to break carbon-intensive lock-ins in terms of technologies and institutions?
- how to combine sustainability with economic development in terms of the transition, specially in developing countries

In light of that, we shall develop an agent-based model that attempts to encompass some of those characteristics. We do not affirm that all other modeling or analysis options are incapable of reproducing such characteristics, nevertheless we stress the fact that agent-based models are normally built with such characteristics in mind, specially diversity, heterogeneity, uncertainty.

Moreover, “A strategy of promoting diversity is generally effective in promoting stability, resilience, durability and robustness of systems. For example, a more sustainable set of energy technologies will have greater diversity" (FOXON et al., 2013, p. 194)

Chapter 3

Computational toolbox: groundwork of the simulation

In this chapter we present our proposed agent-based model. We present a general introduction to the the ODD protocol Grimm et al. (2006) and the overview of the model. Afterwards we present the design concepts of the model. Lastly we describe the most relevant details of the model.

3.1 Agent-based models, ODD protocol and overview of the TeFE model

The overview of a model, according to the ODD protocol encompass: its purpose, entities, main variables and their scales, as well as the process overview and scheduling.

3.1.1 Purpose

The main purpose of the TeFE ABM is to produce runs of electricity systems in which agents that produce electricity and agents that produce electricity-generation assets (which comprise the private agents) interact among themselves and with a technology policy maker, an energy policy maker and a development bank (which comprise the public agents) in the context of an energy transition. All runs may or may not have a simple rule for controlling heterogeneity between policy makers regarding how they do policy.

Such rule has a threshold for heterogeneity among public agents and is executed by another agent called the council entity. The main purpose of the model is to replicate what we consider the pivotal parts of an electricity mix including policy makers, aiming at simplicity and focusing on the interactions among agents. Since the public agents are not hierarchically related to each other, their decision-making structures may be heterogeneous, as such, we aim to analyze emergence of energy transitions in a context in which heterogeneity and interactions play significant roles.

3.1.2 Entities

In our proposed model, we have two main categories of agents: public agents and private agents. There are two more agents: a commercialization chamber and a council entity. Private agents focus on their own profits while public agents rather focus on the evolution of the system itself. All agents follow a satisficing heuristic: they have a certain effort towards a specific activity and will reduce such effort it they judge that their performance on such activity is good enough.

Private agents collect profits and incentives, decide their next steps and analyze system changes. All private agents may reinvest into their activities, nevertheless they focus on saving their profits throughout the year to distribute them among shareholders at the end of the year. In specific terms:

- **Technology providers:** they decide how much to reinvest of their profits, either into R&D or into developing local production capacity. They provide one type of technology of one source and cannot change their source throughout the simulation;

- **Energy producers:** they decide if they will propose a new power plant to the development bank or if they will attempt to reinvest into a new power plant using their own resources, and then they decide the size of that plant. They focus on one main source for that expansion, but may change their main source.

In relation to public agents, they focus on system outcomes. In this sense, all three public agents may focus on increasing the number of innovations (innovation rationale), the insertion of renewables into the mix (renewable rationale) or on increasing the local capacity of renewables (internalization rationale). More specifically:

- **Energy policy maker:** it decides how much incentive to give to a certain source through auctions. It focuses on only one source but may change the incentivized source. It has only one policy in force: auctions with power purchase agreements[1];
- **Technology policy maker:** it decides how much cash flow incentive to give to technology providers of a certain source. It focuses on only one source but may change the incentivized source. It has only one policy in force: cash flow incentives to technology providers[2];
- **Development bank:** it decides how many projects to finance of a certain source. It focuses on only one source but may change the incentivized source. It has only one policy in force: lending at below-market interest rates[3];

The commercialization chamber collects power plants that are built and therefore apt to produce electricity and contracts them according to the merit order, paying each power plant by the price of the most costly unit contracted. The council entity analyzes all public agents in the simulation and may reduce heterogeneity among them.

3.1.3 Main variables and their scales

We have a multitude of variables that may be analyzed. Nevertheless, in the experiments performed we focus on:

- **Change in effort:** ($number \in \mathbb{R}$) what is the degree of change per agent, i.e., what are the accumulated results from the Decision submodel. In other words, how much has one agent changed their effort throughout time? Change in effort accumulates with time and there is no discount effect on it. It is gathered at the entity level, for each technology provider, Energy producer, technology policy maker, energy policy maker and development bank in the simulation. Can be aggregated to the collective of private and public entities.

[1]We have carbon tax and feed-in tariffs modeled in the code, but they were neither implemented or tested.

[2]We use incentives that the policy maker does not check how they were used but we have implemented one category in which incentives are bound to their use (into either R&D or local productive capacity) however a part of the incentive is spent on assessing how they were used by firms. Such category is modeled but not implemented nor tested.

[3]We also have guarantees modeled, nevertheless, since we have yet to implement private banks, such type of incentive was not used.

- **Adaptations:** ($number \in \mathbb{N}$) what is the number of adaptations that each agent underwent until a specific period, i.e., what are the accumulated results from the Evaluative Criteria submodel. In other words, how many times has an agent engaged in changing their decision-making process in a discontinuous way. Adaptation accumulates with time and there is no discount effect on it. It is gathered at the entity level, for each technology provider, Energy producer, technology policy maker, energy policy maker and development bank in the simulation. Can be aggregated to the collective of private and public entities.

- **Satisficing score:** ($number \in \mathbb{R}$) regarding the variable that a entity attempts to satisfice, what is its score, e.g. private entities focus on satisficing profits whereas public entities focus on having satisficing objectives that depend on their rationale behind their policies. In other words, if an agent must rate how itself is doing in relation to its goals, what would that score be? Satisficing score accumulates with time and there is no discount effect on it. It is gathered at the entity level, for each technology provider, Energy producer, technology policy maker, energy policy maker and development bank in the simulation. Can be aggregated to the collective of private and public entities.

Each of those variables are analyzed at the entity level, collective level and system level for: its absolute variable, standard deviation, speed of change [4] and acceleration of change[5].

On top of those variables that we thoroughly analyze, we also analyze to some degree the variables:

- **Avoided emissions:** ($number \in R_+$) what are the avoided emissions of an contracted renewable power plant, i.e., if that renewable power plant was actually fossil, what would the emissions be? It is zero if the plant is not contracted and is gathered at the power plant level. It is time specific and does not accumulate over time. Can be aggregated to each technology provider and to the whole system, as well as being aggregated in relation to each source;

[4] $(variable_t - variable_{t-\tau})/\tau$ for $\tau \in (1, 3, 6, 12, 24, 48)$.
[5] $(speed_t - speed_{t-\tau})/\tau$ for $\tau \in (1, 3, 6, 12, 24, 48)$.

- **Electric capacity:** What is the electric capacity of a certain power plant, in MW? It is time specific and does not accumulate over time. Can be aggregated to each technology provider and to the whole system;

- **Electricity generation:**What is the contracted generation of a certain power plant, in MWh? It is time specific and does not accumulate over time. Can be aggregated to each technology provider and to the whole system, as well as being aggregated in relation to each source;

- **Emissions:** ($number \in R_+$) what are the emissions of an contracted fossil power plant. It is zero if the plant is not contracted and is gathered at the power plant level. It is time specific and does not accumulate over time. Can be aggregated to each technology provider and to the whole system, as well as being aggregated in relation to each source.

- **Electricity price:** ($\$ \in \mathbb{R}_+^*$) what is the price of the system, resulting from the Commercialization submodel. The system is priced according to its unit with highest priced that was contracted. It is based on the technology costs and on the margin decided by each Energy producer. It is gathered at the system level, as well as being aggregated in relation to each source;

- **R&D expenditure:** ($\$ \in \mathbb{R}_+$) what is the expenditure of a certain technology provider on R&D at a specific period? Accumulates over time with a discount factor[6] and is gathered at the entity level. Can be aggregated to the system level, as well as being aggregated in relation to each source.

- **Local productive capacity expenditure:** ($\$ \in \mathbb{R}_+$) what is the expenditure of a certain technology provider on local productive capacity at a specific period? Accumulates over time with a discount factor[7] and is gathered at the entity level. Can be aggregated to the system level.

3.1.4 Process overview, submodels and scheduling

Regarding the submodels, the three largest ones are: expansion, decision and evaluative criteria submodels.

[6]in order to reflect depreciation.
[7]in order to reflect depreciation.

Expansion:

This submodel has two parts: first it sends power plants to the development bank, and second it decides if rejected projects will be resent, dropped or, if the energy producer has enough resources, will be financed through reinvestment. The expansion is given by the equation 3.3.

$$\alpha_t = \frac{remaining\_demand_{t-1}}{24 * 30} \tag{3.1}$$

$$\beta_t = demand_{t-1} * (1 - risk_{source}) \tag{3.2}$$

$$expansion_{i,t} = \frac{effort_{i,t}}{n\_of\_EP^{exp(1-effort)}} * (\alpha_t + \beta_t) \tag{3.3}$$

Between the parenthesis there are two terms: the first one is responsible for calibrating the expansion according to the remaining demand[8] and the second one for calibrating the expansion according to the magnitude of system demand[9]. If there is space for more power plants to be contracted($remaining\_demand_{t-1} > 0$) then the numbers of the expansion are larger, whereas if there is no more space for power plants and new power plants will have to compete in terms of price to be contracted ($remaining\_demand_{t-1} < 0$) then the numbers of the expansion will be smaller: under this circumstance, the first term becomes negative. The second term is responsible for the desired expansion of the energy producer regardless of the system situation. If the first there is negative, i.e., all the demand is met, then the second term must be significant in order to offset it. The ratio outside of the parenthesis calibrates the expansion to the effort of the energy producer: the higher the effort the larger the desired expansion. The role of the denominator is to transform the capacity of the system itself (between the parenthesis) into a magnitude fit for a firm.

The second term of the expansion is multiplied by the complementary of the risk of source that the energy producer chose as main source. The first term, which comprises of demand yet to be met, is not multiplied since, if there is more demand than supply, all new plants will be contracted [10]. That means that, the higher the risk of the

[8]Since the remaining demand is measure in MWh and the expansion is measured in MW, we have to divide it by $24 * 30$

[9]This one already in MW.

[10]Agents do not exploit this by putting extremely high margins.

source, the lower the expansion will be. Then the energy producer checks all technologies that meet one of the criteria. Those criteria are:

1. Be a technology that uses the main source of the energy producer;
2. Be a technology that may enter auctions;
3. Be a technology that may be financed by the development bank.

If one of those conditions are met, and either it is the first technology to be considered or that technology has a higher NPV than the previously chosen technology, then the analyzed technology becomes the chosen technology for the power plant project. In the second case, there is a chance that a technology with lower NPV will be chosen in place of the previously chosen[11]. If the desired expansion is below the minimum lump investment of the source, then the project does not go through, unless the power plant may access PPAs or public funds, in which case the expansion will occur with just one single lump. While calculating the NPV of a power plant with a certain technology, if that technology may access subsidized funds, then the interest rate considered is lower than the market-level interest rate. Having decided the technology for the power plant project, then that project is sent to the energy policy maker, if there is an auction planned for the source of the power plant, or to the development bank in order to receive financing.

Moreover, if the source of the technology differs from the main source considered by the energy producer then the project will only exist if:

1. The score of the other source is above the score of the main source
2. the test $1 - aversion\_to\_change > U(0, 1)$ is true

Having met those condition then the project is sent to the development bank. Moreover, if those conditions are met, then the Evaluative Criteria submodel will be triggered to check if the main source will be adapted to the source of the technology of the power plant that became a project.

The second part of this submodel is responsible for determining the fate of projects that were either rejected or were bidded to auctions and received PPAs. The projects that fit one of those criteria are inserted into a list of projects and are assigned

[11]That reflects a number of possibilities: imperfect information, technology preferences that go beyond NPV, etc.

a time limit to be financed. If that time limit is met, then the project is dropped by the energy producer. Under that time limit, then the energy producer analyzes if it has sufficient funds to reinvest into the construction of that power plant according to 3.4.

$$condition = \begin{cases} True & resources * effort \geq CAPEX \\ False & otherwise \end{cases} \tag{3.4}$$

If no, then the project is resent to the development bank. If yes, then the energy producer analyzes the NPV of the power plant if it was a reinvestment decision. Afterwards it compares that new NPV to the minimum NPV (NPV_{min}) and maximum NPV (NPV_{max}) of its existing power plants according to equation 3.5.

$$condition = \begin{cases} True & NPV \geq (1 - effort) * U(NPV_{min}, NPV_{max}) \\ False & otherwise \end{cases} \tag{3.5}$$

The higher the effort, the higher the chance that the NPV condition will be met. If the condition is met, then the energy producer reinvests into that power plant, decreasing the CAPEX from its resources.

Decision

This submodel is present on: technology providers, energy producers, technology policy maker, energy policy maker and development bank. In this submodel, agents analyze the system and decide their next level of effort.

$$\theta_{i,t} = \overline{\Gamma^{norm}_{[t-1-\tau,t-1]}} - \gamma^{norm}_{i,t-1} \mid \gamma \in \Gamma \tag{3.6}$$

First entities get the θ from the system itself, according to equation 3.6. In that equation, they first gather all γ indicators from period $t-1-\tau$, with τ being the entity's memory, into a set of indicators Γ. Indicators are discounted by a discount factor. Then, those indicators are normalized by the maximum and minimum values, ensuring that all numbers are between zero and one. After that, a specific indicator γ is taken out of the set ($\gamma^{norm}_{i,t-1}$) and is subtracted the mean of the set ($\overline{\Gamma^{norm}_{[t-1-\tau,t-1]}}$). As such, if the mean is above the indicator, than the ratio will be a positive number and larger as that difference increases, with the opposite being true.

$$addition = |N(0, |\theta|)| * \frac{|\theta|}{\theta} \tag{3.7}$$

Having found the θ, than the agent will find its addition according to equation 3.7. In it, a half normal distribution with mean zero and standard deviation of the absolute value of the ratio is taken. The fraction ensures that negative θ will produce negative additions and positive θ positive additions.

$$effort_{i,t} = effort_{i,t-1} + (1 - aversion\_to\_change) * addition * change\_magnitude \tag{3.8}$$

Lastly, the new effort of the agent i ($effort_{i,t}$) is given by its previous value ($effort_{i,t-1}$) plus the addition multiplied by the complementary to the agent aversion to change ($1-aversion\_to\_change$) and by the magnitude of change[12] ($change\_magnitude$). Negative additions reduce the effort, whereas positive additions increase it. Higher aversions to change reduce the addition effect, with the magnitude of change having the same effect but for all entities.

That means that, if the current indicator is below its historic mean, then the agent may increase its effort with higher chances of doing so as the difference between historic mean and current becomes larger. Private entities are analyzing their profits as γ in relation to the profits of their competitors γ.

Public agents' analyses depend on their rationale. If the rationale is to foster renewables, then the public entity is analyzing the avoided emissions of the system. If the rationale is to foster innovation, then the public entity is analyzing the R&D expenditure by technology providers of the system. If the rationale is to foster internalization, then the public entity is analyzing the expenditure on local productive capacity by technology providers of the system. In that sense, what public agents' analyze is if the current level of the indicator is above or below its historic average.

[12] That value is always set to ten in the experiments, which means that it is necessary at least 10 periods to drop an effort from one to zero or to raise it from zero to one.

Evaluative Criteria

This submodel is present on: technology providers, energy producers, technology policy maker, energy policy maker and development bank. It has two parts for all entities except for the technology provider: it analyzes changes in the system regarding the system itself (public entities) or regarding competitors (private entities), and it analyzes changes in the system regarding the sources themselves.

Similar to the decision submodel, private entities are analyzing their profits in relation to the profits of their competitors. Public agents' analyses depend on their rationale. If the rationale is to foster renewables, then the public entity is analyzing the avoided emissions of the system. If the rationale is to foster innovation, then the public entity is analyzing the R&D expenditure by technology providers of the system. If the rationale is to foster internalization, then the public entity is analyzing the expenditure on local productive capacity by technology providers of the system.

$$hist = \begin{cases} \overline{\Gamma^{norm}_{[t-1-2\tau,t-1]}} & public \\ \overline{\Gamma^{norm}_{\forall j \neq i,[t-1-\tau,t-1]}} & private \end{cases} \tag{3.9}$$

First the entity will search for its historic indicator. If it is a public entity, then it gathers all selected indicators from period $t-1-2\tau$ to period $t-1-\tau$. if it is a private entity, then it gathers all selected indicators from period $t-1-\tau$ to $t-1$ that belong to its competitors[13]. Then the agent gets the average of those values.

$$current = \begin{cases} \overline{\Gamma^{norm}_{[t-1-\tau,t-1]}} & public \\ \overline{\Gamma^{norm}_{i,[t-1-\tau,t-1]}} & private \end{cases} \tag{3.10}$$

Then the entity will search for its current indicator. If it is a public entity, then it gathers all selected indicators from period $t-1-\tau$ to period $t-1$. if it is a private entity, then it gathers all selected indicators from period $t-1-\tau$ to $t-1$ that belong to itself. Then the agent gets the average of those values.

[13]Technology providers compete among them, and energy producers compete among themselves.

$$verdict = \begin{cases} Favourable & current > (1 + aversion_{adaptation}) * hist \\ Unfavourable & current < (1 - aversion_{adaptation}) * hist \\ Keep & otherwise \end{cases} \tag{3.11}$$

Afterwards the entity will decide its course of action. If the current indicator is above the historic indicator multiplied by one plus the aversion to adaptation, then the current situation is deemed better than the past periods. Then we subtract one from the impatience of the agent and decide to keep characteristics unchanged. On the other hand, if the current indicator is below the historic indicator multiplied by the complementary to the aversion to adaptation, then the current situation is deemed worse than the past periods. Then we add one to the impatience of the agent and decide to change a characteristic of the agent. If the inequality falls in between, then the impatience and the characteristics remain unchanged. Lower aversion to changes decrease the "keep" range.

Then the entity runs a test in which the result of a beta distribution with $\alpha = 1$ and $\beta = 3$ is compared to a ratio formed by either dividing the lowest indicator between hist and current by the other one. If the result of the distribution is above the ratio, then the agent decides to adapt. If not, then the test is repeated for *impatience* times, i.e., the more impatient an entity, the more times it will perform and adaptation test. Having repeated the test the set number of times, if it failed to reach above the threshold, then the agent will not change a characteristic, nevertheless the change in impatience will accumulate for the next period. In other words, if change is not reached at a certain period, the chances for reaching it next period become higher.

Having decided to adapt, then the agent will randomly choose from a list of possibilities and randomly choose a new value for that characteristic from the list. The only exception to this is if the entity chooses to change source. Since sources are ranked one in relation to the others, the agent sorts them by value, from higher to lower, and then runs a $Poisson(0.355)$ distribution[14] in order to decide between the first, second or

[14]The highest ranked source has 70% chance of being chosen.

third source option[15]. The relevance of the distribution is that is randomizes decisions while respecting the order of possibilities.

The second part of this submodel is directly responsible for attributing values to the sources themselves. The score of a source is first discounted by the discount factor. Then we will add two values to it: a backwards value, that reflects the current state of affairs; and a forwards value, that reflects the possibilities. For private entities those values reflect profits, whereas for public entities, those values reflect how in line with the public policy goals that source is.

Regarding the backwards value, for public entities it reflects the profits of agents with each source at the previous period. For public entities, depending on their rationales, it reflects how much emissions has that source avoided, or how much was the R&D expenditure of that source, or how much was the expenditure in local productive capacity for that source.

The forwards value reflects, for private entities, how much would their profits be if all demand was supplied by that entity using the best technology from each source and producing at the highest price for that source. For public entities with the rationale of fostering renewables, the forwards value is quite similar, but instead of focusing on profits it focuses on avoided emissions, predicting what would be avoided emissions if all the current capacity was changed for the greenest technology of each source. Regarding the other two rationales, the forwards value is comprised of the backwards value plus all profits from technology providers of each source.

Having both values for each source, we then get the result from a normal distribution using each value as mean with the standard deviation being the standard deviation of values for sources regarding the backwards or the forwards values. Having those results, we them add both the backwards and forwards results to each source accordingly.

Other submodels

The remaining submodels are:

- **Collecting:** Entity analyzes all interactions from the previous time period, selects those in which the entity was on the receiving end of the interaction and checks if

[15] If the result is above two, then the last one is chosen. Public entities are merely choosing between two, so if the result is above one, then the last one is chosen.

that interaction increased its cash flow. Then the entity increases its resources as well as its satisficing score with the cash flow from the previous period. Present on: technology and energy producers;

- **Money to shareholders:** After 12 months[16] the entity takes $(1 - effort)$ of its current financial resources and gives it to its shareholders as dividends. Since an entity's effort means how much it is willing to compromise of its resources into attempting to leapfrog on front of competition, then the complement of effort means how of an entity's resources the entity is not willing to compromise. The satisficing score is not changed by this process. An assumption is that all of the resources that an entity is not willing to compromise are given as dividends. Present on: technology and energy producers;

- **CAPEX definition:** We assume that if there are significant transportation costs to a technology, then reinvestment of a technology provider into local productive capacity reduces those transportation costs[17] and thus reduces CAPEX.

$$CAPEX_{k',t} = min(CAPEX^{*}_{k',t-1}, CAPEX_{k',t-1}^{\frac{CAPEX^{*}_{k',0} * capacity\_thresh_{k}}{capacity_{k}}}) \tag{3.12}$$

  Equation 3.12 shows how reinvestment into local productive capacity affects CAPEX of technologies. In it the CAPEX of a k' technology that belongs to its k technology producer at a period t is given the minimum between its base CAPEX ($CAPEX^{*}_{k',t-1}$), which is the CAPEX without the capacity effect[18] and between that base CAPEX to the power of the ratio between the capacity threshold of the technology provider ($capacity\_thresh_{k}$) times the starting CAPEX of the technology ($CAPEX^{*}_{k',0}$) and the reinvestment into local productive capacity of the technology provider at the previous period ($capacity_{k}$). As such, CAPEX reduces as investment in local productive capacity surpasses the starting CAPEX of the technology multiplied by a threshold. There is a cap to this process however: a CAPEX is only allowed to be halved in intervals of 120 periods (10 years). Present on: technology providers;

[16] Technically at the end of the "year".
[17] For example, for having industrial plants closer to power plants' sites
[18] Technology innovation that affects CAPEX affects the base CAPEX.

- **Innovation:** A technology provider may innovate if its expenditure is above a certain threshold ($RnD\_threshold$). Having met that condition, then we follow the equation 3.13 in order to check if its result was above one.

$$a_{k,t} = Poisson(1 + tech\_age_{k',t}) + N(0,1) \tag{3.13}$$

In the equation, an innovation occurs if the sum of a Poisson with λ equal to one plus the inverse of the maturity of the technology $(1 + tech\_age_{k',t})$ with a Normal of mean zero and standard deviation of one is above one. Equation 3.13 follows the innovation process present on Fagiolo and Dosi (2003) in which there are low chances of high jumps in productivity and high chances of low jumps in productivity[19], replicating radical and marginal innovation processes. If the result of the innovation equations is above one, then innovation occurs and either CAPEX or OPEX[20] is multiplied by the inverse of the result: the higher the result, the lower costs will be for that technology in the next period.

$$RnD\_threshold_{k,t} = U(1, a_{k,t}) * RnD\_threshold_{k,t-1} + U(0, RandD_{k,t-1}) \tag{3.14}$$

If innovation occurs, then the threshold is changed following equation 3.14. In that equation, the new threshold for innovation to occur as a function of increase in R&D expenditure becomes the result of an uniform distribution between 1 and the result of the innovation equation multiplied by the previous threshold plus the result of an uniform distribution between zero and the current level of R%D expenditure. Higher degrees of innovation may increase the threshold significantly and the higher the expenditure in R&D the higher the chance that the next threshold will be significantly higher. Moreover, innovation may also chance the maturity level of the technology. If the innovation was above the threshold for radical innovation, then we add one to the maturity of the technology, thus impacting the innovation

[19]Their model uses productivity, TeFE model however uses that result to decrease either CAPEX or OPEX

[20]We randomly decide among the two each time there is innovation.

equation by reducing the chances for radical innovations, i.e., as radical innovations occur, their chance for happening decrease. Present on technology providers;

- **Reinvestment:** If the technology provider has resources and its effort is above zero, then it will reinvest those resources. A technology provider may reinvest into R&D or into local productive capacity according to its strategy. Having met the conditions, then the technology provider reinvest a fraction of its resources that is proportional to its efforts. Present on technology providers;

- **Cash flow incentive:** First the technology policy maker determines its current budget by multiplying its effort by its available resources. Then the technology policy maker divides that budget by the number of technology providers that research the incentivized source. Lastly the technology policy maker tells the technology providers that received incentives how much their financial cash flow has increase. Present on: technology policy maker;

- **Auction:** First the energy policy maker announces that there will be an auction after a certain amount of periods. Then, the energy policy makers collects all power plant projects that use the incentivized source and were bidded to the auction between the announcement of the auctions and the auction itself. Once the period for the auction to take place comes, then the energy policy maker sorts all collected power plant projects according to their price, from lowest to highest. Then the energy policy maker awards PPAs to projects until the auction capacity is met. The auction capacity is a function of the energy policy maker's effort: the more effort the larget the auction capacity is. Having decided which projects were awarded PPAs or not, then the energy policy makers tells the energy producers responsible for the projects the auction outcome. Present on: energy policy maker;

- **Accreditation:** The development bank selects technology firms that are above a threshold related to the entity's rationale. Power plants that use the technologies from those accredited technology firms may access the subsidized funds. The development bank first sorts the technologies from the incentivized source regarding: their avoided emissions, if the entity's rationale is to foster renewables; the R&D expenditure of the technology provider responsible for the technology, if the entity's rationale is to foster innovation; and the expenditure on local productive capacity of the technology provider responsible for the technology, if the entity's rationale is to foster internalization of industrial chains. Having sorted the technologies, then the development bank accredits the technologies that are on the $1-effort$ quantile of the list of possible technologies. The highest the effort, the more technologies will be accredited. The list of accredited technologies is reset every 24 months (two years). Present on: development bank;

- **Lending:** First the development bank determines its interest rate as a function of its effort: higher efforts mean lower interest rates. Then the bank decides its budget for financing those projects by multiplying its available resources by its current effort. Then the bank collects all power plant projects that were addressed to it and selects all those that used a technology that belong to the incentivized source. Afterwards, the development bank sorts then in relation to its rationale: by their avoided emissions, if the entity's rationale is to foster renewables; by the R&D expenditure of the technology provider responsible for the technology, if the entity's rationale is to foster innovation; and by the expenditure on local productive capacity of the technology provider responsible for the technology, if the entity's rationale is to foster internalization of industrial chains. Then the development bank checks if the NPV of the first plant is above a threshold[21] and reduces the CAPEX of the plant from the budget. If the budget is enough to finance that plant, then the energy producer responsible for that power plant project receives the finance, if not the project is rejected. This process continues until all projects are analyzed or until the development bank's resources are brought down to zero. Present on: development bank;

- **Coordination:** The coordination submodel runs once every three periods (three months). First the council entity analyzes selected characteristics of the policy makers[22] and checks how many of those characteristics are different if the coordination approach is to reduce heterogeneity. The entity then gets the ratio of heterogeneity by dividing the number of different characteristics over the total number of characteristics. If there are more than one policy maker, then the criteria for the

[21]We set the threshold to zero, i.e., the development bank wants projects that at least can payback themselves.

[22]Memory, threshold for change, threshold for adaptation, threshold for disclosing change in incentives, periodicity, level of effort and incentivized source

characteristic must be met at least for two and does not count double if all policy makers have different characteristics. If the ratio is above the coordination threshold (0, 0.25, 0.5 or 0.75 respectively for high, high intermediate, intermediate and low intermediate) then the entity coordinates accordingly to its coordination approach: it will randomly make entries of that characteristic among the policy makers homogeneous until the level of heterogeneity is at the threshold. Then that characteristic is taken out of the numerator of the ratio and, if the ratio is still above the threshold, the coordination processes continues, if not, then the process ends. Present on: council entity;

- **Commercialization:** The commercialization chamber analyzes all plants that are built on that period. Then the entity sorts all plants by: 1) if the plant has a PPA or not; and 2) their prices. Then the entity determines the prices for plants without PPAs following the merit order, i.e., those plants will have the price of the last contracted unit (which is the one with highest price). After that, the entity contracts plants until a certain limit (the current expansion goal) is met. Lastly, the entity tells the energy producers the outcome: if their power plant was contracted or not and at which price. Present on: commercialization chamber;

3.1.5 Initialization

The initialization of the model occurs as following:

1. We enter the global parameters as well as the parameters for the initial value of variables. For example: the threshold for activation of the council entity; the mean, standard deviation, maximum and minimum for the initial value of the effort of an agent to be drawn from a normal distribution, etc.;

2. Then we create the agents in the following order: (1) Technology providers, (2) Energy producers, (3) Commercialization chamber, (4) Development Bank, (5) Energy policy maker, (6) Technology policy maker, (7) council entity (if it is present);

3. Then we start the simulation at the time zero, with each agent acting in the order that they were created. For the first 72 periods, all stochastic processes have the weight of its random distributions set to 100%;

4. In the last period we save the information of the run, beginning with period 72 and ending in period 552, go to the next seed and proceed with the next run, repeating until the desired number of runs is achieved.

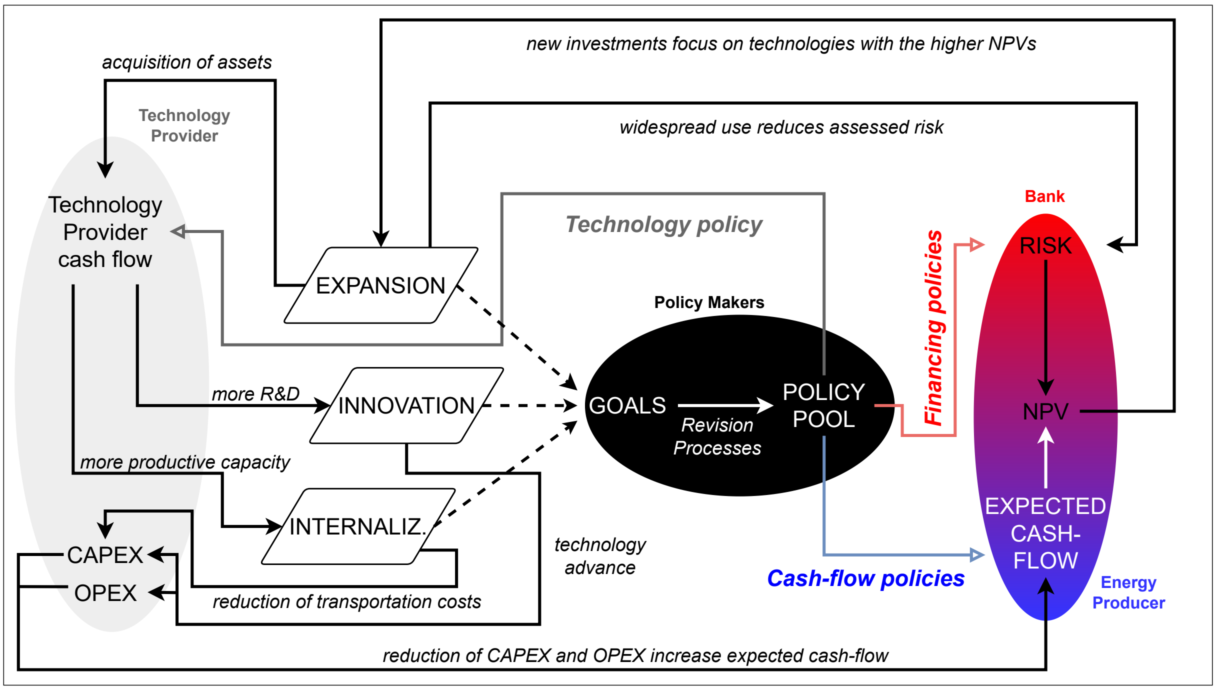

Figure 3.1: How policies affect the system. Source: own elaboration.

Figure 3.1 shows how the interactions of private and public agents occur in the simulation. The expected cash-flow of an asset is given by the current technology characteristics. That expected cash-flow together with the perceived risk leads into the net present value of that investment. The expansion of the system by technology providers occurs in the direction of technologies with higher predicted net present values. In turn, the expansion of a source tends to reduce its perceived risk. With the expansion of the system, the technology producers responsible for the assets added to the electricity mix increase their cash flow through the acquisition of assets. That cash flow may then be transformed into: reinvestment into productive capacity, leading to decrease in CAPEX; reinvestment into R&D which may lead to innovation and thus reduction of costs; or simply into more profits. Respectively they increase: the innovation of the system, the internalization of the system and the private score of that technology provider. The reduction of costs will then impact the technologies in the next period.

All the while we have the policy makers analyzing how the system is doing in terms of the expansion, innovation and/or internalization of renewables. Policy makers then adjust their policy efforts according to the trajectory of the system, following a satisficing heuristic. Energy policy affects the expected cash-flow, public financing directly affects the risk and the technology policy affects the cash flow of technology providers.

3.2 Design of the TeFE model

The design concepts of a model, according to the ODD protocol encompass: basic principles, emergence, adaptation, objectives, prediction, sensing, interaction, stochasticity and collectives[23].

3.2.1 Basic principles

The basic principle of the TeFE ABM is simplicity, since we consider that simplicity is key: "... the best model is one which permits the encoding of the observed data together with the model with the fewest number of binary digits" (RISSANEN, 1998, p. 118). Building from that principle and from the theoretical and empirical toolboxes we them add the following principles: complexity, fundamental uncertainty, satisficing routines, bounded rationality, policy mixes, exploit/explore heuristics, path dependence and non-ergodicity.

3.2.2 Emergence

Some effects emerge from the interactions between agents: change, adaptation, heterogeneity, technology innovation, technology adoption and speed of system change. We focus our analysis on the last one by analyzing an index comprised of the speeds of change of each agent, of each private entity or of each public entity.

Change emerges from the interaction between entity and the system as whole. Private entities change as a response to changes in their system position in relation to its competitors, under the condition that such changes must be deemed significantly negative. Public entities change as a response to system changes, specially regarding comparisons between renewable and fossil indicators.

Adaptation emerge also from the interaction between entity and the system as whole and thus from different configurations of action arenas Ostrom (2005). The

[23]Observation is displayed in the appendix B.

difference is that adaptation takes longer to emerge but its effects may endure for longer periods. If action arenas' configurations are deemed negative by an entity and if those configurations remain as such, from the point-of-view of the entity itself[24], for a significant period, then agents may engage in adapting their decision-making structure. For public entities, the decision to adapt depends on their rationales, since those shape how public entities analyze the system itself.

Technology innovation emerges stochastically from higher expenditures on R&D by technology providers. It may occur in function of higher cash flows for technology providers that are more willing to reinvest into R&D. If a technology provider access incentives or its technology is being more adopted, then there is a higher chance for technology innovation of that agent.

Technology adoption is also related to technology innovation since the more adopted a technology is, the higher the chance for it to undergo technology innovation. On the other hand, the more innovation a technology undergoes, the more likely it is that such technology is cheaper, which is a significant factor for adoption. On the other hand, more innovative technologies tend to surpass less innovative technologies and thus more innovative technologies tend to be more adopted. It emerges from the interactions between energy producers and policy makers.

Heterogeneity emerges from interactions among all entities. Heterogeneity emerges as the synthesis between path dependence, change and adaptation, with stochasticity playing a relevant role regarding heterogeneity. Incentives influence the pathways of heterogeneity emergence in the system, nevertheless heterogeneity directly shape the incentives given to private entities.

On top of the heterogeneities that emerge from interactions we also have a council entity that may reduce heterogeneity between policy makers, attempting to coordinate the policymaking process in the context of energy transition. As such, the council entity may reduce heterogeneity in the system itself by reducing heterogeneity among policy makers regarding their different policymaking activities. Thus, the council entity would then set a cap to the maximum heterogeneity between policy makers.

Speed of system change emerges from the interplay between all previous emergent phenomena and therefore from interactions among agents. It encompasses the dy-

[24]For example, a technology provider see as negative that it lagged behind competition in terms of profits, but do not see as negative if all profits went down.

namics of which those other emergence phenomena occur, being a measure of the system is changing over time.

3.2.3 Adaptation

Adaptation occurs at two levels: effort and decision-making. We normally refer to those two adaptations as "change" and "adaptation", in order to separate the short-term adaptation to the mid-term adaptation. The adaptation of effort is continuous: it ranges from zero to one, meaning with how much effort will an entity[25] pursue its goal. The adaptation of the decision-making structure is discrete, i.e., an entity may change a certain part of decision-making structure in a certain lump, e.g., threshold for adaptation from medium (0.5) to high (0.9). Adaptation of effort is part of the decision submodel, whereas adaptation of the decision-making structure is part of the Evaluative criteria submodel. It is important to notice that, since the effort level of an entity is a stochastic results of its decision-making structure, adaptation of effort is related to the adaptation of the decision-making structure itself. Nevertheless, the opposite is also true since adaptation of effort may also lead to the adaptation of the decision-making structure through feedback loops.

3.2.4 Objectives

Producing simulated runs for energy transitions, emphasizing simplicity, while allowing the analysis of how different governance structures affects the transition process itself.

3.2.5 Prediction

For simplicity, prediction is present only in two instances. First in the form of net present value (NPV) of investments, being analyzed both by energy producers that are willing to invest into power plants and by the development bank that will decide to finance or not such plants. Second in the Evaluative criteria submodel regarding the comparison between sources: energy producers and policy makers predict how their profits or the

[25]excluding the council entity and the commercialization chamber

system, respectively, would be if all demand was supplied by their best ranked technology per source.

The best ranked technology per source depends on their evaluative criteria: for energy producers is the NPV of supplying all the demand using a specific technology at the highest price; for policy makers it depends on their rationale. If a policy maker rationale is the expansion, it analyzes how much avoided emissions there would be. If a policy maker rationale is innovation, it analyzes how much R&D is possible for the technology provider of that specific technology to do[26]. If a policy maker rationale is internalization, it analyzes how much investment into productive capacity is possible for the technology provider of that specific technology to do[27].

3.2.6 Sensing

The variables that agents know in relation to each other are almost all those variables that are not internal for each agent and not directly linked to its internal decision-making process. Agents are aware of other agent's profits, dividends, local productive capacity expenditure, R&D expenditure, technologies available, portfolio of power plants, rationale (regarding policy makers), incentives (regarding policy makers) and incentivized sources (regarding policy makers). The important thing is that private agents are not individualizing their competition: one agent simply labels characteristics as belonging to them or to their competition. In other words, competitors are treated equally, i.e., agents do not respond more to competition that comes from more well established firms than to competition by less established firms. The council entity is aware of policy maker's internal decision-making variables, but the policy makers themselves are not aware of those variables regarding the others policy makers.

3.2.7 Interaction

Figure 3.2 depicts the direct interactions between agents in the TeFE model. Not all interactions occur all periods and all direct interactions are between one agent and another, not between groups.

[26] Current R&D expenditure plus profits per technology provider.
[27] Current productive capacity expenditure plus profits per technology provider.

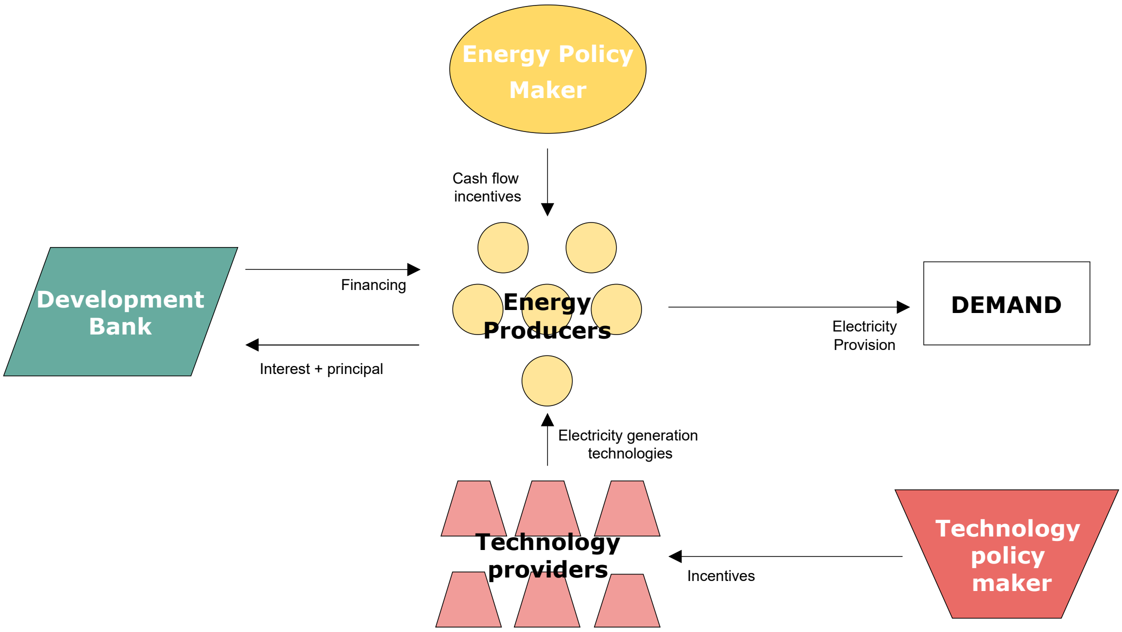

Figure 3.2: The interactions between agents. Energy producers acquire electricity generation assets from technology providers, being financed either by a development bank or through reinvestment. The Energy and Technology policy makers give out cash flow incentives to, respectively, energy producers and technology providers. Electricity is produced in order to meet a certain demand.
Source: own elaboration.

If an energy producer decides to expand its portfolio of power plants, it will analyze the available technologies from the technology providers and decide for one technology to be used on the power plant project. After that the energy producer will send that project to the development bank which will, in the next period decide if the project will be financed or not. If the project is financed, then for the next periods the development bank will receive payments of interest and of the principal. Once that power plant is built it was start providing electricity to meet the demand. All the while we have an energy policy maker providing cash flow incentives to energy producers in the form of PPAs. We also have a technology policy maker providing cash flow incentives to technology providers.

The commercialization chamber would be between the energy producers and the demand. The council entity would be among the policy makers, coordinating them every three periods.

3.2.8 Stochasticity

Stochasticity is present in some submodels. The "money to shareholders", "CAPEX definition", "Cash flow incentive", "auction", "lending", "accreditation" and "commercialization" submodels do not have stochasticity in them mainly because they depend on the effort level of each entity, which in itself already has stochasticity. The exception here is the "commercialization" submodel in which plants are all correctly sorted by price and contracted exactly according to the demand. Stochasticity is presented in the Reinvestment submodel, Innovation submodel, Decision submodel, Evaluative criteria submodel, Expansion submodel, Coordination submodel. Stochasticity is normally present in the form of performing a test by using a $U(0,1)$ distribution against an exogenous threshold in order to see if decisions will be random or not. On top of that, several initial values are randomized with either a normal or uniform distribution.

As such, we pinpoint four main stochastic processes in the model:

1. **Innovation:** the possibility of a firm to innovate is an stochastic process. The result of innovation is given by a random distribution, influenced by known variables, and which cost innovation will reduce is also randomly assigned (either to OPEX or CAPEX). In other words, when, how and where innovation will occur is stochastic. Ex.: a run may have a virtuous cycle of innovation in solar energy, whereas another run may have a similar virtuous cycle of innovation in wind, and a third run may even have several innovation processes that led nowhere;

2. **Decision chains and fundamental uncertainty:** within decision chains we have several random distributions and randomly generated components. Besides that, agents' decisions in one period affect the following through path dependence. Moreover, the result of one's action depends largely on the actions of others, due to the relevance of interactions in the model. In this sense, "best" decisions are impossible to be known beforehand, i.e., there is fundamental uncertainty.

3. **Adaptation processes**: both the effort change and the change of parts of the decision-making process are stochastic processes.

4. **Initial randomness:** The first 6 years of simulation (15% of the periods)[28] have all stochastic processes only having their random components. This serves the purpose

[28] Those periods are never analyzed.

of reducing the weight of the initial values for variables, as well as to organically create initial heterogeneity without simply relying on randomly generated initial values.

Those four points thus advocate for monte carlo runs, in which we normally analyze medians and quarters.

3.2.9 Collectives

There are four collectives: a system that provides electricity (Electricity Provision System); a system that provides electricity generation assets (Asset Provision System); a combination of those two system; and a collection of State agencies that do policy (Policy Maker Mix). The first two collections are relevant because they respectively encompass energy producers and technology producers. Each collection is used by its respective constituent parts when comparing profits: energy producers compare their profits to the profits of entities in the Electricity Provision System, whereas technology providers only compare their profits to the profits of entities in the Asset Provision System. The third collective is relevant for analyzing change in private agents. The last collective is relevant not for its constituent parts directly, but for the council entity that may or may not coordinate agencies within the Policy Maker Mix. With the last two collectives we are able to separate variables in relation to public and private entities.

3.2.10 Input Data

In terms of input data, all variables that range between zero and one are randomized to start in that range. We attempted to calibrate the model using data from Brazil, focusing on having 3% of all variables that are in absolute amounts (demand, number of agents, etc.). We do not claim to have a history-friendly model of Brazil, solely to have a "Brazil-inspired" model, specially since most missing data was estimated from various European and north american sources[29]. Table 3.1 depicts the initial values for technologies in the simulation.

As such, we have laid down the foundations of the methodological toolbox regarding the ABM to be used. We now present results and discuss them.

[29] In the github we have the full list with all entry values.

Table 3.1: Initial values for technologies in the model. Source: own elaboration based on (IRENA, 2018)

TRAIT	**SOURCE**		
	Thermal	**Wind**	**Solar**
CAPEX	29,040,000	3,750,000	205,000
OPEX	100,000	4,250	117
MW	30	1.5	0.10
Capacity factor	50.0%	29.0%	17.6%
Lifetime	30	25	25
Building time	2	1	0.5
Renewable	False	True	True
emissions	100	-2.90	-0.12
break-even price	16.73	53.48	63.16

Chapter 4

Results and discussion

In this chapter, following the description of the proposed simulation model, we present and later discuss our model's results. With the experiments our main objective is to study the relevance of heterogeneity in energy transition processes. We analyze heterogeneity with a Kolmogorov-Smirnoff test comparing nine system elements under three different time frames divided by three vectors for nine scenarios.

Regarding the scenarios, they can divided by: number of policy makers and degree of homogenization. Regarding the division by number of policy makers:

- **No policy maker:** Runs are performed only with fifty energy producers and ten technology providers. All elements are present except for public score, public change and public adaptation, since there are no public agents in this scenario. In tables and graphs is called "Baseline" for short. We have performed 100 simulation runs that fit this criteria;

- **One policy maker:** Runs are performed with one policy maker on top of the previous number of energy producers and technology providers. As such the run may have either technology policy, energy policy or public financing. We have performed 300 simulation runs that fit this criteria;

- **Three policy makers:** Runs are performed with all policy makers on top of the previous number of energy producers and technology providers. It can be either run with or without the council entity, with the latter being the 0.00 scenario for the simulation. If there is the council entity, it may have a degree ranging from low intermediate to high. We have performed 500 simulation runs that fit this criteria;

The second family of scenarios can be further divided into three, depending on the policy maker that is present in the simulation. Each scenario has 100 simulation runs performed. Those are:

- **Just technology policy maker:** There is only technology policy in the runs. Technology producers must reinvest in order to acquire new power plants. Power plants are contracted solely based on their price, since there is no auction structure in which plants are awarded PPAs. In tables and graphs is called "Tech" for short. We have performed 100 simulation runs that fit this criteria;

- **Just energy policy maker:** There is only energy policy in the runs. Technology producers must reinvest in order to acquire new power plants. Technology innovation depends solely on the cash flow generated by energy producers acquiring new assets from technology providers. In tables and graphs is called "Energy" for short. We have performed 100 simulation runs that fit this criteria;

- **Just development bank:** There is only public financing in the runs. Technology innovation depends solely on the cash flow generated by energy producers acquiring new assets from technology providers. Power plants are contracted solely based on their price, since there is no auction structure in which plants are awarded PPAs. In tables and graphs is called "Bank" for short. We have performed 100 simulation runs that fit this criteria;

While the degree of homogenization is drawn from a continuous interval between zero and one, we consider four degrees in our experiments: high, high intermediate, low intermediate and low. The scenario without homogenization may be understood as a scenario in which the homogenization approach has degree zero.

1. **High:** the threshold for homogenization is zero, which means that all policy makers' characteristics must be the same. The degree is one. In tables and graphs is called "1.00" for short. We have performed 100 simulation runs that fit this criteria;

2. **High intermediate:** the threshold for homogenization is 0.25, which means that up to one quarter of policy makers' characteristics may be different. The degree is 0.75. In tables and graphs is called "0.75" for short. We have performed 100 simulation runs that fit this criteria;

3. **Low intermediate:** the threshold for homogenization is 0.5, which means up to half of policy makers' characteristics may be different. The degree is 0.5. In tables and graphs is called "0.50" for short. We have performed 100 simulation runs that fit this criteria;

4. **Low:** the threshold for homogenization is 0.75, which means that up to three quarters of policy makers' characteristics may be different. The degree is 0.25. In tables and graphs is called "0.25" for short. We have performed 100 simulation runs that fit this criteria;

5. **Zero:** The threshold is one, which means that the council entity is never activated and thus, there is no forced homogenization between policy makers. In tables and graphs is called "0.00" for short. We have performed 100 simulation runs that fit this criteria;

6. **No degree:** There is no threshold since there is only one or no policy maker in the scenario. We have performed 400 simulation runs that fit this criteria;

As such, there are three possible aggregation of scenarios:

- **By degree:** aggregating by degree there are five divisions: no degree (when there are no policy makers or only one), 0.00 (in the 0.00 scenario), 0.25, 0.50, 0.75 and 1.00 (depending on the degree of the council entity);

- **By number of policy makers:** aggregating by number of policy makers we have three subdivisions: with no policy makers, with one policy maker and with three policy makers.

- **By presence of council:** aggregating by presence or not of the council: with council and without council

Table 4.1 summarizes the differences between the three possible aggregations. It is important to notice that all aggregations do not have the same number of scenarios, and therefore of runs. This ultimately means that, when calculating a percentage that has as denominator the number of tests performed, the denominator itself will be different. That is a reason why we sometimes choose to compare scenarios (or entries) with an index rather than just by the percentage of tests under or above a significance level over the total of tests.

Table 4.1: Differences between scenarios regarding number of policy makers, degree of coordination and coordination approach.

Scenario	Number	Degree	Council
Baseline	0	None	False
Tech	1	None	False
Energy	1	None	False
Bank	1	None	False
0.00	3	0	False
0.25	3	0.25	True
0.25	3	0.5	True
0.75	3	0.75	True
1.00	3	1	True

4.1 Scenario results

Figure 4.1 shows how little the expansion of generation is: growing to less than 8 TWh per month in over 30 years of simulation. Moreover, the interquartile range of renewable and thermal generation do not overlap, meaning that, for 50% of the distribution around the trajectory of the median, there is little probability that renewable generation comes close to thermal generation. In other words, regarding a transition towards low-carbon systems, the absence of policy appears to fail to lead the system towards such transition.

Figure 4.2 shows how only having technology policy does not increase the output of the system significantly, but is able to at least make the interquartile range of thermal and renewable generations overlap at later periods.

Figure 4.3 shows how the use of energy policy seems to drive agents away from using thermal energy, but it alone is not capable of moving agents towards renewable energies. Similarly to the no policy scenario, the interquartile ranges do not overlap.

Figure 4.4 shows how having public financing leads the system into producing more electricity than before, around 15 TWh. Nevertheless, after 200 periods of simulation, renewable generation stagnates around 6 TWh. This indicates how crucial public financing is to lead the system into more adoption, but unable to, just by itself, continue to offset thermal in a sustained fashion.

Figure 4.5 shows how the 0.00 scenario is able to sustain an increase of renewables to 6 TWh and beyond, in a sustained fashion during the length of the simulation. This scenario also delivers the most generation out of the scenarios seem until now. In

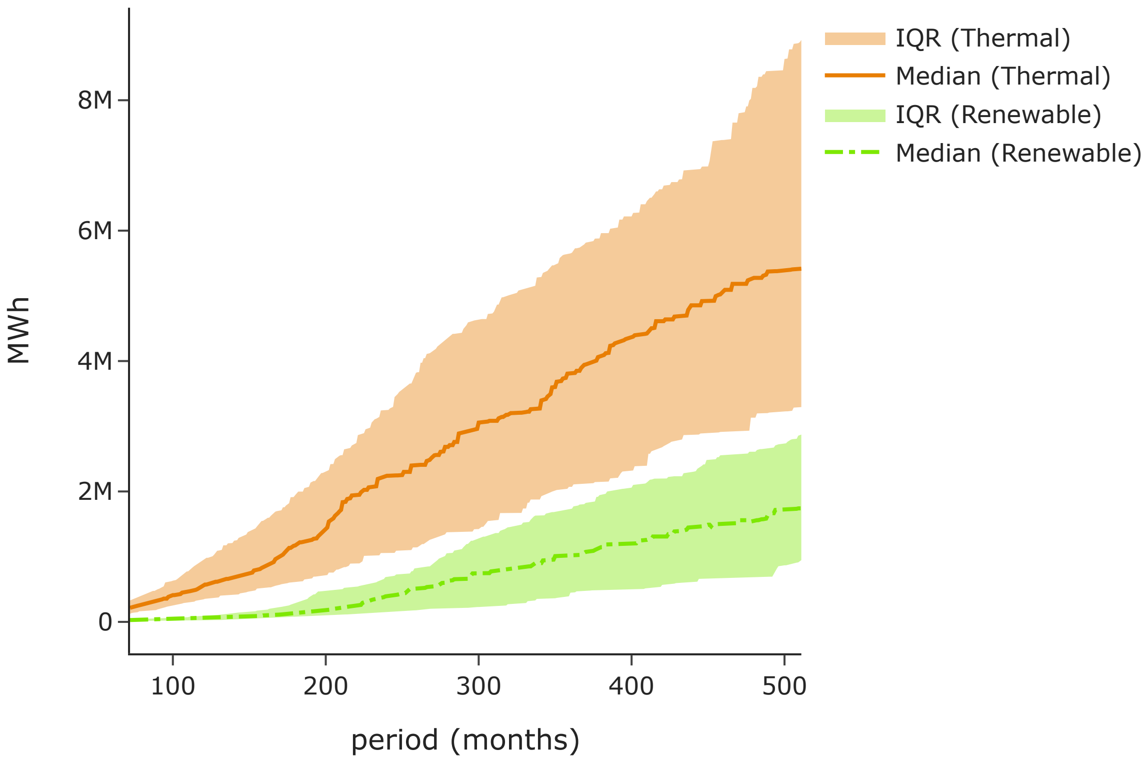

Figure 4.1: Electric generation in MWhs in the no policy scenario.

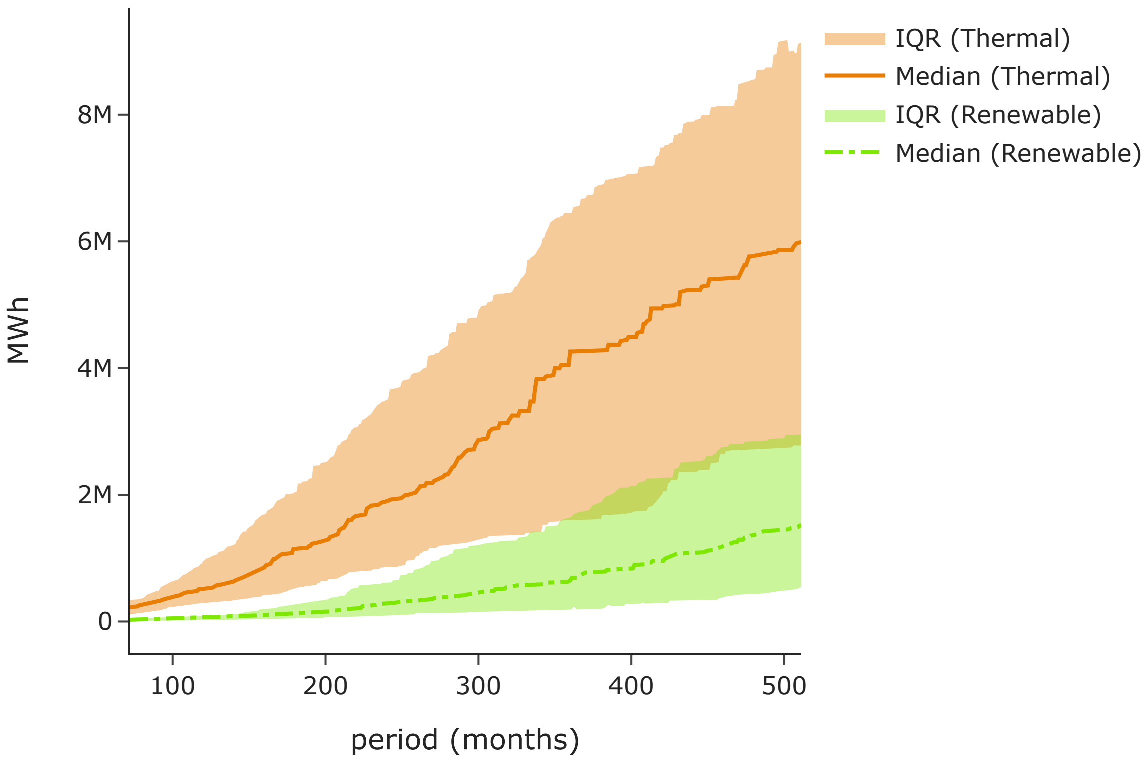

Figure 4.2: Electric generation in MWhs in the technology scenario.

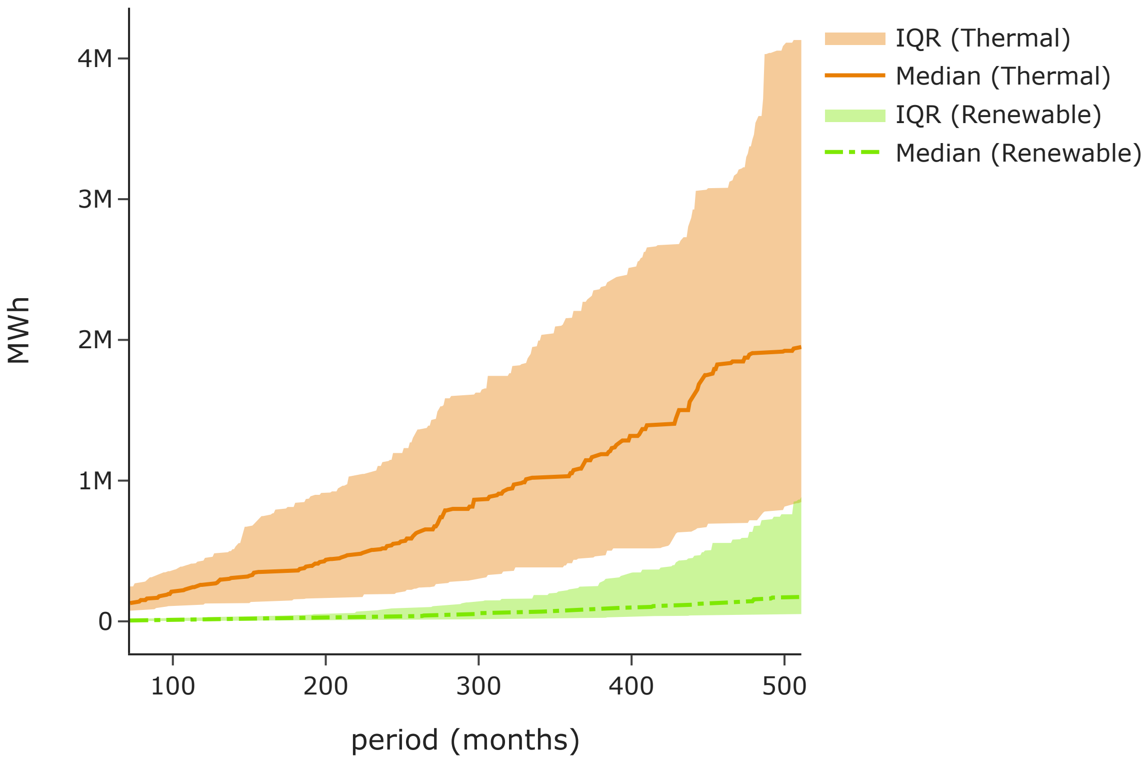

Figure 4.3: Electric generation in MWhs in the energy scenario.

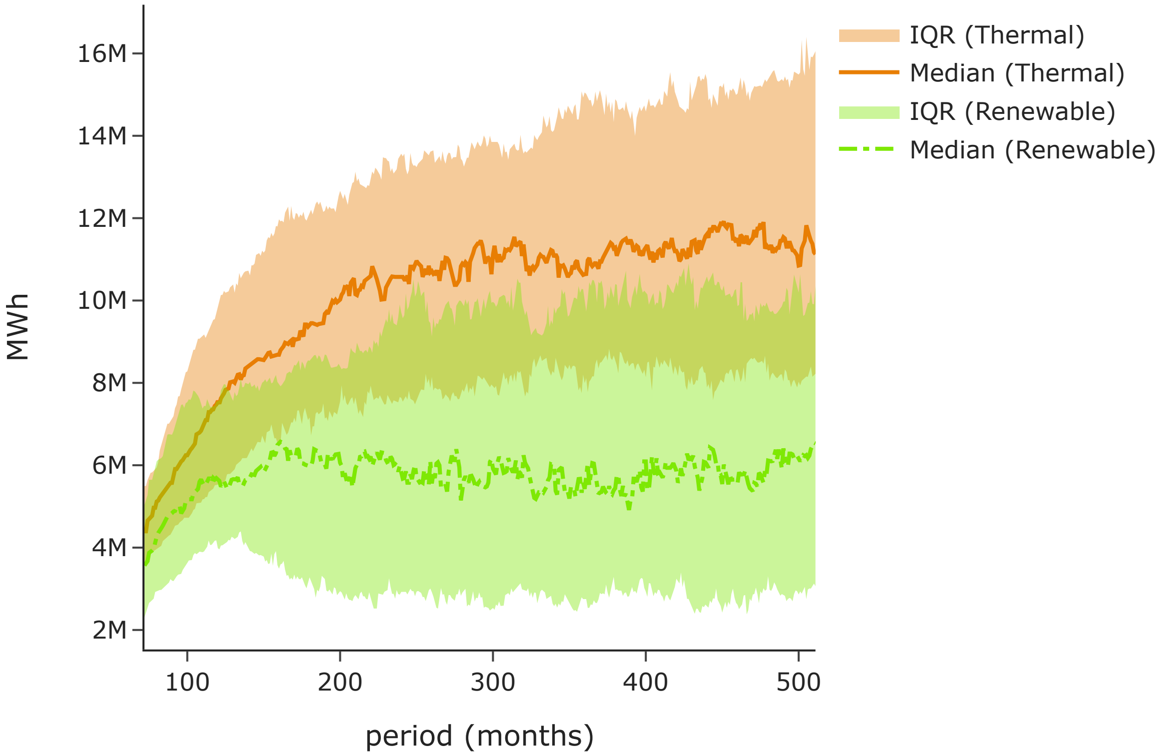

Figure 4.4: Electric generation in MWhs in the financing scenario.

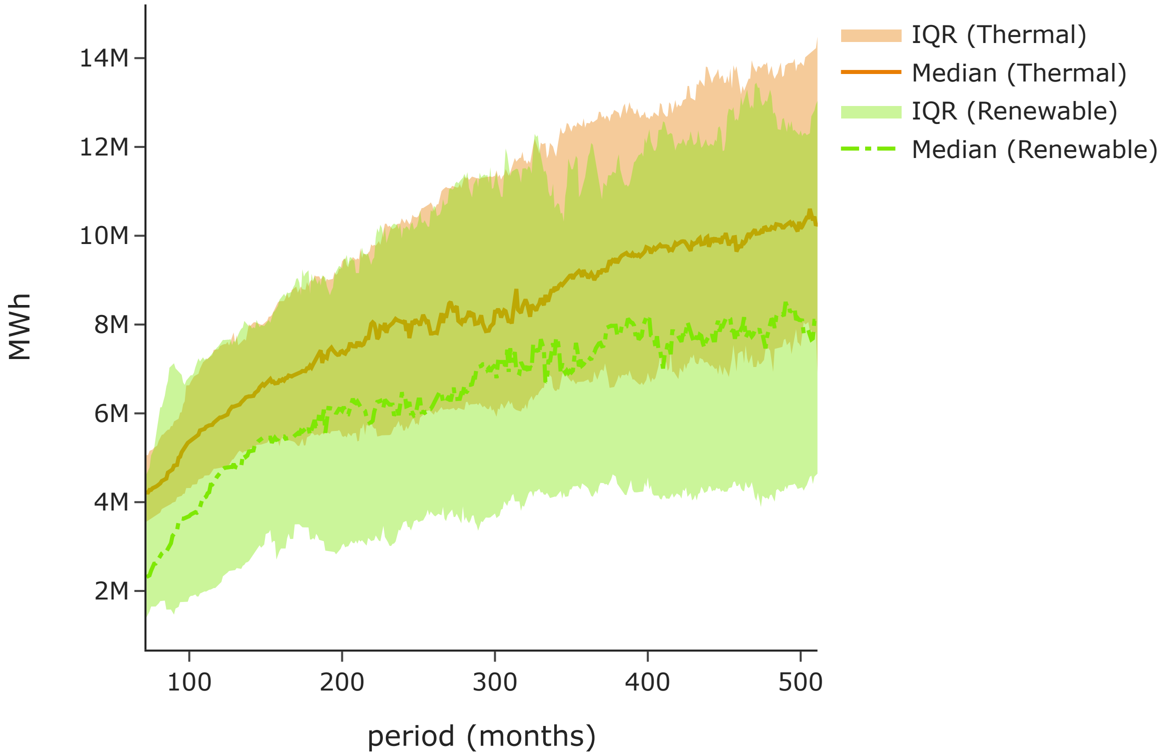

Figure 4.5: Electric generation in MWhs in the 0.00 scenario.

this way, it seems that, by combining all three previously seem policies, we are able to foster the entry and adoption of renewables in an enduring and sustained way.

Figures 4.6, 4.7, 4.8 and 4.9 depict different trajectories of scenarios without policy maker, with just one policy maker and of the 0.00 scenario. Figures 4.7, 4.8 and 4.9 depict trajectory of vectors, whereas figure 4.6 depicts the trajectory of the values of elements themselves.

Figure 4.6 depicts the trajectories for break-even price, adaptation, internalization, innovation, public and private scores, and for public and private efforts in the scenario without policy makers, with just the technology policy maker, with just the energy policy maker, with just the development bank and in the 0.00 scenario. The break-even price results from the adoption, internalization and innovation processes, meaning that the changes in the price co-evolve with the changes in those other three elements. Immediately we can see that the bank and 0.00 scenarios have similar trajectories and

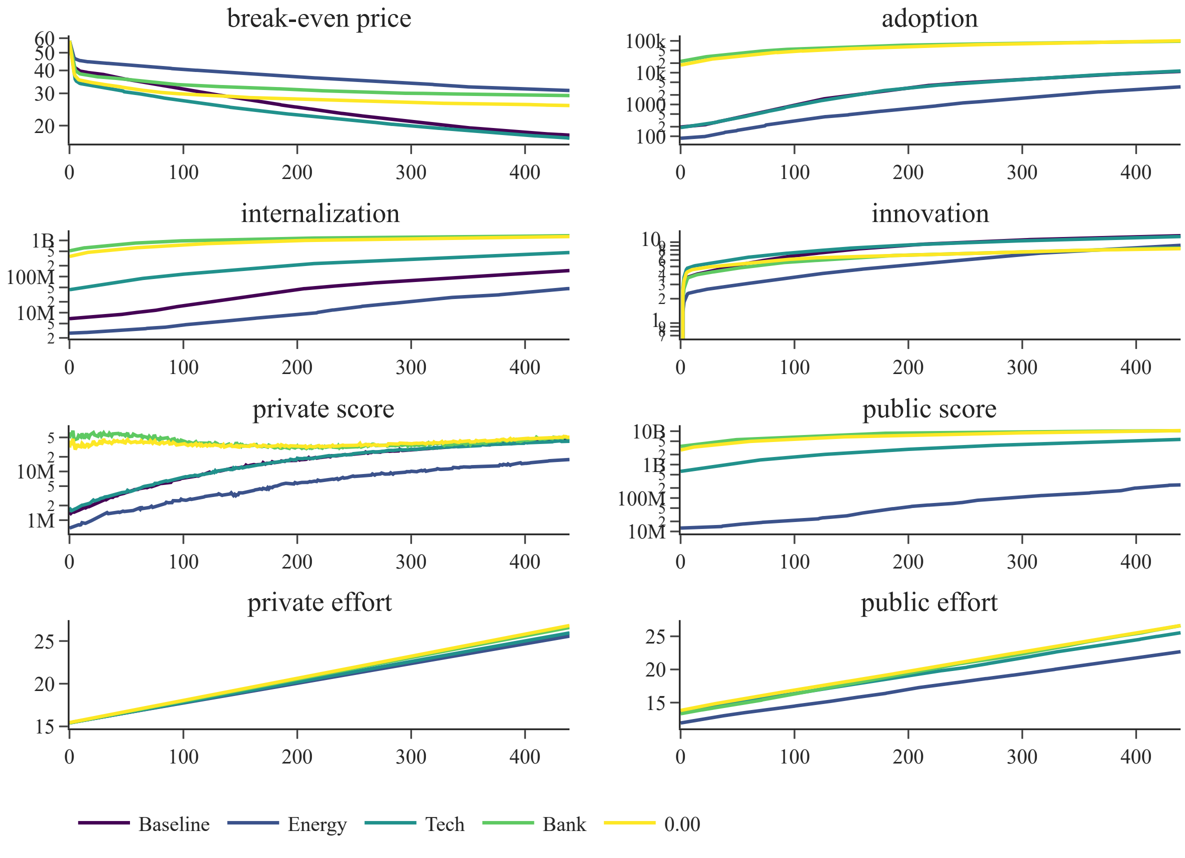

Figure 4.6: Comparison between the no policy, technology, energy, financing and 0.00 scenarios regarding the trajectories of values of break-even price per MWh of renewables (in \$), of adoption of renewables (in MWs), of internalization (in \$), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

magnitudes regarding all elements, thus highlighting the fact that they are scenarios with significant similarities.

Regarding price there are some interesting results: the scenario with the only policy being technology policy is the scenario in which the price drop of renewables is the largest, nevertheless, it is followed by the scenario without any policy maker. Regarding adoption and internalization, the scenario with just the energy policy maker has the lowest trajectory, with the Bank and 0.00 scenarios having the highest trajectories. In terms of innovation, the Energy scenario also figures as the lowest trajectory and the Baseline and Tech scenarios having the highest trajectories, nevertheless trajectories tend to converge in the long run. There is also a convergence of private scores between Bank, 0.00 (which have similar trajectories once again), Baseline and Tech scenarios. The private scores in the Energy scenario do also grow over time, but to much smaller numbers. Regarding public scores, the Energy scenario has a significantly lower trajectory and the Tech scenario closes its gap to the Bank and 0.00 scenarios over time, from those two scenarios having public scores five times higher to having just twice the public score. Regarding the variations in effort, for the private effort the trajectories are very similar, nevertheless the 0.00 scenario has slightly more variation, which indicates more adaptation of private agents to policies and to the context. Regarding public effort change, the Energy scenario follows the other closely, but slightly below the other three.

Figure 4.7 depicts the trajectory of the velocities of elements in the Baseline, Energy, Tech, Bank and 0.00 scenarios. What they depict is the yearly velocity, i.e., the amount which the element increased or decreased in relation to the previous year divided by twelve. 0.00 scenario has higher velocities in the long run, whereas the energy scenario depicts the lower velocities throughout all periods. The velocities of adoption and internalization of the Bank and 0.00 scenarios fall with time, but always remain as the highest velocities. The energy scenario has the lowest velocities regarding both elements. The difference between the Baseline scenario and the tech scenario is more prominent regarding internalization. In terms of innovation, all scenarios remain relatively close to each other. Regarding private scores, the bank and 0.00 scenarios show more variation than the other scenarios. In terms of public score, the velocities of bank and 0.00 scenario fall from 100 million points to below 10 million, but until period 200 they have the highest velocities. The velocity of public score of the energy scenario grows with time, but remains

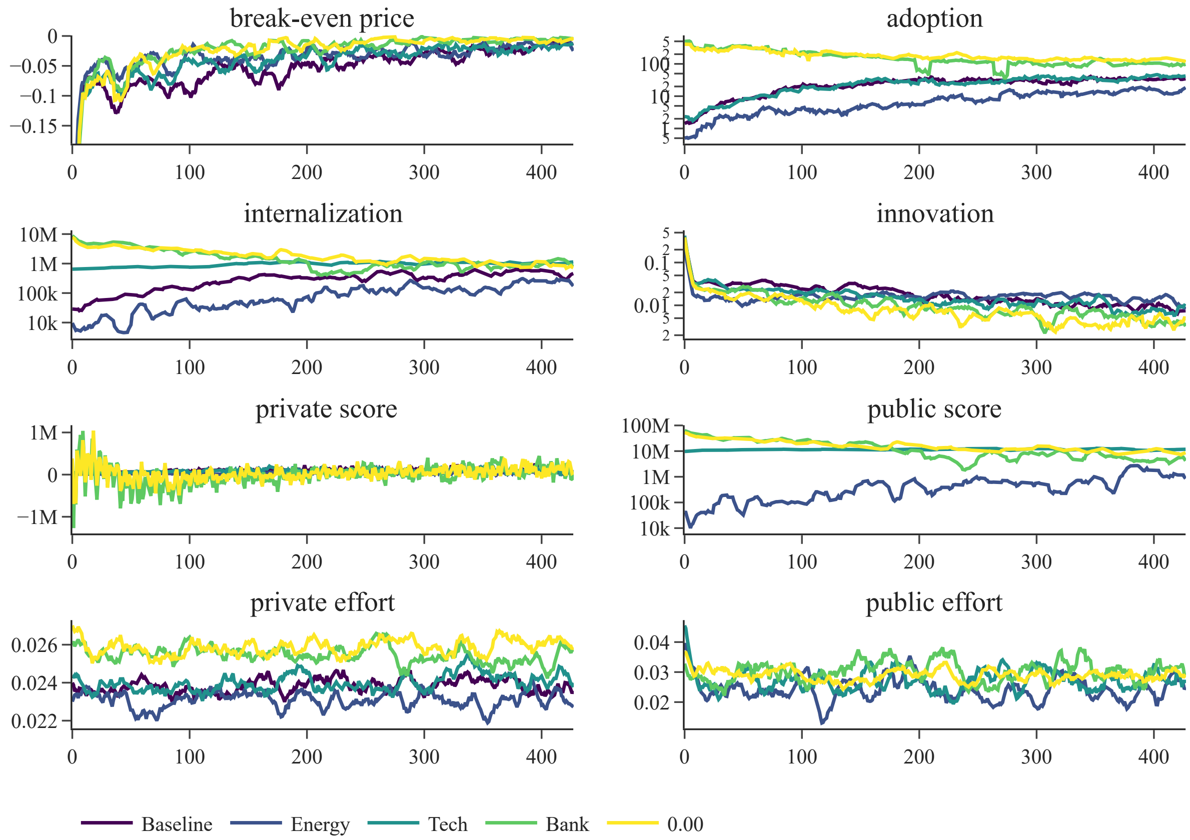

Figure 4.7: Comparison between the no policy, technology, energy, financing and 0.00 scenarios regarding the trajectories of velocity of break-even price per MWh of renewables (in $ per year), of adoption of renewables (in MWs per year), of internalization (in $ per year), of innovation (in results of the innovation equation per year), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

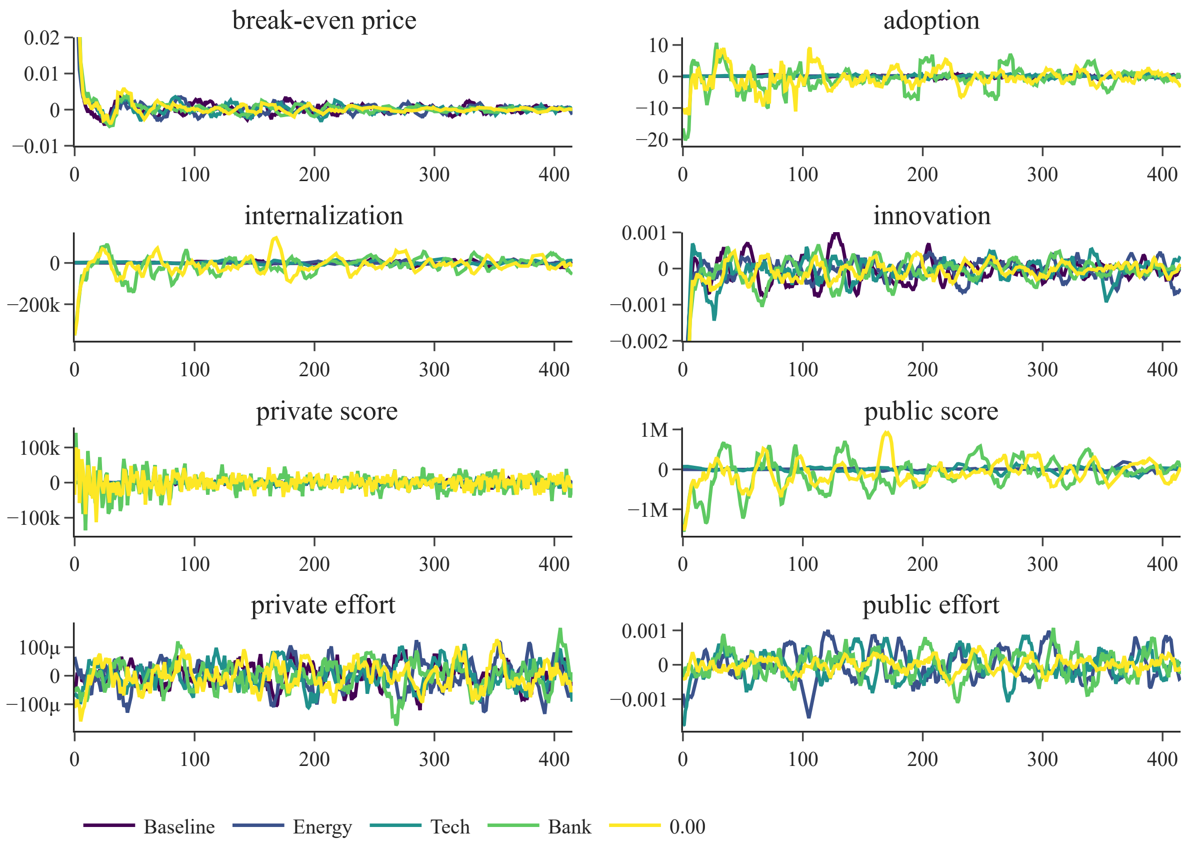

Figure 4.8: Comparison between the no policy, technology, energy, financing and 0.00 scenarios regarding the trajectories of annual acceleration of break-even price per MWh of renewables (in \$), of adoption of renewables (in MWs), of internalization (in \$), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

far below all the others. The Tech scenario has very low variability, remaining around 10 million points. The variation of private effort in the bank and 0.00 scenario are higher than the others. The variation of public effort in the 0.00 scenario is the more stable.

Figure 4.8 depicts the acceleration of the variations of price, adoption, internalization, innovation, private score, public score, private effort and public effort. In terms of price, the variation of the 0.00 scenario's acceleration appears to be the lowest, whereas in terms of internalization and adoption it appears to be higher. The variation of the bank and 0.00 scenario are also higher regarding the scores, nevertheless, with time they become less erratic.

Figure 4.9 depicts the growth rates of price, adoption, internalization, innovation, private score, public score, private effort and public effort. In terms of price, the 0.00 scenario has medium rates until period 200, then having the lowest decrease rate of price. Regarding adoption, bank and 0.00 quickly fall from 30% to below 10% annual

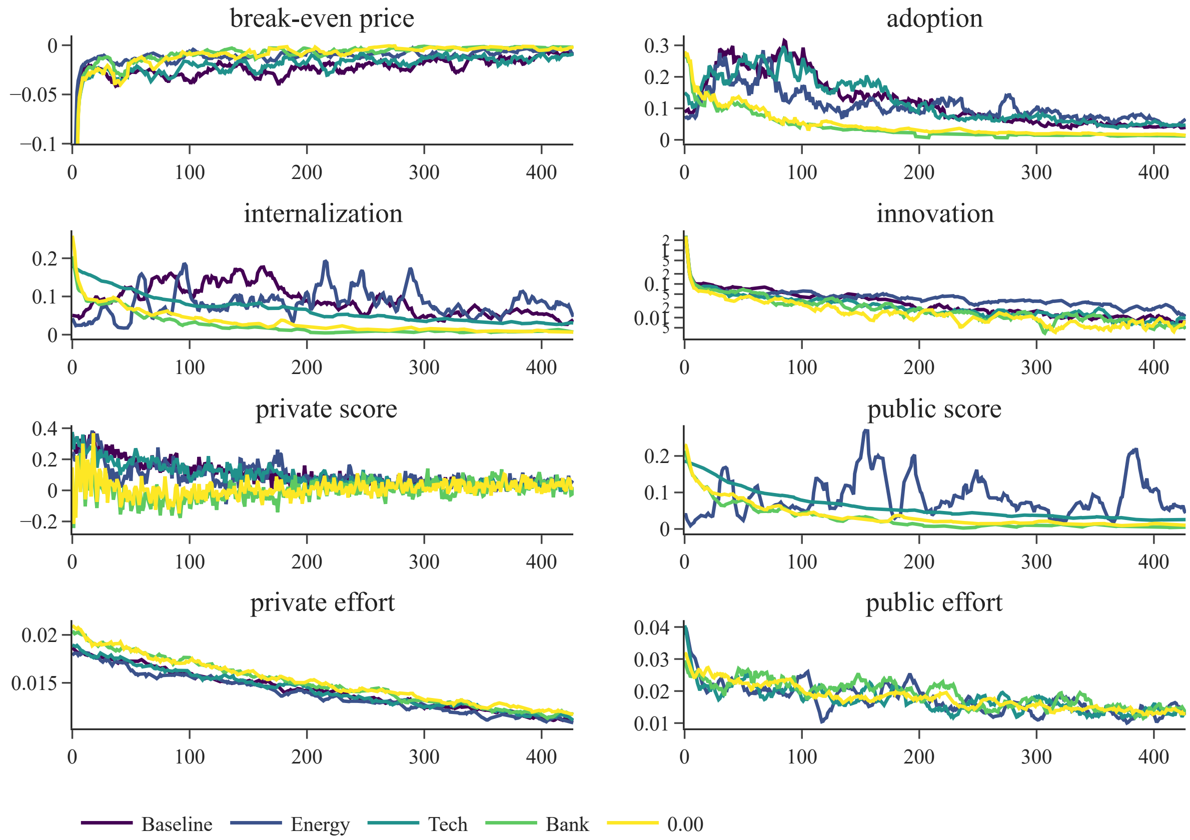

Figure 4.9: Comparison between the no policy, technology, energy, financing and 0.00 scenarios regarding the trajectories of annual growth of break-even price per MWh of renewables (in \$), of adoption of renewables (in MWs), of internalization (in \$), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

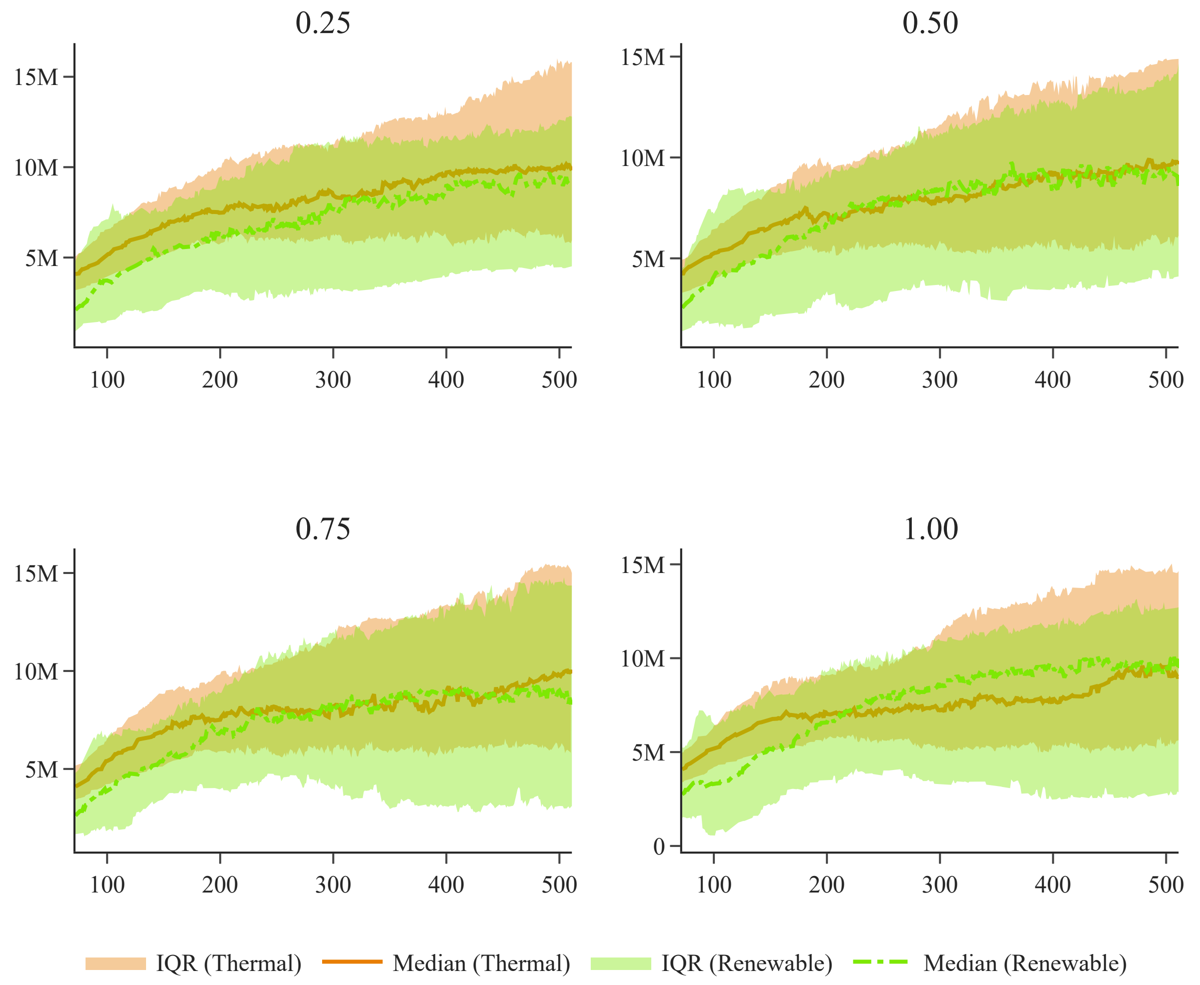

Figure 4.10: Electric generation in MWhs (y axis) in the 0.25, 0.50, 0.75 and 1.00 scenarios over period in months (x axis).

increase in adoption, whereas the other scenarios growth to 30% and then to around 10%. In terms of internalization the results are similar in terms of trajectory, but ranging from 20% to close to 0% in the end of the simulation. Innovation growth rates show that, with time, scenarios diverge. Regarding private score, the bank and 0.00 scenarios start with lower rates and then all scenarios converge to around 0%. Such converge also occurs in relation to public score, nevertheless the Energy scenario is much more erratic in relation to its rates. Regarding private effort, the Bank and 0.00 scenarios always remain slightly above the other scenarios. Finally, regarding public effort, bank and 0.00 scenarios fall in a more stable manner.

Figure 4.10 depicts the electricity generation in scenarios with the council entity. With the council entity homogenizing the policymaking activity of policy makers, renewable generation is then able to close the gap between it and thermal generation (0.25

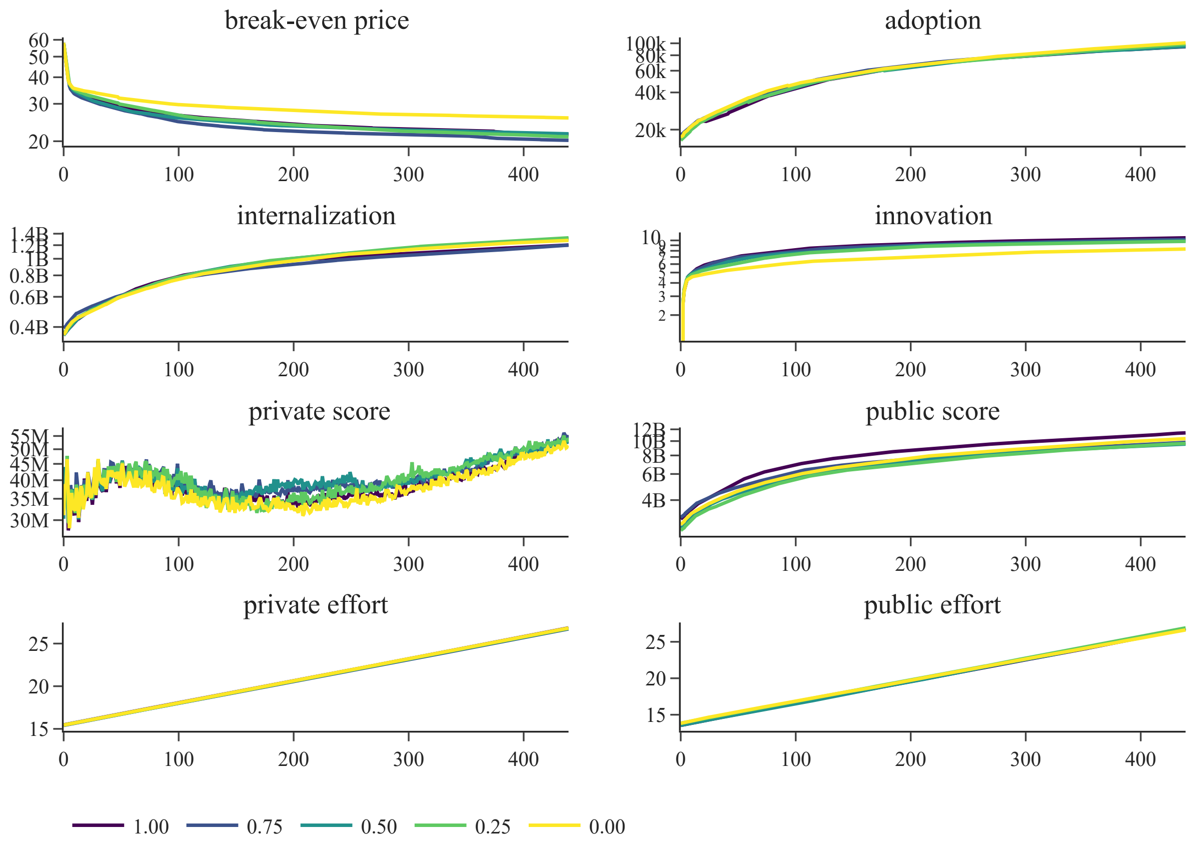

Figure 4.11: Comparison between the 0.00, low intermediate, high intermediate and high scenarios regarding the trajectories of values of break-even price per MWh of renewables (in \$), of adoption of renewables (in MWs), of internalization (in \$), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

scenario) or even to surpass it (in the other scenarios). The scenario 0.50 appears to be the scenario in which the renewable generation is closest to the thermal generation, both regarding the median and the interquartile range.

Figure 4.11 depicts the trajectory of break-even price, adoption, internalization, innovation, private and public scores and private and public efforts, similarly to figure 4.6, regarding the 0.00 scenario and all scenarios with the council entity, i.e., the scenarios 0.25, 0.50, 0.75 and 1.00. Regarding the break-even price, scenarios with council end up with lower break-even prices. Considering that the trajectories of adoption and internalization are fairly similar, the difference in break-even prices is due to the differences in innovation: all scenarios with council have higher values for innovation. In terms of private score, all scenarios follow similar trajectories, with the exception of the 0.50 scenario between periods 150 and 300, in which the private score maintains higher values. The public scores of the 1.00 scenario are slightly above all others, but the 0.00 scenario

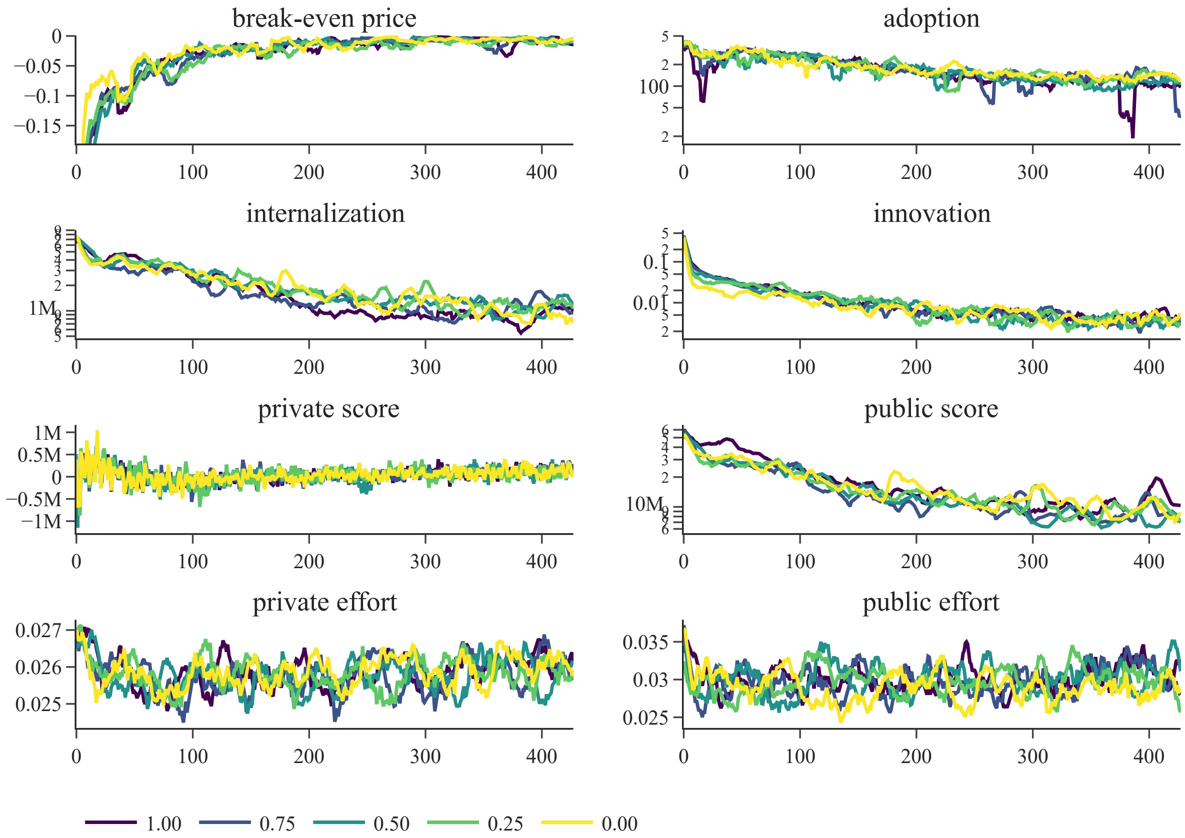

Figure 4.12: Comparison between the 0.00, low intermediate, high intermediate and high scenarios regarding the trajectories of annual velocities of break-even price per MWh of renewables (in $), of adoption of renewables (in MWs), of internalization (in $), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

public score lies in the middle of the others. The trajectories of the private and public efforts are very similar.

Figure 4.12 depicts the velocities of increase or decrease of break-even price, adoption, internalization, innovation, private and public scores, and private and public efforts. Regarding the break-even price, the velocities are more stable and relatively close. In terms of the adoption, the 1.00 scenario has several abrupt drops throughout the simulation. Regarding the velocities of internalization, the 0.00 shows higher velocities, specially in the middle of the simulation. Regarding innovation, the 0.00 scenario velocity falls faster, but catches up before period 100. The velocities of private score peak in the start of the simulation, all scenarios are relatively close to each other although the 0.00 scenario appears to stay in the middle. Regarding the public score, the 1.00 and 0.00 scenarios alternate in terms of which scenario has higher velocities. Private and public effort fluctuate around small ranges.

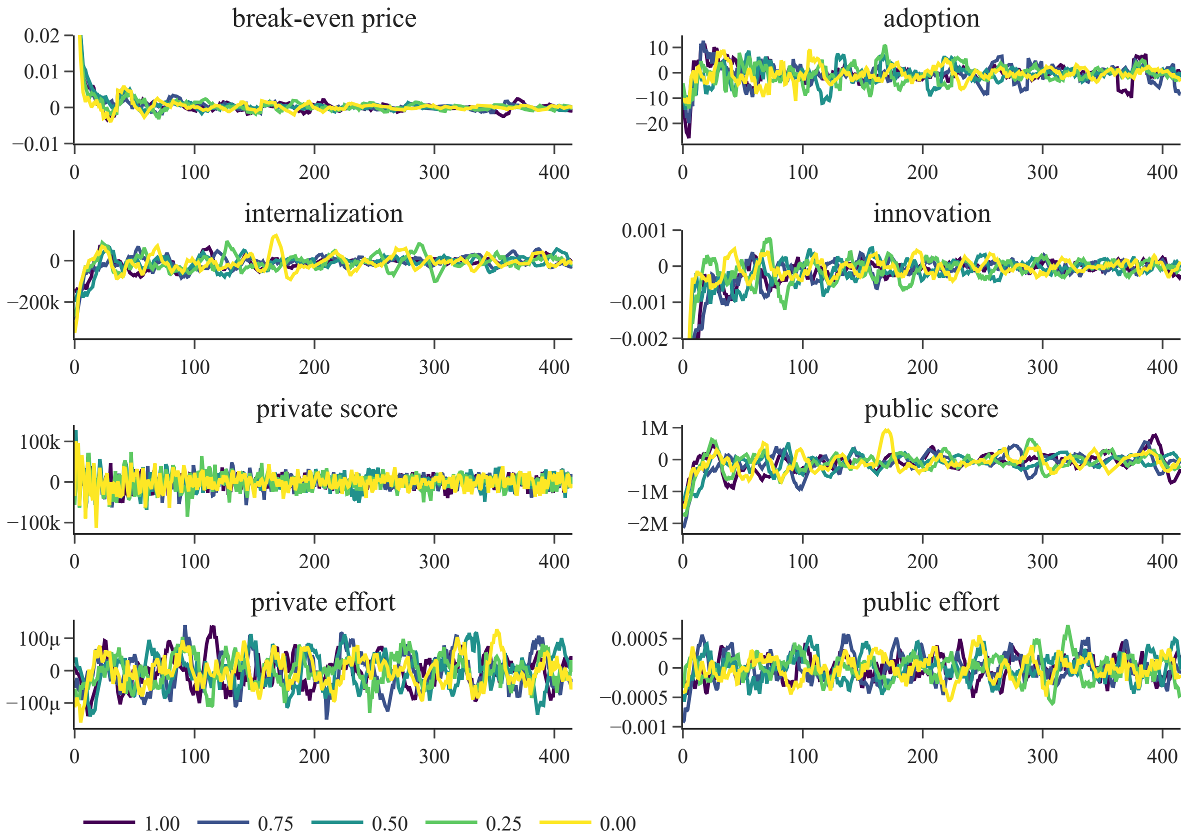

Figure 4.13: Comparison between the 0.00, low intermediate, high intermediate and high scenarios regarding the trajectories of annual accelerations of break-even price per MWh of renewables (in $), of adoption of renewables (in MWs), of internalization (in $), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

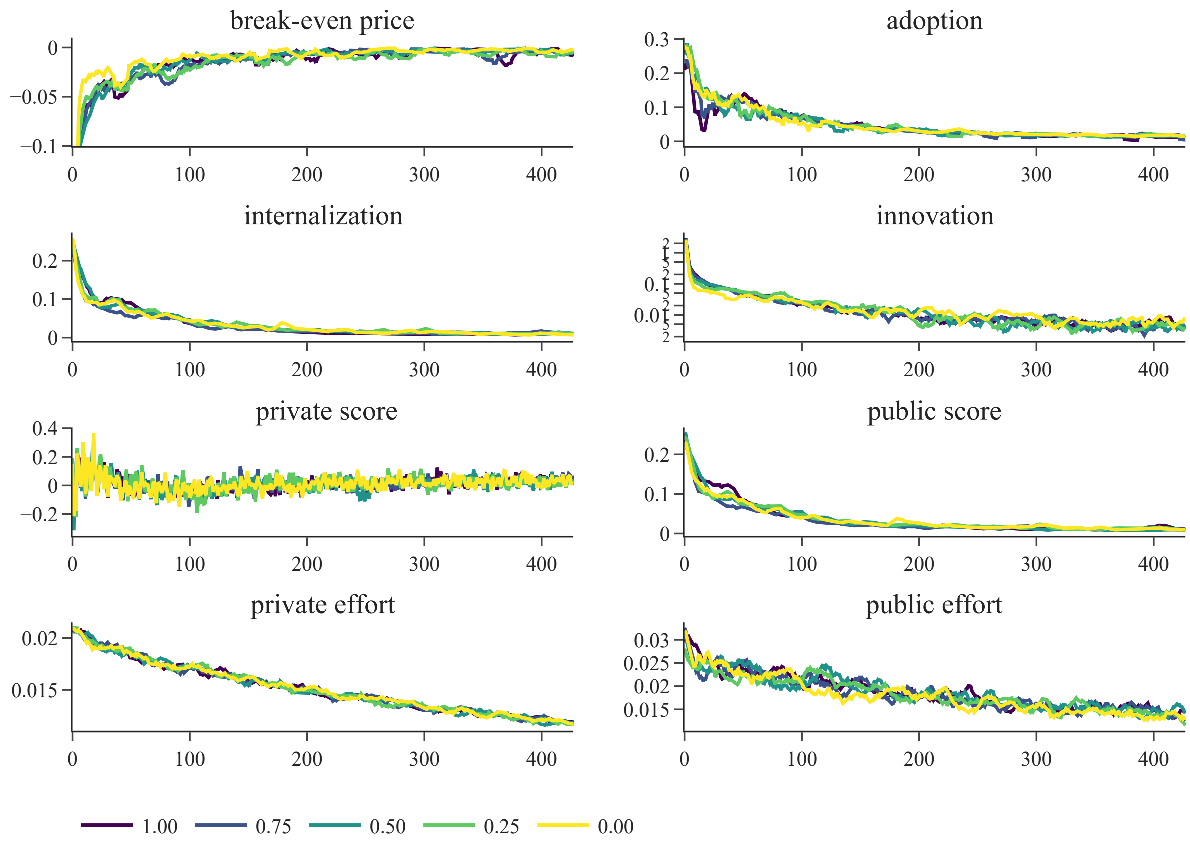

Figure 4.14: Comparison between the 0.00, low intermediate, high intermediate and high scenarios regarding the trajectories of annual growth of break-even price per MWh of renewables (in $), of adoption of renewables (in MWs), of internalization (in $), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

Figure 4.13 depicts the acceleration of break-even price, adoption, internalization, innovation, private and public scores, and private and public effort changes. Regarding the break-even price, the 0.00 scenario falls faster but the 1.00 scenario appears to fluctuate more. In terms of adoption, the 0.00 scenario fluctuates less with less and the 0.50 scenario fluctuates a fair amount. The acceleration of innovation of the scenario 0.00 fluctuates the most. In relation to private score, the 0.00 scenario seems to fluctuate the least. The acceleration of the public score in the 0.00 scenario is the one who fluctuates the most. Regarding the private effort and public effort changes' accelerations, they all fluctuate around small ranges.

Figure 4.14 depicts the trajectories of growth of break-even price, adoption, internalization, innovation, private score, public score, private effort and public effort. Regarding the break-even price, the price drop of the 0.00 scenario is the first to decline. In terms of adoption, the 1.00 scenario fluctuates the most. In terms of the internalization, innovation, and private score all scenarios have similar trajectories. The growth of public score and private effort have similar trajectories. The scenarios fluctuate heavily in relation to public effort, but they fluctuate around a small range.

Table 4.2: Mean scores for value and vectors, and sum of value and vector scores per scenario for all elements. We first normalize between 0 and 1 the first quarter, median and third quarter for values, velocities and accelerations per element per scenario. We use the complement of CAPEX and OPEX normalized scores. Then we get the mean of those normalized scores for all elements for each scenario. The value score only takes into account the values of the elements themselves, whereas the vector score takes into account annual velocity and acceleration. We also provide mean, median, standard deviation and median absolute deviation for each column. Source: own elaboration.

SCENARIOS	SCORES value	vector	sum
Baseline	1.3193	1.6933	3.0126
Tech	1.5681	1.7470	3.3151
Energy	0.0000	1.2728	1.2728
Bank	2.1777	1.6108	3.7885
0	2.3596	1.5985	3.9581
0.25	2.6081	1.5603	4.1684
0.5	2.6257	1.6538	4.2795
0.75	2.6591	1.4937	4.1529
1	2.7399	1.5067	4.2466
Mean	2.006	1.571	3.577
Median	2.360	1.599	3.958
std	0.905	0.139	0.969
MAD	0.300	0.092	0.288

Since trajectories for the 0.00, 0.25, 0.50, 0.75 and 1.00 scenarios were relatively close to each other, we devised a score to allow for a straightforward comparison between scenarios. First we gathered the median, first quarter and third quarter values for all elements regarding their absolute values, their velocities and their accelerations. Then, we normalized those values, in order to have scores between zero and one relative to each element and to each quarter and median and relative to the absolute value, velocity and acceleration[1]. For example, the median value for adoption ranges from 855 MWs (score 0) to 75267 MWs (score 1). For CAPEX and OPEX we took the complement of that score: the focus is on the reduction of costs. Afterwards, we sum the normalized scores of the first quarter, median and third quarter per value, velocity and acceleration for each scenario and each element. In table 4.2 we get the mean of each score, in order to still

[1]Apendix C depicts the tables with the normalized values used here.

be able to compare scenarios to the baseline even with that scenario not having public score and public effort, regarding value and vector. The vector score gets the mean of the velocity and acceleration per element per scenario. The sum column sums both scores for each scenario. From the sum column we can acknowledge how having a development bank affects scores significantly. Moreover, having an acting council entity puts a scenario above the others.

The scenario in which there is full homogenization (1.00 scenario) may have the highest score regarding values, but not by much in relation to the scenarios with the council entity. Moreover, the 1.00 scenario have a vector score lower than the Bank scenario, the 0.00 scenario and all other scenarios with an active council entity, except for the 0.75 scenario. This means that there are strong arguments for choosing scenarios with an intermediate degree of homogenization rather than the scenario with full homogenization. This becomes more clear if we split those scores into categories (table 4.3). In that table, for two subdivisions, the value score does not grow with degree.

Table 4.3: Sum of the scores for value and vectors per scenario for CAPEX and OPEX (A), all elements but public_effort and public_score (B), public_score and private_score (C), private_effort and public_effort (D). We first normalize between 0 and 1 the first quarter, median and third quarter for values, velocities and accelerations per element per scenario. For CAPEX and OPEX we use the complement of the normalized score. Then we sum the normalized scores for the first quarter, median and third quarter. The value score only takes into account the values of the elements themselves, whereas the vector score takes into account annual velocity and acceleration. Source: own elaboration.

	SCORE	Baseline	Tech	Energy	Bank	0.00	0.25	0.50	0.75	1.00
A	value	4.595	5.655	0.000	2.084	3.777	4.851	5.104	5.351	5.326
	vector	9.046	7.820	6.641	4.577	4.898	3.024	4.221	3.216	3.002
B	value	9.235	10.881	0.000	14.15	15.66	18.10	18.43	18.47	18.99
	vector	23.71	24.02	20.02	20.62	20.98	19.78	21.23	19.53	19.22
C	value	*	2.142	0.000	5.769	5.295	5.330	5.431	5.521	5.703
	vector	*	8.355	4.017	6.250	7.265	7.453	7.449	6.841	7.141
D	value	*	2.904	0.000	4.846	5.793	5.752	5.491	5.388	5.698
	vector	*	5.688	3.084	9.064	7.870	8.080	8.979	7.923	8.506

4.2 Experiments

We use a Kolmogorov–Smirnov test for two samples[2], testing for the two-sided null hypothesis. The null hypothesis is that the tested series are drawn from the same distribution, as such rejecting the null hypothesis (p-value below a certain *ad-hoc* threshold) means that it is unlikely that both series come from the same distribution[3].

In other words, what we are testing is, depending on the specific difference that the test wants to capture (e.g. the role of different approaches), are scenarios different? What we mean by different is, analyzing the trajectory of the elements of a certain scenario, are those trajectories different from other scenarios? In this sense, we are capturing differences between scenarios regarding the evolution of their elements. Such evolution is captured in terms of the trajectory of velocity of those elements. As such, if two trajectories are different, it means that, according to the Kolmogorov-Smirnov test, it is not likely that those two trajectories come from the same distribution, i.e., it is unlikely that the two trajectories come from the same scenario. In other words, the choice between one scenario over the other means choosing one trajectory over the other in that case.

We select nine system elements: public score, private score, private change, public change, renewable adoption, renewable innovation, renewable investment, CAPEX, OPEX. The "scores" are the mean satisficing score of public or private agents. Their trajectory captures the magnitude and direction of change in how agents are in relation to other agents and to the context regarding their satisficing heuristics over time. In other words, it captures the overall analysis of their relative positions. The "changes" are the mean variations in effort by public or private agents. Their trajectory captures the direction of changes in the decisions regarding effort of agents over time. In other words, it captures the change in effort by agents. Adoption is the sum of MWs of renewable energy. Its trajectory captures the direction of adoption of renewables over time. Innovation is the sum of results of the innovation equation. Its trajectory captures the direction and magnitude of innovation of renewable energy in the model over time. Since we use the result of the innovation equation rather than the number of innovations, we actually cap-

[2]In the code, they are two lists.

[3]We are aware that, regarding the test and the null hypothesis, by rejecting the null hypothesis we may only say that it is unlikely that both series are drawn from the same distribution, however, for sake of space and for sake of simplicity of argument, from now on we will consider that, by rejecting the null hypothesis, both series are statistically different one from the other. We generalize that argument to say that thus both distributions are different one from the other.

tures the progress of the innovation itself (e.g. by how much was the CAPEX reduced). Internalization captures the trajectory and magnitude of expenditure on local productive capacity by technology providers. CAPEX and OPEX capture the trajectory and magnitude of decreases in CAPEX and OPEX respectively, due to innovation and internalization processes. In graphs, in order to streamline the analysis, we use the break-even price of MWh for renewables, which captures the trajectory and magnitude of decreases in both CAPEX and OPEX at the same time 4.1.

$$break\_even\_price_{k,t} = \frac{OPEX_{k,t} + CAPEX_{k,t} * lifetime_{k,t}^{-1}}{MW_{k,t} * CF_{k,t} * 24 * 30} \tag{4.1}$$

The three vectors used are: velocity, acceleration and growth. Velocity is a vector that describes the change in position under a certain time period. Acceleration is a vector that describes the change in velocity under a certain time period. Growth is a vector that describes the variation of a variable in a certain time period. The three measures used are vectors, meaning that not only magnitude is captured, but also direction.

Regarding the time periods used, we have three possibilities: a one period time frame, a twelve period time frame, and a forty-eight period time frame. Since one period is one month, those three time frames are: one month (short-term change), one year (mid-term change) and four years (long-term change) variations[4].

We perform eight experiments[5] as summarized in table 4.4.

Due to the denominator of percentages, i.e., the number of tests per entry, sometimes being different, in those instances we rely on an index. That index follows the equation 4.2.

$$index_i = \frac{rejected_i / rejected_{total}}{tests_i / tests_{total}} = \frac{rejected_i / tests_i}{rejected_{total} / tests_{total}} \tag{4.2}$$

In the equation 4.2, if the number of tests that rejected (or did not reject) the null hypothesis over the total number of tests that rejected (or did not) the null hypothesis is equal to the percentage of tests performed per entry over the number of tests performed, then the index is one. If the index is equal to two, then it means that

[4]In the appendix C we show an experiment in which we analyzed how different time frames are from one another. Those three are significantly different from each other.

[5]In the appendix C there are additional experiments.

Table 4.4: Differences between experiments regarding tests performed, how much of tests rejected the null hypothesis, the percentage of those tests out of the total, share of tests performed per entry out of the total, and share index

EXPERIMENT	total	below	%	Share tests	Share below	index
Energy	630	582	92.38%	7.94%	9.01%	1.1350
No policy	504	451	89.48%	6.35%	6.98%	1.0994
Technology	630	562	89.21%	7.94%	8.70%	1.0960
Financing	630	522	82.86%	7.94%	8.08%	1.0180
General	5544	4344	78.35%	69.84%	67.23%	0.9627
Mean	1588	1292	0.865	0.200	0.200	1.062
Median	630.0	562.0	0.892	0.079	0.087	1.096
Std	2212	1707	0.057	0.279	0.264	0.070
MAD	0.00	40.00	0.032	0.000	0.006	0.039

the percentage of tests that reject the null hypothesis is twice greater than the percentage of tests of that entry. On the other hand, if the index is equal to 0.5, then it means that the percentage of tests that reject the null hypothesis is half the percentage of tests of that entry. Another way to interpret is how much above or below is the percentage of rejected tests over performed tests for that entry over the percentage rejected tests over tests performed for all entries, i.e., the mean percentage.

Regarding each specific experiment:

1. **General:** The aim of this test is to analyze how different scenarios are from each other. We analyze if the trajectory of elements are different between every possible pair of scenarios. Since there are eight scenarios to compare, with seven to nine elements under three vectors analyzed with a variation of either month-on-month, year-on-year or every four years, each scenario is compared with 63 (no policy scenario) or 81 (all other scenarios) tests, which means 5544 tests in total. We check how different one scenario is from the one it is being compared to in a similar fashion as the previous experiment, by the percentage of tests that rejected the null hypothesis over the total tests performed in the comparison. To be more specific, what we test is that, for the same element, for the same vector, for the same time frame, are the trajectories from the 0.00 scenario and from another scenario likely drawn from the same distribution or not;

2. **Policy:** The aim of this test is to check if any policy affects energy transitions. We analyze if the trajectory of elements are different between the scenario with no policy maker and all the other scenarios. Since there are no public entities, we do not test the public score and public change. Since there are eight scenarios to compare, with seven elements under three vectors analyzed with a variation of either month-on-month, year-on-year or every four years, each scenario is compared to the no policy scenario with 63 tests, which means 504 tests in total. In that sense, we measure how different a scenario is from the no policy scenario by the percentage of tests that rejected the null hypothesis at a 5% significance level. For example, if out of the 63 tests, one comparison rejected 36, we assume that that specific scenario is 57% different from the no policy scenario. To be more specific, what we test is that, for the same element, for the same vector, for the same time frame, are the trajectories from the no policy scenario and from another scenario likely drawn from the same distribution or not;

3. **Technology policy:** The aim of this test is to check how only having technology policy affects energy transitions. We analyze if the trajectory of elements are different between the scenario with just the technology policy maker and all the other scenarios. Since there are nine scenarios to compare, with nine elements under three vectors analyzed with a variation of either month-on-month, year-on-year or every four years, each scenario is compared to the scenario with just the technology policy maker with 63 or 81 tests, which means 630 tests in total. In that sense, we measure how different a scenario is from the scenario with just the technology policy maker by the percentage of tests that rejected the null hypothesis at a 5% significance level. To be more specific, what we test is that, for the same element, for the same vector, for the same time frame, are the trajectories from the scenario with just the technology policy maker and from another scenario likely drawn from the same distribution or not;

4. **Energy policy:** The aim of this test is to check how only having energy policy affects energy transitions. We analyze if the trajectory of elements are different between the scenario with just the energy policy maker and all the other scenarios. Since there are eight scenarios to compare, with seven to nine elements under three vectors analyzed with a variation of either month-on-month, year-on-year or every

four years, each scenario is compared with 63 (no policy scenario) or 81 (all other scenarios) tests, which means 630 tests in total. We check how different one scenario is from the one it is being compared to in a similar fashion as the previous experiment, by the percentage of tests that rejected the null hypothesis over the total tests performed in the comparison. To be more specific, what we test is that, for the same element, for the same vector, for the same time frame, are the trajectories from the 0.00 scenario and from another scenario likely drawn from the same distribution or not;

5. **Financing policy:** The aim of this test is to check how only having public financing affects energy transitions. We analyze if the trajectory of elements are different between the scenario with just the development bank and all the other scenarios. Since there are eight scenarios to compare, with seven to nine elements under three vectors analyzed with a variation of either month-on-month, year-on-year or every four years, each scenario is compared with 63 (no policy scenario) or 81 (all other scenarios) tests, which means 630 tests in total. We check how different one scenario is from the one it is being compared to in a similar fashion as the previous experiment, by the percentage of tests that rejected the null hypothesis over the total tests performed in the comparison. To be more specific, what we test is that, for the same element, for the same vector, for the same time frame, are the trajectories from the 0.00 scenario and from another scenario likely drawn from the same distribution or not;

Table 4.5: Differences between experiments regarding their aims.

EXPERIMENT	aim
General	Are trajectories of different scenarios different?
Policy	Does policy affect trajectories?
Technology	Does just technology policy affect trajectories?
Energy	Does just energy policy affect trajectories?
Financing	Does just public financing affect trajectories?

We perform Kolmogorov-Smirnov tests, which means that we test pairs of trajectories. Given the number of scenarios (nine), the number of vectors (three), the number of time frames (three), the number of elements (nine), the possibility of normalizing a trajectory[6] and trajectories of IQR, MAD and standard deviation, we have 2054 possible entries to test. This means that more than 4 million tests may be performed between trajectories.

4.3 General experiment

In this experiment we test the non-normalized trajectories of elements comparing each possible pair of scenarios. Tables 4.6 and 4.7 aggregate results respectively by number of policy makers and by degree.

Table 4.6: Percentage of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between each pair of scenarios, aggregated by number of policy makers (row and column headers). Source: own elaboration

NUMBER	**0.00**	**1**	**3**
0.00	0%	80.42%	94.92%
1.00	80.42%	0%	89.05%
3.00	94.92%	89.05%	0%
Mean	0.5845	0.5649	0.6132
Median	0.8042	0.8042	0.8905
Std	0.5113	0.4911	0.5319
MAD	0.0725	0.0432	0.0293

Analyzing table 4.6 we rapidly understand that the scenarios with three policy makers stand out from scenarios with just one and specially from the baseline scenario without policy makers. Scenarios without the council entity are 84.17% different from scenarios with the council entity, which means that the presence of a council entity, regardless of its threshold, makes scenarios significantly unique. Table 4.7 aggregates results per degree, highlighting the difference between scenarios with and without the council entity: scenarios without the council entity (with degree none) are almost 90% different from other scenarios in terms of the median difference. Analyzing the scenario 0.00, in which there is a council entity but it never acts, this scenario has a median difference of 60% from other scenarios, being that median close to the differences from this scenario to all other scenarios with an acting council entity. This median falls when analyzing the other scenarios, from 60% to around 50%. It is important to notice that the absolute median deviation of scenarios 0.25, 0.5, 0.75 and 1.00 are higher than the

[6]Important for comparisons that just want to capture the difference in trajectory, not in magnitude.

others because such scenarios are significantly different from both scenarios without the council entity and from the 0.00 scenario.

Table 4.7: Percentage of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between each pair of scenarios, aggregated by degree (row and column headers). Source: own elaboration.

DEGREE	**None**	**0**	**0.25**	**0.5**	**0.75**	**1**
None	0%	89.22%	89.87%	89.87%	91.50%	90.85%
0.00	89.22%	0%	60.49%	59.26%	61.73%	59.26%
0.25	89.87%	60.49%	0%	44.44%	49.38%	50.62%
0.50	89.87%	59.26%	44.44%	0%	49.38%	44.44%
0.75	91.50%	61.73%	49.38%	49.38%	0%	43.21%
1.00	90.85%	59.26%	50.62%	44.44%	43.21%	0%
Mean	0.7522	0.5499	0.4913	0.4790	0.4920	0.4806
Median	0.8987	0.6049	0.4938	0.4938	0.4938	0.5062
Std	0.4031	0.3273	0.3250	0.3239	0.3302	0.1960
MAD	0.0065	0.0123	0.1111	0.0988	0.1235	0.0741

Table 4.8 aggregates experiment results by pair of scenarios, depicting the percentage of tests performed between elements of both scenarios that rejected the null hypothesis. As such, we interpret such percentage as how different one scenario is from the other. Scenarios are, in general, different from each other: the mean percentage is 68.78%, the median percentage is 79.37%, the standard deviation between scenarios is 30.5% and the median absolute deviation is 15.87%. If we rank scenarios by the mean, median, standard deviation and median absolute deviation, we will have scenarios with no policy maker or just one policy maker with higher means and medians, whereas the other scenarios will have higher median absolute deviations. If we rank by standard deviation, all scenarios have standard deviations close to each other, except for the 0.00 and Bank scenarios, with lower standard deviation.

Analyzing the individual pairs of scenarios in table 4.8 we immediately can see that the Baseline, Tech and Energy scenarios are different from the other scenarios, with the Energy scenario being the most unique. The scenarios with council entity all are less than 50% different from each other. They all are 3 p.p. more different from the Bank scenario than the 0.00 scenario is from the Bank scenario. The Bank scenario itself seems like a scenario between the other scenarios with one or Baseline policy maker and the scenarios with three policy makers.

Table 4.8: Percentage of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between each pair of scenarios (row and column headers). The greener the cell, the higher its percentage. We also provide mean, median, standard deviation and median absolute deviation of columns, with the green coloring being relative to each row. Source: own elaboration.

SCENARIO	Baseline	Tech	Energy	Bank	0.00	0.25	0.50	0.75	1.00
Baseline	0%	61.90%	87.30%	92.06%	95.24%	95.24%	95.24%	93.65%	95.24%
Tech	61.90%	0%	82.72%	91.36%	93.83%	93.83%	93.83%	93.83%	96.30%
Energy	87.30%	82.72%	0%	92.59%	95.06%	95.06%	93.83%	95.06%	96.30%
Bank	92.06%	91.36%	92.59%	0%	74.07%	76.54%	77.78%	83.95%	76.54%
0.00	95.24%	93.83%	95.06%	74.07%	0%	60.49%	59.26%	61.73%	59.26%
0.25	95.24%	93.83%	95.06%	76.54%	60.49%	0%	44.44%	49.38%	50.62%
0.50	95.24%	93.83%	93.83%	77.78%	59.26%	44.44%	0%	49.38%	44.44%
0.75	93.65%	93.83%	95.06%	83.95%	61.73%	49.38%	49.38%	0%	43.21%
1.00	95.24%	96.30%	96.30%	76.54%	59.26%	50.62%	44.44%	43.21%	0%
Mean	0.795	0.786	0.820	0.739	0.665	0.628	0.620	0.634	0.624
Median	0.929	0.926	0.932	0.809	0.679	0.685	0.685	0.728	0.679
Std	0.333	0.328	0.327	0.306	0.316	0.331	0.331	0.330	0.237
MAD	0.024	0.012	0.019	0.086	0.173	0.247	0.247	0.216	0.241

Table 4.9: Mean, median, standard deviation and median absolute deviation of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between selected pair of scenarios, with the green coloring being relative to each row indicating higher values. Source: own elaboration.

SCENARIO	Baseline	Tech	Energy	Bank	0.00
Mean	0.841	0.825	0.905	0.869	0.877
Median	0.897	0.881	0.913	0.921	0.937
Std	0.152	0.143	0.056	0.125	0.130
MAD	0.040	0.040	0.040	0.016	0.016

Table 4.9 highlights the previous analysis in relation to the scenario with just one or Baseline policy maker and to the 0.00 scenario. What differs from table 4.8 are the means, medians, standard deviations and median absolute deviations. In terms of mean, the energy scenario is the more different from the others, being followed by the 0.00, Bank, Baseline and Tech scenarios. In terms of median, the first three scenarios switch around to 0.00, Bank and Energy scenarios in order. In terms of the standard deviation, the Energy scenario has the lowest. In terms of median absolute deviation, the Bank and 0.00 scenarios have the lowest values.

Table 4.10: Indexes (percentage of tests below threshold over percentage of tests performed) of Kolmogorov-Smirnov tests that reject the null hyphotesis a 5% significance level between selected pair of scenarios. The greener the cell, the higher its percentage. We also provide the median absolute deviation of columns, with the green coloring being relative to each row. We also provide the median of rows, with the red coloring being relative to the median column. Source: own elaboration.

SCENARIO	Baseline	Tech	Energy	Bank	0.00	*Median*
Baseline	*	0.7400	0.9750	1.0551	1.0675	1.0150
Tech	0.7358	*	0.9238	1.0470	1.0517	0.9854
Energy	1.0377	0.9887	*	1.0612	1.0655	1.0495
Bank	1.0943	1.0920	1.0341	*	0.8303	1.0630
0.00	1.1321	1.1215	1.0616	0.8489	*	1.0916
MAD	0.0472	0.0664	0.0433	0.0071	0.0079	*

Table 4.10 depicts result experiments' only regarding the scenarios without policy maker, with just one policy maker and regarding the 0.00 scenario. In that table we have the indexes per column, the ratio between percentage of tests below threshold for that entry over the percentage of tests performed for that entry regarding the total number of tests in the column. As such, one may interpret 1.0675 meaning that, in the universe of tests performed regarding the 0.00 scenario, tests regarding that scenario and the scenario without policy makers had a percentage of tests that rejected the null hypothesis 6.75% above the mean percentage. In that sense, we can perceive that the Tech and Baseline scenario are more alike than the others. The Bank and 0.00 scenarios also appear to more alike than the others.

Table 4.11 also focuses the analysis on certain scenarios, this time, scenarios with three policy makers. That table depicts the percentage of tests that reject the null hypothesis between the pairs of scenarios. First we can perceive that the 0.00 scenario

Table 4.11: Percentage of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between pair of scenarios (row and column headers) with three policy makers, with the green coloring being relative to each row indicating higher values. Source: own elaboration.

SCENARIO	**0.00**	**0.25**	**0.50**	**0.75**	**1.00**
Mean	0.575	0.492	0.460	0.496	0.484
Median	0.571	0.492	0.452	0.484	0.468
Std	0.020	0.091	0.074	0.054	0.064
MAD	0.008	0.056	0.048	0.024	0.032

is always the one most different from the others, which is something that shows from it having the highest mean and median. Nevertheless, by having small standard deviation and median absolute deviation, we can understand that the four scenarios with the council entity are relatively close to each other in respect to how much different they are from the 0.00 scenario. This really shows when just looking at those fours scenarios with the council entity: the lowest percentage is 38.1% (low and low intermediate) whereas the highest percentage is 49.21% (low and high intermediate and low and high). Low intermediate is the scenario that is closest to all the others. High intermediate is the scenario more different from the others, excluding the 0.00 scenario.

Table 4.12: Indexes (percentage of tests below threshold over percentage of tests performed) of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between pair of scenarios with three policy makers. The greener the cell, the higher its index. We also provide the median absolute deviation of columns, with the green coloring being relative to each row. We also provide the median of rows, with the red coloring being relative to the median column. Source: own elaboration.

SCENARIO	**0.00**	**0.25**	**0.50**	**0.75**	**1.00**	***Median***
0.00	*	1.1807	1.2000	1.2121	1.2000	1.2000
0.25	1.0051	*	0.9000	0.9697	1.0250	0.9874
0.50	0.9846	0.8675	*	0.9697	0.9000	0.9348
0.75	1.0256	0.9639	1.0000	*	0.8750	0.9819
1.00	0.9846	0.9880	0.9000	0.8485	*	0.9423
MAD	0.0103	0.0602	0.0500	0.0606	0.0750	*

Table 4.12 returns with the index analysis this time for just the scenarios with three policy makers. With that table, we can see that the difference from 0.00 to the other scenarios is more prominent when compared within scenarios with the council entity then in the universe of scenarios without the council entity. In other words, the 0.00 scenario always stand out in relation to comparisons of scenarios with the council entity, whereas

the scenarios with the council entity do not stand out in relation to mean percentage of the 0.00 scenario.

Table 4.13: Indexes (percentage of tests below threshold over percentage of tests performed in the column) of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between each pair of scenarios. The greener the cell, the higher its index. We also provide the median absolute deviation of columns, with the green coloring being relative to each row. We also provide the median of rows, with the red coloring being relative to the median column. Source: own elaboration.

SCENARIO	Baseline	Tech	Energy	Bank	0.00	0.25	0.50	0.75	1.00	*Median*
Baseline	*	0.6940	0.9450	1.1111	1.2821	1.3605	1.3793	1.3258	1.3699	1.3039
Tech	0.6918	*	0.8954	1.1026	1.2631	1.3404	1.3589	1.3283	1.3851	1.2957
Energy	0.9756	0.9272	*	1.1175	1.2797	1.3580	1.3589	1.3458	1.3851	1.3127
Bank	1.0288	1.0241	1.0023	*	0.9972	1.0935	1.1264	1.1885	1.1010	1.0611
0.00	1.0643	1.0518	1.0290	0.8940	*	0.8642	0.8582	0.8739	0.8524	0.8840
0.25	1.0643	1.0518	1.0290	0.9238	0.8143	*	0.6437	0.6991	0.7281	0.8691
0.50	1.0643	1.0518	1.0157	0.9387	0.7977	0.6349	*	0.6991	0.6393	0.8682
0.75	1.0466	1.0518	1.0290	1.0132	0.8310	0.7055	0.7152	*	0.6215	0.9221
1.00	1.0643	1.0795	1.0424	0.9238	0.7977	0.7231	0.6437	0.6117	*	0.8608
MAD	0.009	0.014	0.013	0.067	0.116	0.309	0.349	0.306	0.346	*

Table 4.13 expands the index analysis to all scenarios. In this table it is important to notice how the median absolute deviation grows from 0.09 regarding the indexes of the Baseline scenario to 0.346 regarding the indexes of the High scenario. This means that indexes for scenarios with three policy makers are more different between each other than within scenarios with just one policy maker or without any. Moreover, there are significant jumps regarding the median absolute deviation: from around 1% in the Baseline, Tech and Energy scenarios to 6.7% in the Bank scenario, then to 11.6% in the 0.00 scenario and then to around 30% for the scenarios with the council entity.

4.4 No policy experiment

In this experiment we test the non-normalized trajectories of elements comparing one scenario to the no policy scenario. The no policy scenario has no public policy, so: energy providers must reinvest in order to fund their new power plants that have no assurance that will be contracted in the future; and technology providers only rely on the cash flow generated by the purchase of power plants by energy providers.

We performed 504 tests, out of which 451 rejected the null hypothesis, i.e., 89.45% of the tests in this experiment. Table 4.15 aggregates experiment results per element tested. When comparing element trajectory to its trajectory in the no policy

Table 4.14: Indexes (percentage of tests below threshold over percentage of tests performed in the column) of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level for elements aggregated by scenario. The greener the cell, the higher its percentage. We also provide the mean, median, standard deviation and median absolute deviation of columns, with the green coloring being relative to each row. We also provide the mean, median, standard deviation and median of rows, with the red coloring being relative each column. Source: own elaboration.

	SCENARIO	Baseline	Tech	Energy	Bank	0.00	0.25	0.50	0.75	1.00	ROW			
											Mean	*Median*	*Std*	*MAD*
ELEMENT	adoption	93.1%	94.4%	98.6%	84.7%	80.6%	76.4%	73.6%	73.6%	72.2%	0.83	0.81	0.10	0.01
	CAPEX	91.7%	90.3%	88.9%	88.9%	86.1%	75.0%	70.8%	80.6%	75.0%	0.83	0.86	0.08	0.04
	innovation	86.1%	83.3%	91.7%	80.6%	83.3%	68.1%	65.3%	70.8%	70.8%	0.78	0.81	0.09	0.04
	internalization	98.6%	98.6%	100%	91.7%	81.9%	81.9%	77.8%	86.1%	94.4%	0.90	0.92	0.08	0.07
	OPEX	97.2%	90.3%	94.4%	79.2%	80.6%	72.2%	77.8%	76.4%	68.1%	0.82	0.79	0.10	0.03
	private_effort	73.6%	70.8%	77.8%	61.1%	47.2%	52.8%	51.4%	47.2%	48.6%	0.59	0.53	0.12	0.19
	private_score	86.1%	86.1%	94.4%	75.0%	48.6%	54.2%	52.8%	52.8%	52.8%	0.67	0.54	0.18	0.18
	public_effort	*	90.5%	85.7%	92.1%	74.6%	69.8%	69.8%	66.7%	66.7%	0.77	0.72	0.11	0.05
	public_score	*	100%	100%	95.2%	87.3%	81.0%	84.1%	82.5%	77.8%	0.88	0.86	0.09	0.09
COL	*Mean*	0.89	0.89	0.92	0.83	0.74	0.70	0.69	0.71	0.70				
	Median	0.92	0.90	0.94	0.85	0.81	0.72	0.71	0.74	0.71				
	Std	0.09	0.09	0.07	0.11	0.15	0.11	0.11	0.13	0.13				
	MAD	0.06	0.04	0.06	0.07	0.06	0.04	0.07	0.07	0.04				

scenario, the element that rejects the least of tests is private effort still rejecting 73.61% of its tests. With the exception of that entry, all other entries are close to each other, which is highlighted by the small median absolute deviation between entries (3.9%).

Table 4.16 aggregates experiment results' by scenario. The scenario that is closest to the no policy scenario is the technology policy maker scenario, in which 61.9% of the tests comparing itself to the no policy scenario reject the null hypothesis. The second closest is the energy policy maker scenario with 87.3% of its tests rejecting the null hypothesis. Apart from those two, all other scenarios have similar ratios (between 92.06% and 95.24%).

Table 4.17 depicts four different aggregations for this experiment results': by presence of council, by number of policy makers, by time frame of the trajectory; by vector of the trajectory. Scenarios with a presence of the council reject 10 p.p. more tests than scenarios without the council entity. Similarly, scenarios with three policy makers reject 14.5 p.p. more tests than scenarios with just one policy maker. Aggregating by time we can see that the differences between scenarios and the no policy scenarios are more prominent in the long run. And regarding vectors, velocity and growth reject almost all tests performed involving them, whereas tests with acceleration vectors reject 77.38% of their tests.

Table 4.15: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario without policies aggregated by element at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

ELEMENT	Total	5% p-value		Share		
		below	Ratio	tests	below	index
internalization	72	71	98.61%	14.29%	15.74%	1.1020
OPEX	72	70	97.22%	14.29%	15.52%	1.0865
adoption	72	67	93.06%	14.29%	14.86%	1.0399
CAPEX	72	66	91.67%	14.29%	14.63%	1.0244
innovation	72	62	86.11%	14.29%	13.75%	0.9623
private_score	72	62	86.11%	14.29%	13.75%	0.9623
private_effort	72	53	73.61%	14.29%	11.75%	0.8226
Mean	72.00	64.43	0.895	0.143	0.143	1.000
Median	72.00	66.00	0.917	0.143	0.146	1.024
Std	0.000	6.133	0.085	0.000	0.014	0.095
MAD	0.00	4.000	0.056	0.000	0.009	0.062

Table 4.16: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario without policies aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

SCENARIO	Total	5% p-value		Share		
		below	Ratio	tests	below	index
0.50	63	60	95.24%	12.50%	13.30%	1.0643
0.25	63	60	95.24%	12.50%	13.30%	1.0643
1.00	63	60	95.24%	12.50%	13.30%	1.0643
0.00	63	60	95.24%	12.50%	13.30%	1.0643
0.75	63	59	93.65%	12.50%	13.08%	1.0466
Bank	63	58	92.06%	12.50%	12.86%	1.0288
Energy	63	55	87.30%	12.50%	12.20%	0.9756
Tech	63	39	61.90%	12.50%	8.65%	0.6918
Mean	63.00	56.38	0.895	0.125	0.125	1.000
Median	63.00	59.50	0.944	0.125	0.132	1.055
Std	0.000	7.230	0.115	0.000	0.016	0.128
MAD	0.000	0.500	0.008	0.000	0.001	0.009

Table 4.17: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario without policies aggregated by presence of council, number of policy makers, time frame and vectors at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

		Total	5% p-value		Share		
			below	Ratio	tests	below	index
COUNCIL	**True**	252	239	94.84%	50.00%	52.99%	1.0599
	False	252	212	84.13%	50.00%	47.01%	0.9401
NUMBER	**3**	315	299	94.92%	62.50%	66.30%	1.0608
	1	189	152	80.42%	37.50%	33.70%	0.8987
TIME	**48**	168	162	96.43%	33.33%	35.92%	1.0776
	12	168	149	88.69%	33.33%	33.04%	0.9911
	1	168	140	83.33%	33.33%	31.04%	0.9313
VECTOR	**velocity**	168	163	97.02%	33.33%	36.14%	1.0843
	growth	168	158	94.05%	33.33%	35.03%	1.0510
	acceleration	168	130	77.38%	33.33%	28.82%	0.8647

Table 4.18 is an attempt at ranking the different aggregations by how much significant they are for the experiment. We understand that if the entries have significantly different percentages, or indexes in order to take the denominators into account, then choosing or analyzing one entry over another has more weight to it. Following that understanding, the difference in number of policy makers and the presence or not of the council entity are relevant aggregations when identifying how different one scenario is from the no policy scenario. We built such ranking by using the median absolute deviations of entries per aggregation. We do not aim to use the numbers of the different median absolute deviations in comparison one with another, only to use them to compare and rank aggregations.

Table 4.18: Median absolute deviation of indexes per aggregation in the no policy experiment. Source: own elaboration

AGGREGATION	MAD
number	0.08101
element	0.06208
time	0.05987
council	0.05987
vector	0.03326
scenario	0.00887

4.5 Technology policy experiment

In this experiment we test the non-normalized trajectories of elements comparing each scenario to the scenario just with the technology policy maker. This scenario has only one policy maker and it does technology policy, increasing the cash flow of technology producers with incentives.

We performed 630 tests, out of which rejected 562 tests (89.21%). Table 4.19 presents the results of this experiment aggregated by element. In this scenario, since we are comparing scenarios to a scenario with a policy maker, we also have the public score and the public effort elements. All tests performed involving public score rejected the null hypothesis. The element which tests rejected the null hypothesis the least was private effort.

Table 4.19: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario with just the technology policy maker aggregated by element at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

ELEMENT	Total	5% p-value		Share		
		below	Ratio	tests	below	index
public_score	63	63	100%	10.00%	11.21%	1.1210
internalization	72	71	98.61%	11.43%	12.63%	1.1054
adoption	72	68	94.44%	11.43%	12.10%	1.0587
public_effort	63	57	90.48%	10.00%	10.14%	1.0142
CAPEX	72	65	90.28%	11.43%	11.57%	1.0120
OPEX	72	65	90.28%	11.43%	11.57%	1.0120
private_score	72	62	86.11%	11.43%	11.03%	0.9653
innovation	72	60	83.33%	11.43%	10.68%	0.9342
private_effort	72	51	70.83%	11.43%	9.07%	0.7940
Mean	70.00	62.44	0.894	0.111	0.111	1.002
Median	72.00	63.00	0.903	0.114	0.112	1.012
Std	3.969	5.961	0.088	0.006	0.011	0.099
MAD	0.000	3.000	0.042	0.000	0.005	0.047

Table 4.20 aggregates experiment results by scenario. The scenario closest to the scenario with just a technology policy maker is the no policy scenario: tests between both scenarios rejected 61.9 % of null hypothesis. Interestingly, scenarios with the council entity are the most different from the scenario with just a technology policy maker.

Nevertheless, all scenarios from high intermediate to 0.00 are tied, rejecting 93.83 % of their tests.

Table 4.20: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario with just the technology policy maker aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

SCENARIO	**Total**	**5% p-value**		**Share**		
		below	**Ratio**	**tests**	**below**	**index**
1.00	81	78	96.30%	12.86%	13.88%	1.0795
0.75	81	76	93.83%	12.86%	13.52%	1.0518
0.50	81	76	93.83%	12.86%	13.52%	1.0518
0.25	81	76	93.83%	12.86%	13.52%	1.0518
0.00	81	76	93.83%	12.86%	13.52%	1.0518
Bank	81	74	91.36%	12.86%	13.17%	1.0241
Energy	81	67	82.72%	12.86%	11.92%	0.9272
Baseline	63	39	61.90%	10.00%	6.94%	0.6940
Mean	78.75	70.25	0.884	0.125	0.125	0.991
Median	81.00	76.00	0.938	0.129	0.135	1.052
Std	6.364	13.06	0.115	0.010	0.023	0.129
MAD	0.000	1.000	0.012	0.000	0.002	0.014

Table 4.21 depicts various aggregations of experiment results'. The difference between the presence or not of the council is of 11 p.p., with scenarios with the council having 5.87% more of the share of tests below significance level than the share of tests. Scenarios with more policy makers are progressevely more different than the scenario with just the technology policy maker. The differences between scenarios become more acute with higher time frames. The vectors of velocity and growth are the ones that better capture differences between scenarios.

Table 4.22 ranks aggregations by the median absolutes deviations of their indexes. The aggregation that appears to better capture differences between scenarios and the scenario with just the technology policy maker scenario is the aggregation by number of policy makers (MAD of 0.0908), whereas aggregation by time frame captures the least difference between scenarios (MAD of 0.0276)

Table 4.21: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario with just the technology policy maker aggregated by presence of council, number of policy makers, time frame and vectors at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

		Total	5% p-value		Share		
			below	Ratio	tests	below	index
COUNCIL	**True**	324	306	94.44%	51.43%	54.45%	1.0587
	False	306	256	83.66%	48.57%	45.55%	0.9378
NUMBER	**3**	405	382	94.32%	64.29%	67.97%	1.0573
	1	162	141	87.04%	25.71%	25.09%	0.9757
	0	63	39	61.90%	10.00%	6.94%	0.6940
TIME	**48**	210	206	98.10%	33.33%	36.65%	1.0996
	12	210	179	85.24%	33.33%	31.85%	0.9555
	1	210	177	84.29%	33.33%	31.49%	0.9448
VECTOR	**velocity**	210	204	97.14%	33.33%	36.30%	1.0890
	growth	210	200	95.24%	33.33%	35.59%	1.0676
	acceleration	210	158	75.24%	33.33%	28.11%	0.8434

Table 4.22: Median absolute deviation of indexes per aggregation in the technology experiment.

AGGREGATION	MAD
number	0.08165
council	0.06045
element	0.04671
vector	0.02135
scenario	0.01384
time	0.01068

4.6 Energy policy experiment

In this experiment we test the non-normalized trajectories of elements comparing each scenario to the scenario with just the energy policy maker. This scenario has just one policy maker and it does energy policy, promoting energy auctions that award PPAs for selected renewable power plants.

Table 4.23 aggregates experiment results by element. All trajectories of internalization and public score reject the null hypothesis, meaning that the internalization and evaluation of the system by public agents in the scenario with just the energy policy maker are quite unique. Once again private effort trajectories are the least unique, rejecting just 77.78% of their tests. Trajectories of OPEX and CAPEX appear in the middle, rejecting 94.44% and 88.89% of tests repectively. In index terms, internalization and adoption have respectively a share of tests below significance level 8.25% and 6.74% above their share of tests performed, whereas innovation has a share of tests below significance level 0.77% below its share of tests performed.

Table 4.23: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario with just the energy policy maker aggregated by element at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

ELEMENT	Total	5% p-value		Share		
		below	Ratio	tests	below	index
internalization	72	72	100%	11.43%	12.37%	1.0825
public_score	63	63	100%	10.00%	10.82%	1.0825
adoption	72	71	98.61%	11.43%	12.20%	1.0674
private_score	72	68	94.44%	11.43%	11.68%	1.0223
OPEX	72	68	94.44%	11.43%	11.68%	1.0223
innovation	72	66	91.67%	11.43%	11.34%	0.9923
CAPEX	72	64	88.89%	11.43%	11.00%	0.9622
public_effort	63	54	85.71%	10.00%	9.28%	0.9278
private_effort	72	56	77.78%	11.43%	9.62%	0.8419
Mean	70.00	64.67	0.924	0.111	0.111	1.000
Median	72.00	66.00	0.944	0.114	0.113	1.022
Std	3.969	6.225	0.074	0.006	0.011	0.080
MAD	0.000	3.000	0.056	0.000	0.005	0.060

Table 4.24 aggregates experiment results by scenario. Once again scenarios with three policy makers appear to be the most different from the scenario with just the

energy policy maker, rejecting between 96.3% and 93.8%. It is followed closely by the scenario with just the development bank (92.59%). Interestingly, the scenario closer to the scenario with just the energy policy maker is the scenario with just the technology policy maker. This means that both scenarios share a number of similar trajectory of elements between them and different from the scenario without policy.

Table 4.24: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario with just the energy policy maker aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

SCENARIO	Total	5% p-value		Share		
		below	Ratio	tests	below	index
1.00	81	78	96.30%	12.86%	13.40%	1.0424
0.75	81	77	95.06%	12.86%	13.23%	1.0290
0.25	81	77	95.06%	12.86%	13.23%	1.0290
0.00	81	77	95.06%	12.86%	13.23%	1.0290
0.50	81	76	93.83%	12.86%	13.06%	1.0157
Bank	81	75	92.59%	12.86%	12.89%	1.0023
Baseline	63	55	87.30%	10.00%	9.45%	0.9450
Tech	81	67	82.72%	12.86%	11.51%	0.8954
Mean	78.75	72.75	0.922	0.125	0.125	0.998
Median	81.00	76.50	0.944	0.129	0.131	1.022
Std	6.364	7.978	0.048	0.010	0.014	0.051
MAD	0.000	1.000	0.012	0.000	0.002	0.013

Table 4.25 depicts various aggregations of experiment results'. Scenarios with the council entity are more different from the scenario with just the energy policy maker. Similarly, scenarios with three policy makers are more different from the scenario with just the energy policy maker. Differences between scenarios become more prominent as we the time frame variation. In relation to vectors, acceleration is the vector that least explain differences between scenarios and the scenario with just the energy policy maker.

Table 4.26 attempts to rank the differences between aggregations of this experiment results'. Element appears to be aggregation that better capture differences between scenarios, whereas the actual aggregation by scenario appears to be the aggregation that least captures their differences. Aggregations by presence of council and number of policy makers rank higher but still below the mid point.

Table 4.25: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario with just the energy policy maker aggregated by presence of council, number of policy makers, time frame and vectors at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

		Total	5% p-value		Share		
			below	**Ratio**	**tests**	**below**	**index**
COUNCIL	**True**	324	308	95.06%	51.43%	52.92%	1.0290
	False	306	274	89.54%	48.57%	47.08%	0.9693
NUMBER	**3**	405	385	95.06%	64.29%	66.15%	1.0290
	1	162	142	87.65%	25.71%	24.40%	0.9488
	0	63	55	87.30%	10.00%	9.45%	0.9450
TIME	**48**	210	209	99.52%	33.33%	35.91%	1.0773
	12	210	193	91.90%	33.33%	33.16%	0.9948
	1	210	180	85.71%	33.33%	30.93%	0.9278
VECTOR	**velocity**	210	209	99.52%	33.33%	35.91%	1.0773
	growth	210	202	96.19%	33.33%	34.71%	1.0412
	acceleration	210	171	81.43%	33.33%	29.38%	0.8814

Table 4.26: Median absolute deviation of indexes per aggregation in the energy experiment.

AGGREGGATION	MAD
time	0.06701
element	0.06014
vector	0.03608
council	0.02987
scenario	0.01336
number	0.00382

4.7 Public financing experiment

In this experiment we test the non-normalized trajectories of elements comparing each scenario to the scenario with just the development bank. This scenario has just one policy maker and it does public financing.

Table 4.27 aggregates experiment results' by elements. It is important to notice how the public score and public effort trajectories are the elements that reject the most number of tests performed, respectively 95.24% and 92.06%. In index terms, they respectively have a share of rejected tests 14.94% and 11.11% above their share of tests performed (both having 10% of the tests performed). Following them we have internalization, CAPEX, adoption, innovation and OPEX, with innovation and OPEX having a slightly larger share of tests performed than their share of rejected tests.

Table 4.27: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario with just the development bank aggregated by element at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

ELEMENT	Total	5% p-value		Share		
		below	Ratio	tests	below	index
public_score	63	60	95.24%	10.00%	11.49%	1.1494
public_effort	63	58	92.06%	10.00%	11.11%	1.1111
internalization	72	66	91.67%	11.43%	12.64%	1.1063
CAPEX	72	64	88.89%	11.43%	12.26%	1.0728
adoption	72	61	84.72%	11.43%	11.69%	1.0225
innovation	72	58	80.56%	11.43%	11.11%	0.9722
OPEX	72	57	79.17%	11.43%	10.92%	0.9555
private_score	72	54	75.00%	11.43%	10.34%	0.9052
private_effort	72	44	61.11%	11.43%	8.43%	0.7375
Mean	70.00	58.00	0.832	0.111	0.111	1.004
Median	72.00	58.00	0.847	0.114	0.111	1.023
Std	3.969	6.384	0.107	0.006	0.012	0.129
MAD	0.000	3.000	0.069	0.000	0.006	0.084

Table 4.28 aggregates experiment results' by scenario. The scenario that is more similar to the scenario with just the development bank is the 0.00 scenario, rejecting just 74.07% of tests performed. In index terms, it has 12.86% of tests performed and 11.49% of rejected tests, meaning that the share of rejected tests is 10.6% lower than the share of tests. The scenarios that are more different from the scenario with just the

development bank are the scenarios with no or just one policy maker, all rejecting more than 91% tests performed, or, index terms, all having a share of rejected tests 10% than their share of performed tests.

Table 4.28: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario with just the development bank aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

SCENARIO	Total	5% p-value		Share		
		below	Ratio	tests	below	index
Energy	81	75	92.59%	12.86%	14.37%	1.1175
Baseline	63	58	92.06%	10.00%	11.11%	1.1111
Tech	81	74	91.36%	12.86%	14.18%	1.1026
0.75	81	68	83.95%	12.86%	13.03%	1.0132
0.50	81	63	77.78%	12.86%	12.07%	0.9387
0.25	81	62	76.54%	12.86%	11.88%	0.9238
1.00	81	62	76.54%	12.86%	11.88%	0.9238
0.00	81	60	74.07%	12.86%	11.49%	0.8940
Mean	78.75	65.25	0.831	0.125	0.125	1.003
Median	81.00	62.50	0.809	0.129	0.120	0.976
Std	6.364	6.386	0.079	0.010	0.012	0.095
MAD	0.000	3.500	0.056	0.000	0.007	0.067

Table 4.29 depicts various aggregations for experiment results'. In terms of council presence, the scenario with just the development bank is closer to scenarios with presence of the council entity than without its presence. In relation to number of policy makers, the scenario with just the development bank is closer to scenarios with three policy makers, being fairly different to scenarios with just one policy maker (91.98% tests are rejected) and with no policy maker (92.06% tests are rejected). Once again, differences between scenarios are more prominent as the time frame variations increases. Once again, acceleration is the vector that least explain differences between scenarios.

Table 4.30 attempts to rank aggregations of experiment results' by median absolute deviation. Vector and element are the first and second in that rank and council and number are the penultimate and last in that rank. Aggregation by scenario figures in the middle of that ranking.

Table 4.29: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the scenario with just the development bank aggregated by presence of council, number of policy makers, time frame and vectors at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

		Total	5% p-value		Share		
			below	Ratio	tests	below	index
COUNCIL	False	306	267	87.25%	48.57%	51.15%	1.0531
	True	324	255	78.70%	51.43%	48.85%	0.9499
NUMBER	0	63	58	92.06%	10.00%	11.11%	1.1111
	1	162	149	91.98%	25.71%	28.54%	1.1100
	3	405	315	77.78%	64.29%	60.34%	0.9387
TIME	48	210	204	97.14%	33.33%	39.08%	1.1724
	12	210	172	81.90%	33.33%	32.95%	0.9885
	1	210	146	69.52%	33.33%	27.97%	0.8391
VECTOR	velocity	210	197	93.81%	33.33%	37.74%	1.1322
	growth	210	192	91.43%	33.33%	36.78%	1.1034
	acceleration	210	133	63.33%	33.33%	25.48%	0.7644

Table 4.30: Median absolute deviation of indexes per aggregation in the financing experiment.

DESEGREGATION	MAD
time	0.14943
element	0.08381
scenario	0.06705
council	0.05160
vector	0.02874
number	0.00106

Conclusion

In this thesis, we had four main chapters: one chapter that dealt with theory related to change, another that analyzed empirical aspects of energy transitions, another chapter that focused on presenting the proposed agent-base model used, and finally one chapter for presenting model results' and discussing them. In the first chapter we focused on the toolbox to be used focusing on the theories to be used: institutional economics, evolutionary economics, co-evolution and complexity. After that we focused on the toolbox from the point-of-view of empirical aspects of the transition itself. Then we opened the toolbox regarding the methodology that the simulation model uses. Lastly, we presented results from experiments made using such toolbox and later discussed them.

Climate change is a reality that we must face. Energy is one of the top emitters of greenhouse gases, with electricity production from fossil-fueled power plants being a significant portion of that. For an energy transition which decreases the emissions of greenhouse gases while maintaining or increasing electricity output, it is crucial that electricity mixes switch from fossil to low-carbon sources. We focus on renewables as options to fossil, to be more specific, on solar photovoltaic and wind. Agents may switch from fossil to renewables if they perceive that the economic opportunities of such change are higher than the risks of switching. Considering only economic reasons for such change, one firm may switch from fossil to renewable if: the comparison of opportunities becomes more favorable towards renewables, or if the risks of switching decrease. Regarding both phenomena, policy then becomes crucial. We focus on three policies: an energy policy, done by an energy policy maker, consisting of an auction with long-term power purchase agreements; a technology policy, done by a technology policy maker, consisting of cash flow incentives to agents that produce electricity provision assets and do R&D on those technologies; and a public financing instrument, done by a development bank, consisting of direct lending at lower interest rates. Auctions reduce risks of switching, by assuring demand and cash flow to energy providers that switch to renewables. Incentives to technology producers may increase the opportunities of renewables by allowing for more innovation through more investment in R&D or for less costly technology through more investment in local productive capacity. Public financing increases the opportunities of renewables by having lower interest rates and reduces risk by assuring that renewables will have a bank that accepts to finance renewable capacity.

In this sense, a combination of policies seems to provide the best answer for an energy transition: combining the risk reduction and the increase in opportunities of renewables in different fronts of action. Nevertheless, policy mixes are not a surefire method against climate change since policy mixes may have incongruities in terms of different goals and different instruments used. We analyze how the introduction of a simple rule that homogenizes the different policymaking activities of policy makers affects the energy transition. We focus our analysis on nine system elements: reduction of CAPEX and OPEX, changes in the adoption, internalization and innovation rates of renewable technologies, trajectories of changes in decision by private and public agents, and trajectories of goal-achievement of private and public agents. We trust such rule to an agent: a council entity.

Model results show that the introduction of this very simple rule makes scenarios significantly different from scenarios without policy makers, with only one policy and even from the scenario with all three policy makers but without such rule. The homogenization process has thresholds: it may range from low (one quarter homogeneity) to high (full homogeneity). We notice how increases in the homogeneity of the system do not necessarily make scenarios more different from one another. In terms of element trajectories, increasing the homogeneity does not make results necessarily more desirable and does not make vectors of change (velocity and acceleration of change) faster. As such, we identify intermediate levels of heterogeneity as better options for the simple rule introduced. By having intermediate levels of heterogeneity, there is a balance between confluence among policy makers and independence to take decisions that best suit policy makers' evaluation of the system itself, according to their specific rationales.

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Appendix A

Further theoretical topics

We argue that mainstream economics is epistemologic and methodologically redutionistic, using Fang and Casadevall (2011) terms. Epistemologically reductionism is the understanding that knowledge in a certain domain can always be reduced to another body of scientific knowledge, e.g. mainstream economics explains society without using social and political sciences, psychology or anthropology (POLANYI; PEARSON, 1977b,a; VEBLEN, 1898; VEBLEN, 1909). On the other hand, methodological reductionism is the understanding that the scientific explanation of any object can be correctly elucidated by reconstitution, i.e., the aggregation of separate conclusions about smaller parts of an object is the correct analysis of the complete object.

In relation to methodological reductionism, Prado (2009) uses another term: classical reductionism. As Fang and Casadevall (2011) state, methodological reductionism can be traced back to the Enlightment and Empiricism, as both Bacon and Descartes analyses general rules and general predictions. Prado (2009) traces back the inspiration of neoclassical economics to XIXth century physics. Methodological or Classical reductionism thus understand that all socio-economic systems are modules that can be separately analyzed. Nevertheless, modules may have significant relations among themselves, thus leading to dubious analyses if one was to separately analyze them[1] (BALDWIN; CLARK, 2002; FRENKEN, 2006; LANGLOIS, 2002, 1992). According to Prado (2009), this possibility leads into meso-economics: the understanding that some patterns are not part of single agents or of the whole system, rather part of the interactions among some agents (ARTHUR, 2015a).

[1]That is specifically relevant for the liberalization of electric industries, as stated by Glachant and Perez (2007).

Holism and complexity are notions that goes against the aforementioned reductionisms. Holism aims to analyze the most complete object possible, and was particularly relevant in biology (FANG; CASADEVALL, 2011; MITTELTRASS, 2012). Complexity on the other hand studies the interactions of complex entities and the consequences of such interactions: pattern-like structures called "phenomena". Complex entities, in contrast with the atomized agents of neoclassical economics, are interdependent, connected, adaptive and diverse entities. Phenomena happen in the meso-economy. As such, complexity studies how phenomena emerge, propagates themselves and ends (ARTHUR, 2015b).

Complexity assumes endogenous non-equilibrium, arising from fundamental uncertainty (DEQUECH, 2011): one agent cannot know ex-ante the ex-post consequences of its actions; and technology and institutions may evolve and change. As such, maximization and perfect rationality are denied. Moreover, there exists positive and negative feedbacks in decisions made within socio-economic systems (ARTHUR, 2015b; FRENKEN, 2006; MUELLER, 2016).

Prado (2009) provides a taxonomy of complex systems. Deductive complex systems can be fully understood; Saltationist complex systems, inspired by Mill (1882/[2009]) analysis, present qualitative changes throughout its evolution; and structural complex systems are structures composed of interactions and positions between elements, being those relations not fully external or fully internal to the elements themselves. In relation to the emergence of phenomena, they are respectively understood as macroscopic patterns of microscopic interactions; unpredictable, irreducible and novel patterns; and manifestations of the different structures within a complex system. Structural complexity is, in methodological terms, close to Critical Realism[2]. Agent-based models are closer however to deductive complex systems.

In order to provide a socio-economic analysis closer to holism and further away from reductionism, one cannot isolate technical progress from institutional change in society. In this sense, Nelson (2002) advocates for a joint-analysis of evolutionary economics and institutional economics. Furthermore, the author advocates that the analysis of "technology" and "institutions" together were the norm before neoclassical economics. Nevertheless, this attention to the co-evolution between technology and institutions faded away with the rise of neoclassical economics. After that, institutional and evolutionary analy-

[2]For more on the matter we recommend Cavalcante (2015).

ses became separated “counter-cultures”. Institutional economics focused on the factors that mold and define human interaction, intra and interfirms, whereas neo-Schumpeterian economics focused on the technological change in an evolutionary fashion.

In mind of this, Prado (2009) analysis of complexity is more related to philosophy of science and methodology. Complexity directly stands in opposition to classic reductionism, central to positivism. Classic reductionism understands that any object's scientific explanation can be correctly elucidated by reconstitution, i.e., by reducing any complete object or causal chain to several smaller parts to be separately analysed. The aggregation of the smaller parts' analysis is the analysis of the complete object. Mittelstrass (2012) goes further when stating that the rise of complexity, especially in biology[3], has deemed the reductionism, and as a matter of fact linear thinking[4] itself, obsolete.

Prado (2009) classic reductionism would be regarded as **methodological reductionism**[5] according to Fang and Casadevall (2011)[6]. The **methodological reductionism** approach can be traced back to Enlightenment and Empiricism. Both Bacon and Descartes helped to pave the way for this understanding in their works analyzing general rules, general predictions, etc[7]. **Epistemological reductionism** understands that knowledge in a certain scientific domain can always be reduced to another body of scientific knowledge, e.g., one can analyze sociological and psychological problems by using economics. **Ontological reductionism** involves both physics and metaphysics in conjunction with philosophy, tackling questions regarding senses, if the physical world is all that there is and more alike. Moreover, holism[8] is understood as an opposing defini-

[3]For more of complexity, reductionism and holism in biology, we recommend Fang and Casadevall (2011).

[4]Linearity and non-linearity compose an important debate on the subject of innovation (KLINE, 1985; NIOSIA, 1999; GODIN, 2006).

[5]“The third category, methodological reductionism, describes the idea that complex systems or phenomena can be understood by the analysis of their simpler components” (FANG; CASADEVALL, 2011, p. 1401) is coherent with Prado's (2009) understanding that classic reductionism means that nothing is more than the sum of its parts.

[6]The authors are related to medicine, biology and immunology fields, not to economics. Nevertheless, their editorial focuses on the application of philosophy of science and methodology to their fields, first by analyzing reductionism, holism and complexity and then by applying these terms. We obviously focus our analysis on the first part of the article, not on its application in health sciences. Furthermore, the use of an article from a different area reiterates the fact that complexity is interdisciplinary.

[7]For a more incisive analysis on the matter we recommend Blaug (1992) and Cavalcante (2007). Both also present interesting analysis of methodology and philosophy of science applied to economics. For more on the former, we recommend Rubin (1979).

[8]“The line of thought pursued here in the case of the concepts complexity, reduction and analogy lead in the philosophy of science to a position that on the one hand turns against the reductionist programme and on the other hand represents the attempt to do justice to the actual complexity of scientific objects, concepts or theories in a different manner as well, namely in the sense of a unity to be regained, a **holistic**

tion of systems in regard to reductionism, i.e., a system, in order to be correctly analyzed, must be studied as a whole rather than through the sum of studies of its parts. According to the author holism leads to emergence, a characteristic of complex systems (FANG; CASADEVALL, 2011; MITTELTRASS, 2012).

Modularity is required for reductionism to be possible. Modularity is the concept that something (e.g. production and services) can be subdivided into smaller parts called "modules"[9] (LANGLOIS, 2002; BALDWIN; CLARK, 2002). Modularity is broken when: the modules have significant interactions between them, i.e., when a significant element happens in between two modules, not being fully captured by separating them; or when cause and effect are disproportional throughout the modules, i.e., when a cause is more of a "cause" than an effect is an "effect", in other words, when the relations between modules are disproportional (GLACHANT; PEREZ, 2007). To Prado (2009), those are respectively meso-economics and disproportional relations between cause and effect.

Prado (2009) summarizes three broad points of view about complex systems:

- **Deductive:** a complex system which can be fully understood. Emergence stands as a macroscopic pattern of microscopic interactions;
- **Saltationist:** a complex system presents qualitative changes throughout its evolution. Emergence are unpredictable, irreducible and novel phenomena;
- **Structural:** the links between elements are not external to them, as the former starts inside the latter connecting different elements. Complex systems are structures composed of relations (or interactions) and positions between elements. Emerging properties are **manifestations** of these structures.

The **deductive** complexity is a "shy" departure from positive modern science. General laws are still possible to be achieved. Models can be represented by formal models which computational algorithms. Although narrow and restricted, by incorporating heterogeneity and interactivity among elements, while using a dynamic analysis, this conception of complexity widens significantly science's capacity to analyse and cover external

unity of disciplinary and transdisciplinary explanations" (MITTELTRASS, 2012, 50–51, emphasis on the original) (MITTELTRASS, 2012, p. 50–51, emphasis in the original). Furthermore, the author defines several different types of holisms. Holism comes from the Greek word *hólos* which means "whole" (COLLINS, 2014).

[9]This concept is applied in networks such as communications or electricity, in which the competitive modules were unbundled and then competition was inserted into a prior monopoly (GLACHANT; PEREZ, 2007; JOSKOW, 2008).

and internal links of natural and social processes. Essentially, it can be understood as a small step towards complexity albeit a large (and definite) step away from classic reductionism and Logical Instrumentalism (and Positivism). Agent based models normally fit into this category.

The **saltationist** complexity has in the writings of John Stuart Mill[10] its beginnings. There would be essentially two types of laws: homopathic, in which the classic reductionism is possible; or heteropathic, in which the concept of composition of causes is not possible. Its two main arguments are that: emergent phenomena are not explained by its generating elements; and they possess its own causal power. The former is related to a negation of both methodological and epistemological reductionisms: new elements cannot be fully understood by the tools used to analyze its generating elements and either by the generating elements themselves. In relation to the second argument it is related to downward causation.

Lastly, **structuralist** complexity understands that the composition of the parts or modules of a systems are as important as how they are related. There are relational properties among the constituting elements of a systems, including opposing relations (trade-offs). According to Prado (2009), the debate among the two former complexities brought the debate to an ontological level, exceeding the scope of this work.

[10]Mill (1882/[2009])

Appendix B

Further topics on the ABM

Data is gathered at the end of each period (month) of the simulation after 6 years (72 periods) of simulation. Every observed data is then agent specific and time specific[1] Data is gathered from every object of the simulation as following:

Technology provider

- Effort (*number* $\in [0, 1]$) How much of firm's profits will be reinvested into either R&D or local productive capacity. In the model: *decision_var*;
- Satisficing score ($\$ \in \mathbb{R}$): what are the current firm profits regarding a specific time. In the model: *profits*;
- Available Resources (*number* $\in \mathbb{R}$): How much money does the entity have at the current period that is available for the entity to perform its operations? In the model: *wallet*;
- Adaptations (*number* $\in \mathbb{N}$): How many times has the firm adapted as a result from the Evaluative criteria submodel. In the model: *LSS_tot*;
- Changes to effort (*number* $\in \mathbb{N}$): What is the degree of change of effort as a result from the Decision submodel. In the model: *LSS_weak*;
- Impatience (*number* $\in \mathbb{N}^*$): In the Evaluative criteria submodel, how many times will the adaptation check be ran. In the model: *impatience*;

[1]For example, a certain agent i at a certain period t has a specific $adaptations_{i,t}$

- Aversion to change ($\% \in [0,1]$): What is the aversion to change that is used in the Decision submodel for that firm. In the model: *past_weight*;
- Dividends ($number \in \mathbb{R}^*_+$): How much of firm's profits were distributed to shareholders. In the model: *dividend*;
- Aversion to adaptation ($\% \in [0,1]$) What is the aversion to adapting that is used in the Evaluative Criteria submodel. In the model: *LSS_thresh*.
- Source ($Text$): What is the source of the technology that the technology provider possesses? In the model: *source*;
- Discount factor ($\% \in [0,1]$): what is the discount factor used by the entity? In the model: *discount*;
- Memory ($number \in \mathbb{N}$): How far back does the entity look back in the Evaluative Criteria and Decision submodels? In the model: *memory*;
- Verdict ($Text$): regarding adaptation, will the agent *change* a part of its decision-making structure or *keep* it as it? In the model: *verdict*;
- Strategy ($text$): Will the technology provider attempt to reinvest into *R&D* or into *local productive capacity*? In the model *strategy*;
- Local productive capacity expenditure ($\$ \in \mathbb{R}$): how much has the firm reinvested into local productive capacity. In the model: *capacity*;
- Capacity threshold ($number \in \mathbb{R}*_+$) How much does the local productive capacity have to for the CAPEX to be decreased. In the model: *capacity_thresh*;
- Technology ($Object$). The technology of the firm. One firm has only one technology and it changes with innovation and reinvestment into local productive capacity according to the reinvestment and innovation submodels. In the model: *technology*;
- R&D expenditure ($\$ \in \mathbb{R}$): how much has the firm reinvested into R&D. In the model: *RandD*
- Innovation index ($number \in \mathbb{R}_+$): What were the results from the innovation equation from the innovation submodel for that company. In the model: *innovation_index*;

- Ratio of reinvestment ($\% \in \mathbb{R}$): How much has the company reinvested into R&D. It can be above one in scenarios in which a firm has low profits and there are high incentives from the Technology Policy Maker. In the model: PCT;

Technology

- Technology provider ($text$): What is the technology provider that owns that power plant. In the model: *TP*;
- Source ($Text$): What is the source of this specific technology? In the model: *source*
- Renewable ($Boolean$): Is the technology renewable ($True$) or fossil based ($False$). In other words, does the use of that technology produce GHG? In the code: *green*;
- Dispatchable ($Boolean$): Is the electricity production of the asset intermittent ($False$) or dispatchable ($True$). In the code: *dispatchable*;
- Capacity factor ($\% \in [0,1]$): What is the percentage of the actual MWh produced over the potential. In the code: *CF*;
- Transportable ($Boolean$): Can that technology be transported across large distances? In other words, can it be shipped internationally[2]? In the code: *transport*;
- Lump of investment ($MW \in \mathbb{R}^*_+$): what is the lump investment for one unit of asset (turbine, generator, panel) of that technology. In the code: *lump*;
- Base CAPEX ($\$ \in \mathbb{R}^*_+$). what is the CAPEX of one lump investment of an asset that uses this technology without the effect of the reinvestment into local productive capacity. In the code: $base\_CAPEX$;
- CAPEX ($\$ \in \mathbb{R}^*_+$): what is the actual CAPEX of one lump investment of an asset that uses this technology? In the code: $CAPEX$;
- OPEX ($\$ \in \mathbb{R}^*_+$):what is the OPEX of one lump investment of an asset that uses this technology? In the code: $OPEX$;

[2]That difference, for example, is crucial to understand the contrast between solar PV, which can be produced centrally and shipped internationally, and wind, which has significant transportation costs that rise significantly which the increase in distance (HUENTELER et al., 2016).

- Emissions (*number* $\in \mathbb{R}_+^*$): how much does one asset of that technology emit[3]. In the code: *emissions*;
- Avoided emissions (*number* $\in \mathbb{R}_+^*$): how much does one asset of that technology avoid in terms of emissions. In the code: *avoided_emissions*;
- Last radical innovation (*number* $\in \mathbb{N}$): the last period in which that technology experienced a radical innovation[4]. In the model: *last_radical_innovation*;
- Last marginal innovation (*number* $\in \mathbb{N}$): the last period in which that technology experienced a marginal innovation. In the model: *last_marginal_innovation*;
- Lifetime (*number* $\in \mathbb{N}$): For how many months will a power plant using that technology stand and be able to produce electricity before being decommissioned. In the model: *lifetime*;
- Building time (*number* $\in \mathbb{N}$): how many months does it take for one power plant of that technology to be built and start operating[5]. In the model: *building_time*;

Energy producer

- Effort (*number* $\in [0, 1]$) How much will the firm attempt to expand its portfolio of plants: *decision_var*;
- Satisficing score ($\$ \in \mathbb{R}$): what are the current firm profits regarding a specific time. In the model: *profits*;
- Available Resources (*number* $\in \mathbb{R}$): How much money does the entity have at the current period that is available for the entity to perform its operations? In the model: *wallet*;
- Adaptations (*number* $\in \mathbb{N}$): How many times has the firm adapted as a result from the Evaluative criteria submodel. In the model: *LSS_tot*;

[3]We use the emissions from one fossil power plant with the initial values for natural gas as standard (base index 100)

[4]The threshold between radical and marginal innovation is exogenous in the model.

[5]We suppose that all lump investments of are concluded at the same time, i.e., the plant does not have parts of it that start producing electricity earlier than other parts.

- Changes to effort (*number* $\in \mathbb{N}$): What is the degree of change of effort as a result from the Decision submodel. In the model: *LSS_weak*;
- Impatience (*number* $\in \mathbb{N}^*$): In the Evaluative criteria submodel, how many times will the adaptation check be ran. In the model: *impatience*;
- Aversion to change ($\% \in [0, 1]$): What is the aversion to change that is used in the Decision submodel for that firm. In the model: *past_weight*;
- Dividends (*number* $\in \mathbb{R}^*_+$): How much of firm's profits were distributed to shareholders. In the model: *shareholder_value*;
- Aversion to adaptation ($\% \in [0, 1]$) What is the aversion to adapting that is used in the Evaluative Criteria submodel. In the model: *LSS_thresh*.
- Source (*Text*): What is the main source that the Energy producer considers? In the model: *source*;
- Discount factor ($\% \in [0, 1]$): what is the discount factor used by the entity? In the model: *discount*;
- Memory (*number* $\in \mathbb{N}$): How far back does the entity look back in the Evaluative Criteria and Decision submodels? In the model: *memory*;
- Verdict (*Text*): regarding adaptation, will the agent *change* a part of its decision-making structure or *keep* it as it? In the model: *verdict*;
- Portfolio of plants (*List*): A list of objects containing that plants that are being constructed or built. In the model: *portfolio_of_plants*;
- Portfolio of projects (*List*): A list of objects containing that plants that the Energy producer is attempting to finance. In the model: *portfolio_of_projects*;
- Periodicity (*number* $\in \mathbb{N}$): after how many periods will the Energy producer be active, i.e., attempt an expansion of its portfolio and analyze what occurred in the system. In the model: *periodicity*;
- Tolerance (*number* $\in \mathbb{N}$): for how many periods will an Energy producer attempt to finance its project? In the model: *tolerance*;

Power plant

- Energy producer (*text*): What is the energy producer that owns that power plant. In the model: *EP*;
- Technology (*Object*): What is the technology used. The Power plant inherites most characteristics from it. In the model: *Technology*;
- Lumps ($number \in \mathbb{N}^*$): Lumps of investment present in that power plant. In the model: *Lumps*;
- CAPEX ($number \in \mathbb{R}_+^*$): CAPEX of the power plant, i.e., CAPEX of the technology multiplied by the number of lumps. In the model: $CAPEX$;
- OPEX ($number \in \mathbb{R}_+^*$): OPEX of the power plant, i.e., OPEX of the technology multiplied by the number of lumps. In the model: $OPEX$;
- Financed (*text*): Who financed the plant, may either be "DBB" for the Development Bank of "Reinvestment" when it was a reinvestment decision. In the model: BB;
- Principal ($number \in \mathbb{R}_+^*$): What is the principal of the power plant in a certain time. If the plant is an reinvestment it is zero. In the model: *principal*;
- Interest rate ($\%in[0, 1]$): What is the interest rate of the financing. If the plant is an reinvestment it is zero. In the model: r;
- Amortization period ($number \in \mathbb{N}^*$): Until which period may the plant be amortized. In the model: *amortization*;
- Period of acquisition ($number \in \mathbb{N}^*$): In which period was the plant contracted. In the model: *period*;
- Capacity ($number \in \mathbb{R}_+^*$): Number of MW of the power plant. In the model: *capacity*;
- Generation ($number \in \mathbb{R}_+^*$): Number of MWh per month of the power plant. In the model: MWh;
- Price ($number \in \mathbb{R}_+$): Price at which the plant is bidded to the commercialization chamber. In the model: *price*;

- Retirement (*number* $\in \mathbb{N}^*$): In which period will the plant be decommissioned. In the model: *retirement*;
- Status (*text*): Is the plant a *project*, is the plant being built (*building*), is the plant built but not contracted (*built*), is the plant built and contracted (*contracted*) or is the plant decommissioned (*retired*).

Technology Policy Maker

- Effort (*number* $\in [0, 1]$) How much of its available resources will be used for incentives: *decision_var*;
- Satisficing score ($\$ \in \mathbb{R}$): what is the current state of the system. Depending on the rationale of the policy maker, the satisficing score may be in relation to avoided emissions, investment in local productive capacity or investment in R&D. In the model: *current_state*;
- Available Resources (*number* $\in \mathbb{R}$): How much money does the entity have at the current period that is available for the entity to perform its operations? In the model: *wallet*;
- Adaptations (*number* $\in \mathbb{N}$): How many times has the policy maker adapted as a result from the Evaluative criteria submodel. In the model: *LSS_tot*;
- Changes to effort (*number* $\in \mathbb{N}$): What is the degree of change of effort as a result from the Decision submodel. In the model: *LSS_weak*;
- Impatience (*number* $\in \mathbb{N}^*$): In the Evaluative criteria submodel, how many times will the adaptation check be ran. In the model: *impatience*;
- Aversion to change ($\% \in [0, 1]$): What is the aversion to change that is used in the Decision submodel for that policy maker. In the model: *past_weight*;
- Aversion to adaptation ($\% \in [0, 1]$) What is the aversion to adapting that is used in the Evaluative Criteria submodel. In the model: *LSS_thresh*.
- Source ($Text$): What is the incentivized source? In the model: *source*;

- Discount factor ($\% \in [0,1]$): what is the discount factor used by the entity? In the model: *discount*;

- Memory ($number \in \mathbb{N}$): How far back does the entity look back in the Evaluative Criteria and Decision submodels? In the model: *memory*;

- Verdict ($Text$): regarding adaptation, will the agent *change* a part of its decision-making structure or *keep* it as it? In the model: *verdict*;

- Memory ($number \in \mathbb{N}$): How far back does the entity look back in the Evaluative Criteria and Decision submodels? In the model: *memory*;

- Threshold to disclose changes ($\% \in [0,1]$): What is the change in effort that is necessary for that change to be disclosed. In the model: *disclosed_thresh*;

- Rationale ($text$): What is the rationale behind the policy maker's policy. In can be either to foster the entry of renewables (*green* in the model), to foster the innovation related to renewables (*innovation* in the model) or to foster an internalization of parts of the productive chain related to renewables (*capacity* in the model).

- Periodicity ($number \in \mathbb{N}$): after how many periods will the policy maker be active, i.e., give out incentives and analyze what occurred in the system. In the model: *periodicity*;

Energy Policy Maker

- Effort ($number \in [0,1]$): Similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;

- Satisficing score ($\$ \in \mathbb{R}$): Similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;

- Available Resources ($number \in \mathbb{R}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;

- Adaptations ($number \in \mathbb{N}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;

- Changes to effort ($number \in \mathbb{N}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Impatience ($number \in \mathbb{N}^*$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Aversion to change ($\% \in [0,1]$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Aversion to adaptation ($\% \in [0,1]$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Source ($Text$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Discount factor ($\% \in [0,1]$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Memory ($number \in \mathbb{N}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Verdict ($Text$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Memory ($number \in \mathbb{N}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Threshold to disclose changes ($\% \in [0,1]$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Rationale ($text$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Periodicity ($number \in \mathbb{N}*$): similar to the same observed data from the Technology Policy Maker, only in relation to the Energy Policy Maker and its variables;
- Time limit for energy producers to insert their projects into the mix ($number \in \mathbb{N}*$): . In the model: PPA_limit;

Development Bank

- Effort ($number \in [0, 1]$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Satisficing score ($\$ \in \mathbb{R}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Available Resources ($number \in \mathbb{R}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Adaptations ($number \in \mathbb{N}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Changes to effort ($number \in \mathbb{N}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Impatience ($number \in \mathbb{N}^*$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Aversion to change ($\% \in [0, 1]$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Aversion to adaptation ($\% \in [0, 1]$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Source ($Text$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Discount factor ($\% \in [0, 1]$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Memory ($number \in \mathbb{N}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Verdict ($Text$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables
- Memory ($number \in \mathbb{N}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables

- Threshold to disclose changes ($\% \in [0,1]$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables

- Rationale (*text*): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables

- Periodicity ($number \in \mathbb{N}$): similar to the same observed data from the Technology Policy Maker, only in relation to the Development Bank and its variables

- Interest rate ($\% \in \mathbb{R}_+$): what is the interest rate used by the development bank to finance renewable projects. In the model: *interest_rate*

- Accredited firms (list of names): what are the firms accredited by the development bank following both its rationale and effort. In the model: *list_of_tps*;

- Receivables ($number \in \mathbb{R}^*_+$): what are the receivables that the development bank is schedule to receive in the future due to its projects. In the model: *receivables*

Commercialization Chamber

- Initial demand ($MW \in \mathbb{R}^*_+$): the initial demand, in MW, of the electric system. In the code: *initial_demand*;

- Demand increase ($\% \in \mathbb{Z}^*_+$): how much larger in relation to the current demand the new demand will be for the system. In the code: *increase*;

- Increase period (($number \in \mathbb{N}^*_+$)): after how many periods will there be an increase in demand. In the code: *when*;

- Remaining demand ($MWh \in \mathbb{R}$): How much of the demand is left to be supplied (if above zero) or there is of excess supply (if below zero). In the code *remaining_demand*;

- Price ($\$ \in \mathbb{N}$): price of system, given by the most costly unit contracted following the merit order. In the code *price*;

- Total Demand ($MWh \in \mathbb{R}^*_+$): Total demand of the system in MWh. It is given by the initial demand (in MW) with any additional increment multiplied by 24 (hours in the day) and 30 (days in the month). In the code: *demand*;

- Risk (List of numbers $\subset \mathbb{R}_+$): What is the assessed risk for each source? It is given by the ratio between the minimum price over the current market price for one MWh. In the code: *risks*;

Coordination Entity

- Coordination approach (*text*): Does the coordination entity coordinates policy makers towards *fostering* heterogeneity or towards *reducing* heterogeneity among them? In the code: *heterogeneity*;

- Coordination threshold ($number \in [0, 1[$): What is the accepted degree for heterogeneity? If above (reducing heterogeneity approach) or below (fostering heterogeneity approach) then the coordination submodel is activated. In the code: *degree*;

- Coordination attempts ($number \in \mathbb{N}$): How many times was coordination necessary because the ratio of different traits was above (if the coordination entity is aiming to control heterogeneity) or below (if the coordination entity is aiming to foster heterogeneity). In the model: *coordinations*.

Appendix C

Further experiment topics

We also have the following tables for the scores of elements per scenario:

SCENARIO	Value			Velocity			Acceleration		
	Q1	median	Q3	Q1	median	Q3	Q1	median	Q3
Baseline	0.014	0.042	0.062	0.114	0.136	0.092	0.980	0.959	0.116
Tech	0.012	0.041	0.062	0.096	0.134	0.100	0.971	1.000	0.157
Energy	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.861	0.000
Bank	1.000	1.000	1.000	0.710	0.774	0.938	0.115	0.133	0.528
0	0.841	0.918	0.993	1.000	1.000	0.920	0.154	0.043	0.712
0.25	0.814	0.912	0.968	0.963	0.979	1.000	0.000	0.000	0.776
0.5	0.813	0.905	0.951	0.819	0.984	0.936	0.195	0.356	0.661
0.75	0.835	0.928	0.964	0.934	0.968	0.993	0.109	0.255	1.000
1	0.800	0.909	0.948	0.837	0.919	0.969	0.338	0.284	0.643

Table C.1: First quarter, median and third quarter for value, velocity and acceleration per scenario regarding the adoption element. Source: own elaboration.

SCENARIO	Value			Velocity			Acceleration		
	Q1	median	Q3	Q1	median	Q3	Q1	median	Q3
Baseline	0.879	0.826	0.570	1.000	1.000	1.000	0.732	0.906	0.408
Tech	1.000	0.976	0.788	0.701	0.803	0.554	1.000	0.725	0.043
Energy	0.000	0.000	0.000	0.236	0.472	0.499	0.972	0.323	0.283
Bank	0.255	0.375	0.453	0.000	0.056	0.102	0.427	1.000	1.000
0	0.547	0.659	0.676	0.096	0.081	0.000	0.978	0.782	0.390
0.25	0.718	0.867	0.915	0.203	0.000	0.123	0.224	0.583	0.387
0.5	0.669	0.796	0.810	0.106	0.109	0.100	0.417	0.701	0.893
0.75	0.854	1.000	1.000	0.303	0.173	0.179	0.281	0.000	0.000
1	0.789	0.942	0.984	0.124	0.024	0.053	0.000	0.645	0.048

Table C.2: First quarter, median and third quarter for value, velocity and acceleration per scenario regarding the CAPEX element. Source: own elaboration.

As further experiments we have:

SCENARIO	Value			Velocity			Acceleration		
	Q1	median	Q3	Q1	median	Q3	Q1	median	Q3
Baseline	0.698	1.000	1.000	0.670	0.946	1.000	0.000	0.065	0.475
Tech	0.826	0.981	0.917	0.634	0.753	0.575	0.606	0.404	0.474
Energy	0.000	0.000	0.000	1.000	1.000	0.374	1.000	1.000	1.000
Bank	0.435	0.378	0.087	0.217	0.258	0.120	0.674	0.458	0.522
0	0.542	0.405	0.080	0.091	0.064	0.000	0.679	0.279	0.302
0.25	0.830	0.819	0.534	0.023	0.000	0.309	0.311	0.532	0.460
0.5	0.874	0.856	0.564	0.000	0.071	0.243	0.316	0.000	0.213
0.75	0.949	0.894	0.646	0.094	0.028	0.184	0.693	0.112	0.101
1	1.000	0.986	0.733	0.103	0.018	0.212	0.640	0.235	0.000

Table C.3: First quarter, median and third quarter for value, velocity and acceleration per scenario regarding the innovation element. Source: own elaboration.

SCENARIO	Value			Velocity			Acceleration		
	Q1	median	Q3	Q1	median	Q3	Q1	median	Q3
Baseline	0.012	0.034	0.054	0.108	0.148	0.108	0.945	1.000	0.237
Tech	0.119	0.192	0.262	0.612	0.558	0.344	0.912	0.995	0.257
Energy	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.933	0.000
Bank	1.000	1.000	1.000	0.627	0.651	0.767	0.088	0.556	0.967
0	0.784	0.871	0.936	0.933	0.959	0.963	0.087	0.000	0.556
0.25	0.810	0.891	0.961	0.963	1.000	0.953	0.000	0.261	1.000
0.5	0.809	0.889	0.945	1.000	0.881	1.000	0.308	0.453	0.682
0.75	0.786	0.814	0.857	0.870	0.777	0.697	0.218	0.283	0.593
1	0.813	0.862	0.881	0.695	0.606	0.866	0.327	0.423	0.357

Table C.4: First quarter, median and third quarter for value, velocity and acceleration per scenario regarding the internalization element. Source: own elaboration.

SCENARIO	Value			Velocity			Acceleration		
	Q1	median	Q3	Q1	median	Q3	Q1	median	Q3
Baseline	0.886	0.795	0.638	1.000	1.000	1.000	1.000	0.000	0.000
Tech	1.000	1.000	0.891	0.706	0.765	0.483	0.559	1.000	0.481
Energy	0.000	0.000	0.000	0.305	0.528	0.633	0.883	0.946	0.560
Bank	0.255	0.319	0.427	0.000	0.103	0.118	0.340	0.432	1.000
0	0.560	0.658	0.677	0.245	0.137	0.056	0.387	0.879	0.868
0.25	0.714	0.795	0.843	0.210	0.226	0.133	0.045	0.037	0.854
0.5	0.862	0.966	1.000	0.368	0.000	0.000	0.000	0.588	0.939
0.75	0.770	0.853	0.874	0.381	0.260	0.151	0.439	0.780	0.269
1	0.790	0.887	0.933	0.081	0.138	0.090	0.301	0.680	0.818

Table C.5: First quarter, median and third quarter for value, velocity and acceleration per scenario regarding the OPEX element. Source: own elaboration.

SCENARIO	Value Q1	Value median	Value Q3	Velocity Q1	Velocity median	Velocity Q3	Acceleration Q1	Acceleration median	Acceleration Q3
Baseline	0.187	0.192	0.231	0.257	0.241	0.247	1.000	0.659	0.117
Tech	0.208	0.230	0.249	0.295	0.278	0.316	0.711	0.674	0.554
Energy	0.000	0.000	0.000	0.000	0.000	0.000	0.474	1.000	0.626
Bank	0.726	0.797	0.831	0.865	0.841	0.836	0.602	0.834	0.049
0	0.912	0.958	0.983	0.998	1.000	0.999	0.616	0.000	0.359
0.25	0.911	0.957	0.971	1.000	0.970	0.972	0.349	0.220	0.350
0.5	0.929	0.929	0.952	0.956	0.971	0.967	0.303	0.578	0.534
0.75	0.796	0.859	0.882	0.940	0.974	0.968	0.000	0.230	1.000
1	1.000	1.000	1.000	0.993	0.998	1.000	0.609	0.905	0.000

Table C.6: First quarter, median and third quarter for value, velocity and acceleration per scenario regarding the private effort element. Source: own elaboration.

SCENARIO	Value Q1	Value median	Value Q3	Velocity Q1	Velocity median	Velocity Q3	Acceleration Q1	Acceleration median	Acceleration Q3
Baseline	0.149	0.387	0.577	1.000	1.000	0.781	0.918	0.215	0.128
Tech	0.153	0.401	0.573	0.981	0.998	0.761	0.909	0.000	0.142
Energy	0.000	0.000	0.000	0.768	0.345	0.000	1.000	0.003	0.000
Bank	0.888	0.923	1.000	0.000	0.000	0.910	0.000	1.000	1.000
0	0.893	0.917	0.846	0.367	0.336	0.857	0.150	0.746	0.910
0.25	0.942	0.997	0.930	0.342	0.557	1.000	0.208	0.362	0.901
0.5	1.000	0.995	0.912	0.467	0.558	0.824	0.286	0.737	0.714
0.75	1.000	1.000	0.909	0.378	0.433	0.841	0.286	0.542	0.819
1	0.933	0.924	0.872	0.443	0.522	0.921	0.322	0.227	0.810

Table C.7: First quarter, median and third quarter for value, velocity and acceleration per scenario regarding the private score element. Source: own elaboration.

SCENARIO	Value Q1	Value median	Value Q3	Velocity Q1	Velocity median	Velocity Q3	Acceleration Q1	Acceleration median	Acceleration Q3
Baseline	*	*	*	*	*	*	*	*	*
Tech	0.760	0.729	0.727	0.384	0.466	0.455	0.186	0.369	1.000
Energy	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.984
Bank	0.715	0.870	0.908	0.836	1.000	1.000	0.242	1.000	0.960
0	1.000	0.976	0.964	0.832	0.793	0.660	1.000	0.572	0.041
0.25	0.913	1.000	1.000	0.941	0.898	0.770	0.983	0.590	0.037
0.5	0.820	0.912	0.949	0.951	0.967	0.852	0.974	0.769	0.155
0.75	0.919	0.966	0.965	0.928	0.916	0.826	0.875	0.180	0.087
1	0.850	0.911	0.938	1.000	0.927	0.819	0.971	0.284	0.000

Table C.8: First quarter, median and third quarter for value, velocity and acceleration per scenario regarding the public effort element. Source: own elaboration.

SCENARIO	Value Q1	Value median	Value Q3	Velocity Q1	Velocity median	Velocity Q3	Acceleration Q1	Acceleration median	Acceleration Q3
Baseline	*	*	*	*	*	*	*	*	*
Tech	0.250	0.339	0.427	0.986	0.813	0.497	0.937	1.000	0.331
Energy	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.901	0.000
Bank	1.000	1.000	0.958	0.487	0.669	1.000	0.000	0.184	1.000
0	0.838	0.884	0.916	1.000	1.000	0.915	0.254	0.000	0.731
0.25	0.791	0.819	0.851	0.904	0.942	0.818	0.403	0.256	0.759
0.5	0.824	0.845	0.854	0.777	0.808	0.897	0.441	0.314	0.627
0.75	0.880	0.860	0.872	0.753	0.805	0.739	0.466	0.185	0.595
1	0.983	0.991	1.000	0.941	0.997	0.910	0.360	0.135	0.553

Table C.9: First quarter, median and third quarter for value, velocity and acceleration per scenario regarding the public score element. Source: own elaboration.

1. **0.00:** The aim of this test is to check how much different scenarios are from the scenario 0.00. We analyze if the trajectory of elements are different between the 0.00 scenario and all the other scenarios. Since there are eight scenarios to compare, with seven to nine elements under three vectors analyzed with a variation of either month-on-month, year-on-year or every four years, each scenario is compared with 63 (no policy scenario) or 81 (all other scenarios) tests, which means 630 tests in total. We check how different one scenario is from the one it is being compared to in a similar fashion as the previous experiment, by the percentage of tests that rejected the null hypothesis over the total tests performed in the comparison. To be more specific, what we test is that, for the same element, for the same vector, for the same time frame, are the trajectories from the 0.00 scenario and from another scenario likely drawn from the same distribution or not;

2. **Deviation:** The aim of this test is to analyze how different scenarios are from each other regarding the trajectory of deviation of elements. We analyze if the trajectory of standard deviation, median absolute deviation and interquartile range of elements are different between every possible pair of scenarios. Since there are three deviations measures for nine scenarios to compare, with seven to nine elements under three vectors analyzed with a variation of either month-on-month, year-on-year or every four years, each scenario is compared with 63 (no policy scenario) or 81 (all other scenarios) tests, which means 1848 tests in total. We check how different one scenario is from the one it is being compared to in a similar fashion as the previous experiment, by the percentage of tests that rejected the null hypothesis

over the total tests performed in the comparison. To be more specific, what we test is that, for the same element, for the same vector, for the same time frame, are the trajectories from the scenario and from another scenario likely drawn from the same distribution or not;

3. **Elements:** The aim of this test is to check if there are some elements that appear to follow similar trajectories. Since there are nine elements to compare, in nine scenarios under three vectors analyzed with a variation of either month-on-month, year-on-year or every four years, each element is compared to another element with 576 or 630 tests, which means 5562 tests in total. To be more specific, what we test is that, for the same vector, for the same degree, for the same approach, for the same number of policy makers, for the same time frame, we test if the trajectories of different elements are likely drawn from the same distribution or not. This test serves to indicate the possibility of co-evolution between trajectories, not between the elements themselves. This test also does not aim to indicate that two elements do not have any co-evolution among them[1].

4. **Time:** for the same element, for the same vector, for the same degree, for the same approach, for the same number of policy makers, we test if the dynamics of different time frames are likely drawn from the same distribution or not. The aim of this experiment is to check if dynamics change based on the time frame used or not.

5. **Vectors:** for the same element, for the same degree, for the same approach, for the same number of policy makers, for the same time frame, we test if the dynamics of different vectors are likely drawn from the same distribution or not. The aim of this experiment is to check if the dynamics of vectors are distinct enough from one another.

C.1 0.00 experiment

In this experiment we test the non-normalized trajectories of elements comparing each scenario to the scenario with three policy makers without the council entity, i.e., our 0.00 scenario. Table C.10 aggregates experiment results' by elements. It is interesting

[1]As a future research we shall do a co-integration tests between those series. As such, this experiment may be interpreted as a preliminary test, at best.

to notice that all but two elements, private score and private effort, have an index above one, meaning that they all have a share of the rejected tests above their share of total tests.

ELEMENT	Total	5% p-value below	5% p-value Ratio	Share tests	Share below	Share index
public_score	63	55	87.30%	10.00%	11.75%	1.1752
CAPEX	72	62	86.11%	11.43%	13.25%	1.1592
innovation	72	60	83.33%	11.43%	12.82%	1.1218
internalization	72	59	81.94%	11.43%	12.61%	1.1031
adoption	72	58	80.56%	11.43%	12.39%	1.0844
OPEX	72	58	80.56%	11.43%	12.39%	1.0844
public_effort	63	47	74.60%	10.00%	10.04%	1.0043
private_score	72	35	48.61%	11.43%	7.48%	0.6544
private_effort	72	34	47.22%	11.43%	7.26%	0.6357
Mean	70.00	52.00	0.745	0.111	0.111	1.002
Median	72.00	58.00	0.806	0.114	0.124	1.084
Std	3.969	10.794	0.155	0.006	0.023	0.209
MAD	0.000	3.000	0.056	0.000	0.006	0.075

Table C.10: Tests below p-value, total number of tests, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the 0.00 scenario aggregated by element at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

Table C.11 aggregates experiment results' by scenario. The scenario without policy maker is the one that is the most different from the 0.00 scenario, rejecting 95.24% of its tests, or, in index terms, having a share of rejected tests 28.21% above its share of total tests. Then, the scenarios with just energy policy maker and technology policy maker are relatively close, rejecting 95.06% and 93.83% of their tests. All scenarios with three policy makers and a council entity reject between 61.73% and 59.26%, all having a percentage of rejected tests below their share of total tests. The scenario with just a development bank is between those two types of scenarios, rejecting 74.07% of its tests.

Table C.12 depicts various aggregations of experiment results'. Aggregating by presence of council, the 0.00 scenario is more similar to scenarios with the council than to scenarios without the council, being those two entries 29.1 p.p. apart from each other. Aggregating by number of policy makers we are able to remove the scenario without policy makers from last aggregation, and by doing so, we see that scenarios with just one policy maker are 87.65% different from the 0.00 scenario. Once again, aggregating by time frame

SCENARIO	Total	5% p-value below	Ratio	tests	Share below	index
Baseline	63	60	95.24%	10.00%	12.82%	1.2821
Energy	81	77	95.06%	12.86%	16.45%	1.2797
Tech	81	76	93.83%	12.86%	16.24%	1.2631
Bank	81	60	74.07%	12.86%	12.82%	0.9972
0.75	81	50	61.73%	12.86%	10.68%	0.8310
0.25	81	49	60.49%	12.86%	10.47%	0.8143
0.50	81	48	59.26%	12.86%	10.26%	0.7977
1.00	81	48	59.26%	12.86%	10.26%	0.7977
Mean	78.75	58.50	0.749	0.125	0.125	1.008
Median	81.00	55.00	0.679	0.129	0.118	0.914
Std	6.364	12.17	0.171	0.010	0.026	0.230
MAD	0.000	6.500	0.086	0.000	0.014	0.116

Table C.11: Tests below p-value, total number of tests, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the 0.00 scenario aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

we see that, the larger the time frame used, the more prominent are differences between scenarios. In terms of vectors, velocity and growth show more prominently the differences between scenarios.

Table C.13 attempts to rank the aggregations by median absolute deviation. The aggregation by scenario is the one with largest median absolute deviation, being followed by the aggregations by council and number.

C.2 Deviation experiment

In this experiment we test the non-normalized trajectories of the deviations of elements: standard deviation, median absolute deviation and interquartile range. Those three measures measure variability and, their trajectory captures different aspects of variability of each element in each scenario for each vector regarding time. For example, the trajectory of standard deviation of public scores in the 0.00 scenario captures, per period, the standard deviation between different runs of the 0.00 scenario regarding just the public score. Standard deviation and median absolute deviation capture deviation from mean and median, respectively, with the latter being less sensitive to outliers and more well suited for smaller samples. Interquartile range captures the distance between

		Total	5% p-value below	Ratio	Share tests	below	index
COUNCIL	**False**	306	273	89.22%	48.57%	58.33%	1.2010
	True	324	195	60.19%	51.43%	41.67%	0.8102
NUMBER	**0**	63	60	95.24%	10.00%	12.82%	1.2821
	1	243	213	87.65%	38.57%	45.51%	1.1800
	3	324	195	60.19%	51.43%	41.67%	0.8102
TIME	**48**	210	191	90.95%	33.33%	40.81%	1.2244
	12	210	157	74.76%	33.33%	33.55%	1.0064
	1	210	120	57.14%	33.33%	25.64%	0.7692
VECTOR	**velocity**	210	181	86.19%	33.33%	38.68%	1.1603
	growth	210	169	80.48%	33.33%	36.11%	1.0833
	acceleration	210	118	56.19%	33.33%	25.21%	0.7564

Table C.12: Tests below p-value, total number of tests, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests against the 0.00 scenario aggregated by presence of council, number of policy makers, time frame and vectors at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

AGGREGATION	MAD
scenario	0.1994
council	0.1954
number	0.1180
time	0.1138
vector	0.1010
element	0.0775

Table C.13: Median absolute deviation of indexes per aggregation in the 0.00 experiment.

the 75th and the 25th quartile of the distribution, leaving out most of outliers in most cases. As such, standard deviation and median absolute deviations captures how distant the distribution is from the mean and median respectively, and the interquartile range captures how spread out the distribution is for 50% of the distribution around the median.

ELEMENT	Total	5% p-value		Share		
		below	Ratio	tests	below	index
CAPEX	288	288	100%	11.69%	12.72%	1.0883
OPEX	288	288	100%	11.69%	12.72%	1.0883
public_score	224	224	100%	9.09%	9.89%	1.0883
innovation	288	286	99.31%	11.69%	12.63%	1.0808
internalization	288	282	97.92%	11.69%	12.46%	1.0657
adoption	288	282	97.92%	11.69%	12.46%	1.0657
public_effort	224	206	91.96%	9.09%	9.10%	1.0009
private_score	288	228	79.17%	11.69%	10.07%	0.8616
private_effort	288	180	62.50%	11.69%	7.95%	0.6802
Mean	273.8	251.6	0.921	0.111	0.111	1.002
Median	288.0	282.0	0.979	0.117	0.125	1.066
Std	28.22	42.14	0.130	0.011	0.019	0.141
MAD	0.000	6.00	0.021	0.000	0.003	0.023

Table C.14: Tests below p-value, total number of tests, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of scenarios regarding standard deviation, interquartile range, quartile coefficient of dispersion and median absolute deviation aggregated by element at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

C.3 Similar trajectory experiment

In this experiment we test the normalized trajectories of different elements in scenarios. We test if two elements, in the same scenario, share a similar trajectory, i.e, if those two trajectories do not reject Kolmogorov-Smirnov test's null hypothesis. If the null hypothesis is not rejected, then it is not unlikely that the trajectory of the two elements are drawn from the same distribution. In this sense, two elements then have a similar trajectory.

SCENARIO	Total	5% p-value below	Ratio	tests	Share below	index
Energy	210	201	95.71%	11.36%	11.88%	1.0454
Tech	210	198	94.29%	11.36%	11.70%	1.0298
Baseline	168	157	93.45%	9.09%	9.28%	1.0207
Bank	210	192	91.43%	11.36%	11.35%	0.9986
0.25	210	191	90.95%	11.36%	11.29%	0.9934
0.50	210	190	90.48%	11.36%	11.23%	0.9882
1.00	210	190	90.48%	11.36%	11.23%	0.9882
0.00	210	187	89.05%	11.36%	11.05%	0.9726
0.75	210	186	88.57%	11.36%	10.99%	0.9674
Mean	273.8	251.6	0.919	0.111	0.111	1.001
Median	280.0	254.0	0.911	0.114	0.112	0.991
Std	18.67	16.05	0.024	0.008	0.007	0.026
MAD	0.000	3.000	0.014	0.000	0.001	0.016

Table C.15: Tests below p-value, total number of tests, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of scenarios regarding standard deviation, interquartile range, quartile coefficient of dispersion and median absolute deviation aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

MEASUREMENT	Total	5% p-value below	Ratio	tests	Share below	index
IQR	616	572	92.86%	25.00%	25.27%	1.0106
QCP	616	572	92.86%	25.00%	25.27%	1.0106
MAD	616	566	91.88%	25.00%	25.00%	1.0000
STD	616	554	89.94%	25.00%	24.47%	0.9788
Mean	616.0	566.0	0.919	0.250	0.250	1.000
Median	616.0	569.0	0.924	0.250	0.251	1.005
Std	0.000	8.485	0.014	0.000	0.004	0.015
MAD	0.000	3.000	0.005	0.000	0.001	0.005

Table C.16: Total number of tests, tests below p-value, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of scenarios regarding standard deviation, interquartile range, quartile coefficient of dispersion and median absolute deviation aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

SCENARIO	Baseline	Tech	Energy	Bank	0.00	0.25	0.50	0.75	1.00
Baseline	0%	78.57%	78.57%	100%	100%	100%	100%	100%	100%
Tech	78.57%	0%	88.89%	94.44%	94.44%	97.22%	97.22%	97.22%	97.22%
Energy	78.57%	88.89%	0%	100%	100%	100%	100%	100%	100%
Bank	100%	94.44%	100%	0%	86.11%	86.11%	88.89%	88.89%	88.89%
0.00	100%	94.44%	100%	86.11%	0%	83.33%	83.33%	83.33%	88.89%
0.25	100%	97.22%	100%	86.11%	83.33%	0%	88.89%	88.89%	86.11%
0.50	100%	97.22%	100%	88.89%	83.33%	88.89%	0%	80.56%	88.89%
0.75	100%	97.22%	100%	88.89%	83.33%	88.89%	80.56%	0%	77.78%
1.00	100%	97.22%	100%	88.89%	88.89%	86.11%	88.89%	77.78%	0%
Mean	0.841	0.828	0.853	0.815	0.799	0.812	0.809	0.796	0.809
Median	1.000	0.944	1.000	0.889	0.847	0.889	0.889	0.889	0.889
Std	0.346	0.333	0.346	0.330	0.327	0.332	0.331	0.331	0.077
MAD	0.000	0.028	0.000	0.042	0.056	0.069	0.083	0.083	0.056

Table C.17: Percentage of tests below threshold of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between each pair of scenarios for standard deviation, median absolute deviation, interquartile range and quartile coefficient of dispersion. Source: own elaboration.

SCENARIO	Baseline	Tech	Energy	Bank	0.00	0.25	0.50	0.75	1.00	*Median*
Baseline	*	0.8397	0.8148	1.0938	1.1155	1.0980	1.1024	1.1200	1.1024	1.1002
Tech	0.8302	*	0.9218	1.0330	1.0536	1.0675	1.0717	1.0889	1.0717	1.0606
Energy	0.8302	0.9500	*	1.0938	1.1155	1.0980	1.1024	1.1200	1.1024	1.1002
Bank	1.0566	1.0093	1.0370	*	0.9606	0.9455	0.9799	0.9956	0.9799	0.9877
0.00	1.0566	1.0093	1.0370	0.9418	*	0.9150	0.9186	0.9333	0.9799	0.9609
0.25	1.0566	1.0390	1.0370	0.9418	0.9296	*	0.9799	0.9956	0.9493	0.9877
0.50	1.0566	1.0390	1.0370	0.9722	0.9296	0.9760	*	0.9022	0.9799	0.9780
0.75	1.0566	1.0390	1.0370	0.9722	0.9296	0.9760	0.8880	*	0.8574	0.9741
1.00	1.0566	1.0390	1.0370	0.9722	0.9916	0.9455	0.9799	0.8711	*	0.9857
MAD	0.000	0.015	0.000	0.030	0.046	0.046	0.077	0.093	0.061	*

Table C.18: Indexes (percentage of tests below threshold over percentage of tests performed in the column) of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between each pair of scenarios for standard deviation, median absolute deviation, interquartile range and quartile coefficient of dispersion. Source: own elaboration.

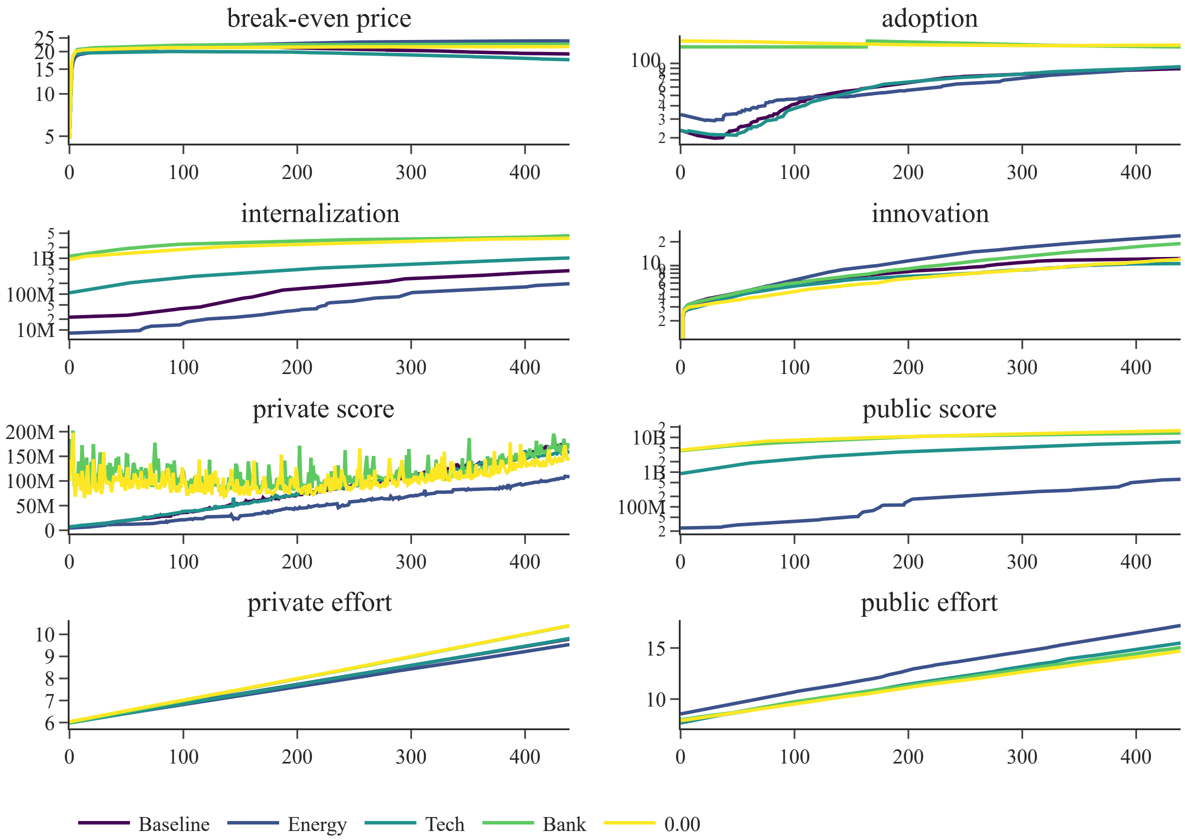

Figure C.1: Comparison between the no policy, technology, energy, financing and scenarios regarding the trajectories of standard deviations of minimum price per MWh of renewables (in $), of adoption of renewables (in MWs), of internalization (in $), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

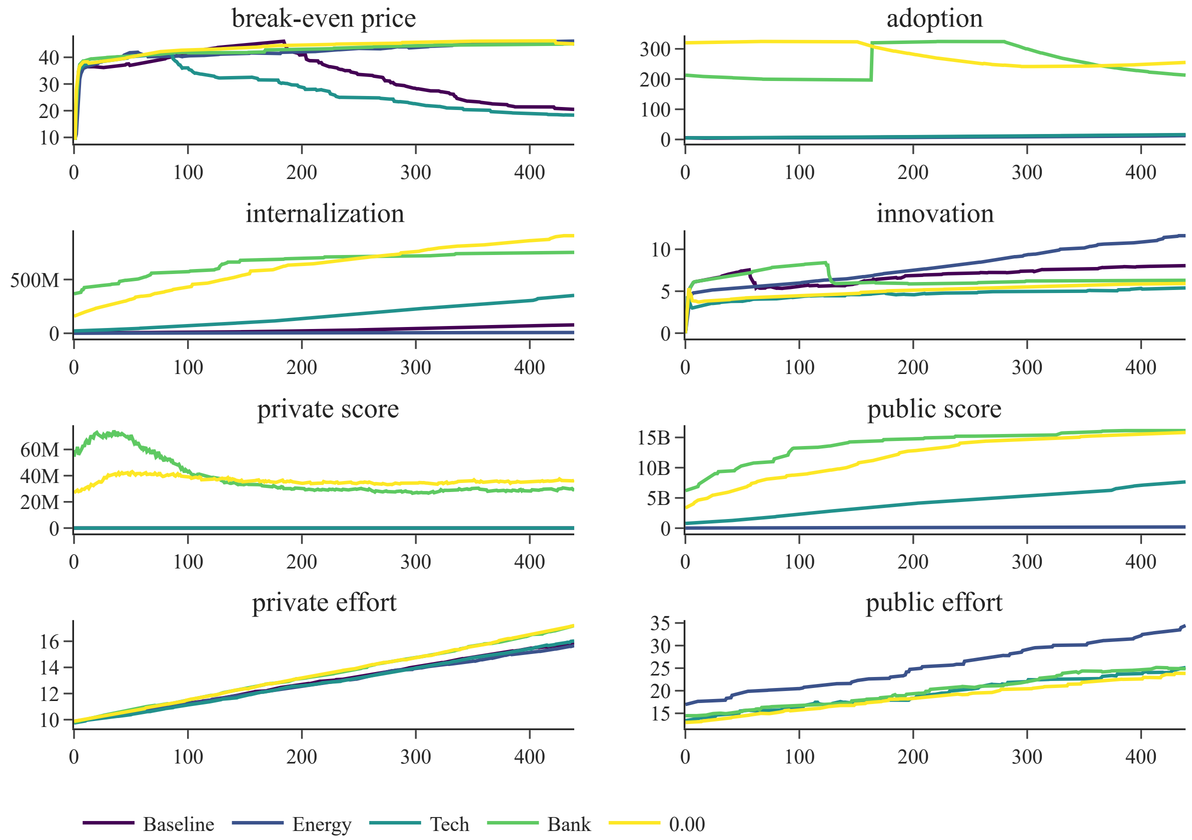

Figure C.2: Comparison between the no policy, technology, energy, financing and 0.00 scenarios regarding the trajectories of interquartile range of minimum price per MWh of renewables (in \$), of adoption of renewables (in MWs), of internalization (in \$), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

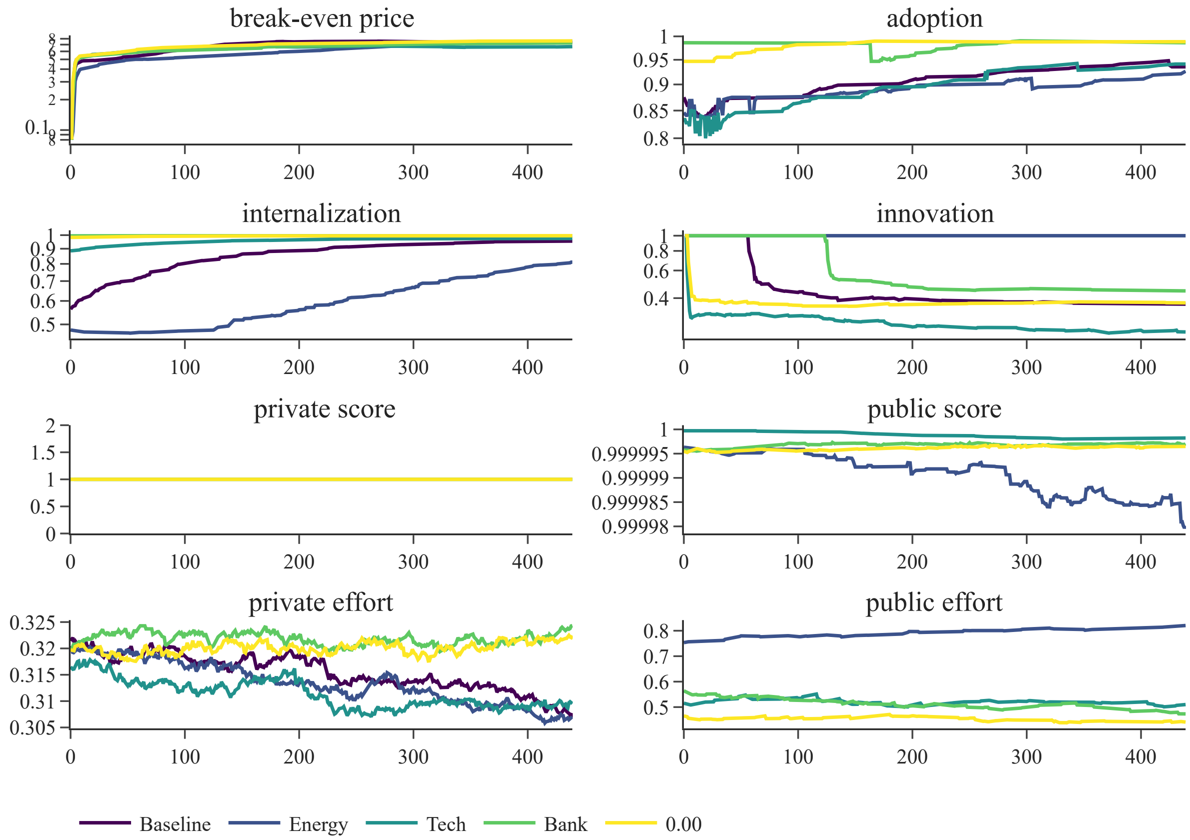

Figure C.3: Comparison between the no policy, technology, energy, financing and 0.00 scenarios regarding the trajectories of the quartile coefficient of dispersion of minimum price per MWh of renewables (in \$), of adoption of renewables (in MWs), of internalization (in \$), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

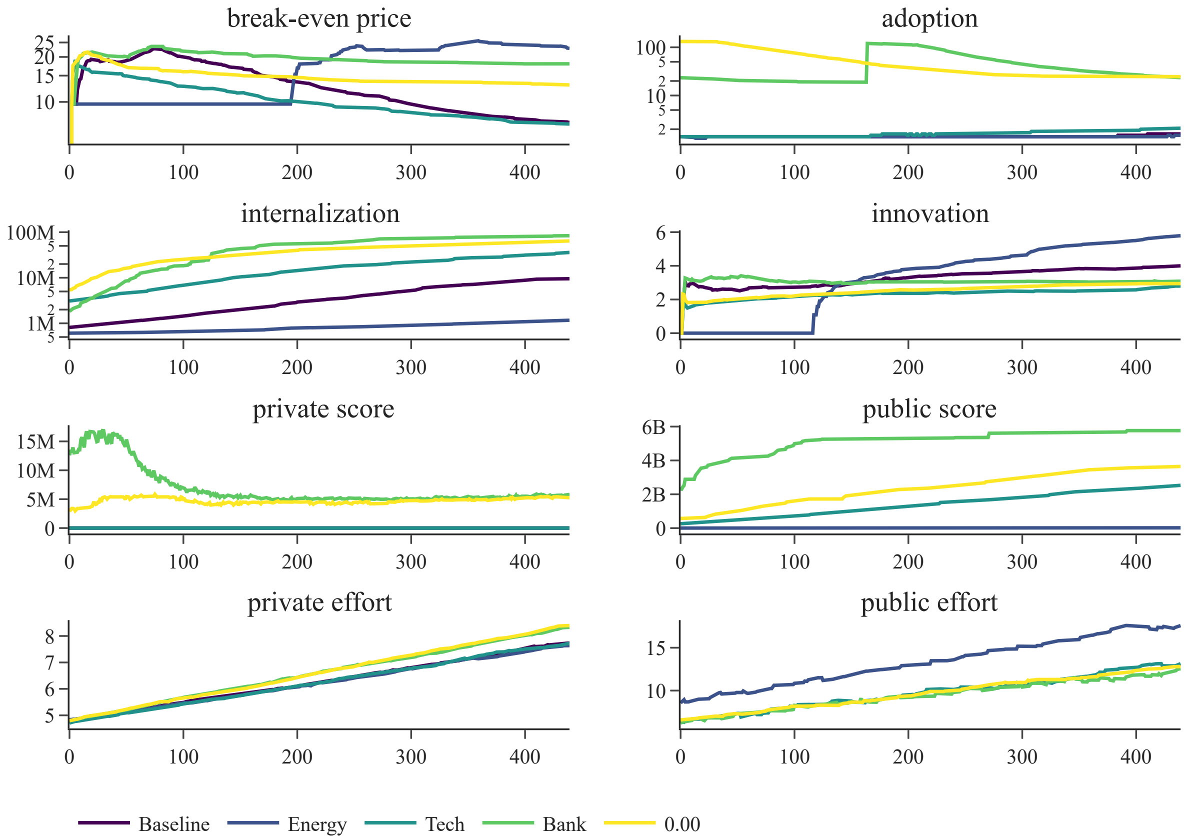

Figure C.4: Comparison between the no policy, technology, energy, financing and 0.00 scenarios regarding the trajectories of median absolute deviation of minimum price per MWh of renewables (in \$), of adoption of renewables (in MWs), of internalization (in \$), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

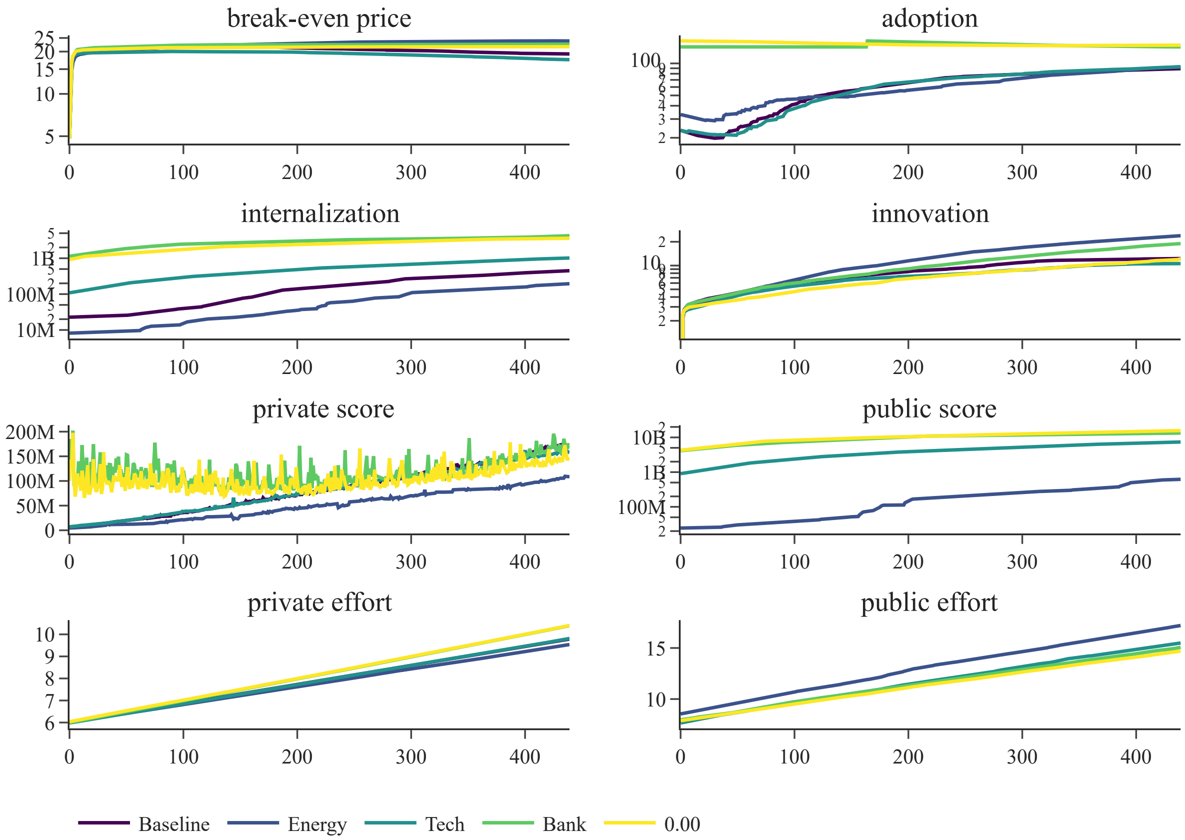

Figure C.5: Comparison between the 0.00, low intermediate, high intermediate and high scenarios regarding the trajectories of standard deviations of minimum price per MWh of renewables (in $), of adoption of renewables (in MWs), of internalization (in $), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

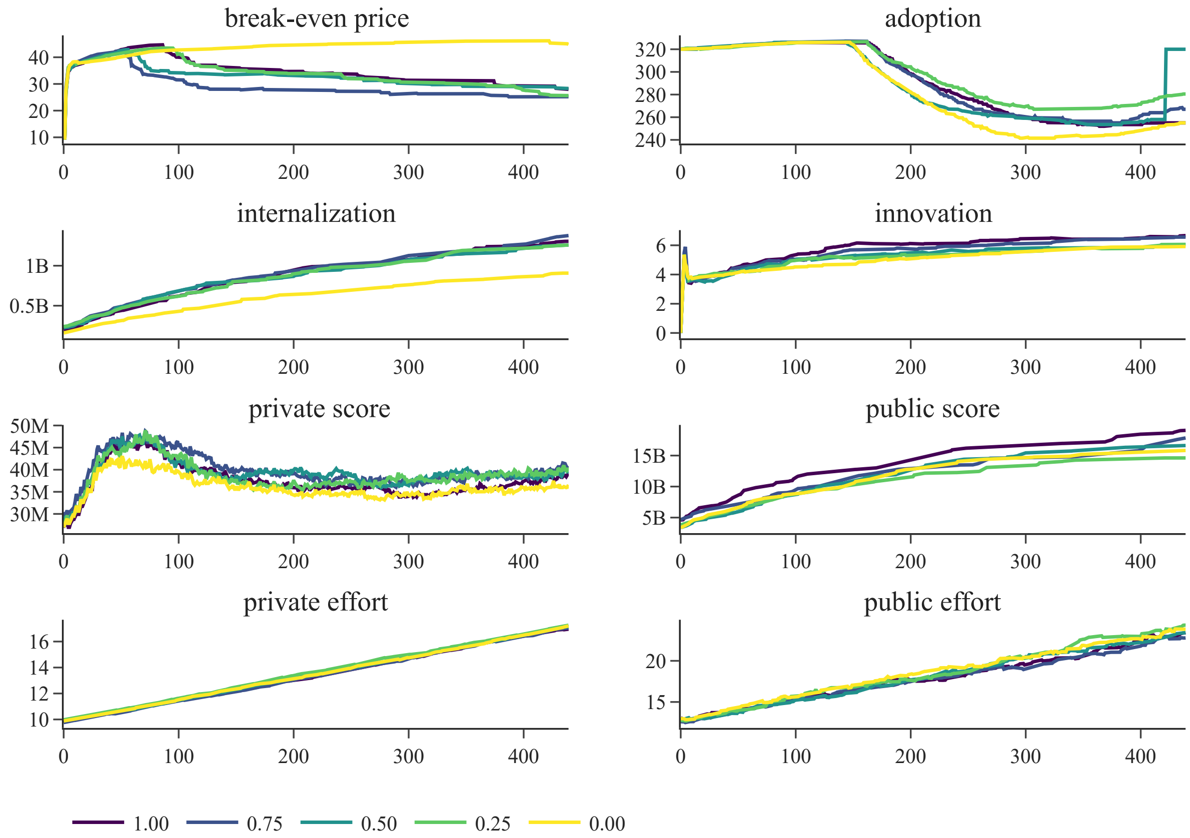

Figure C.6: Comparison between the 0.00, low intermediate, high intermediate and high scenarios regarding the trajectories of interquartile range of minimum price per MWh of renewables (in $), of adoption of renewables (in MWs), of internalization (in $), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

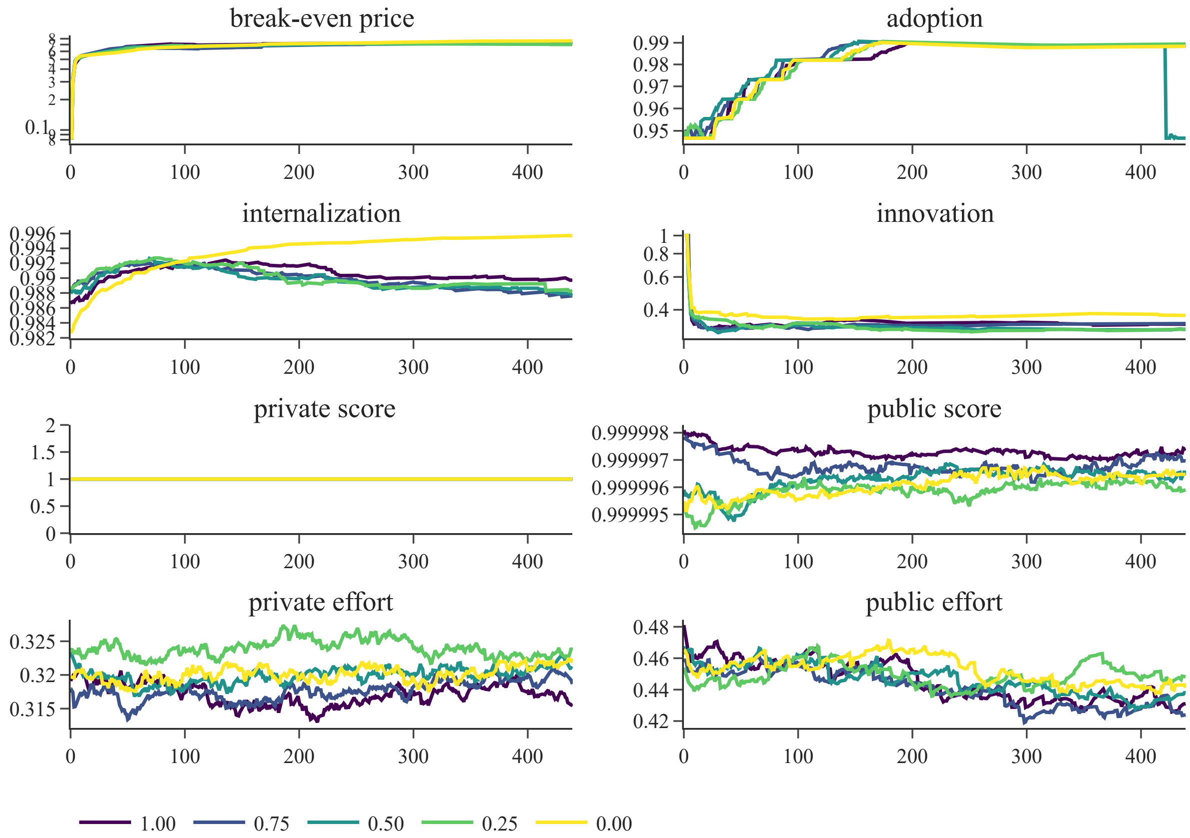

Figure C.7: Comparison between the 0.00, low intermediate, high intermediate and high scenarios regarding the trajectories of the quartile coefficient of dispersion of minimum price per MWh of renewables (in \$), of adoption of renewables (in MWs), of internalization (in \$), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

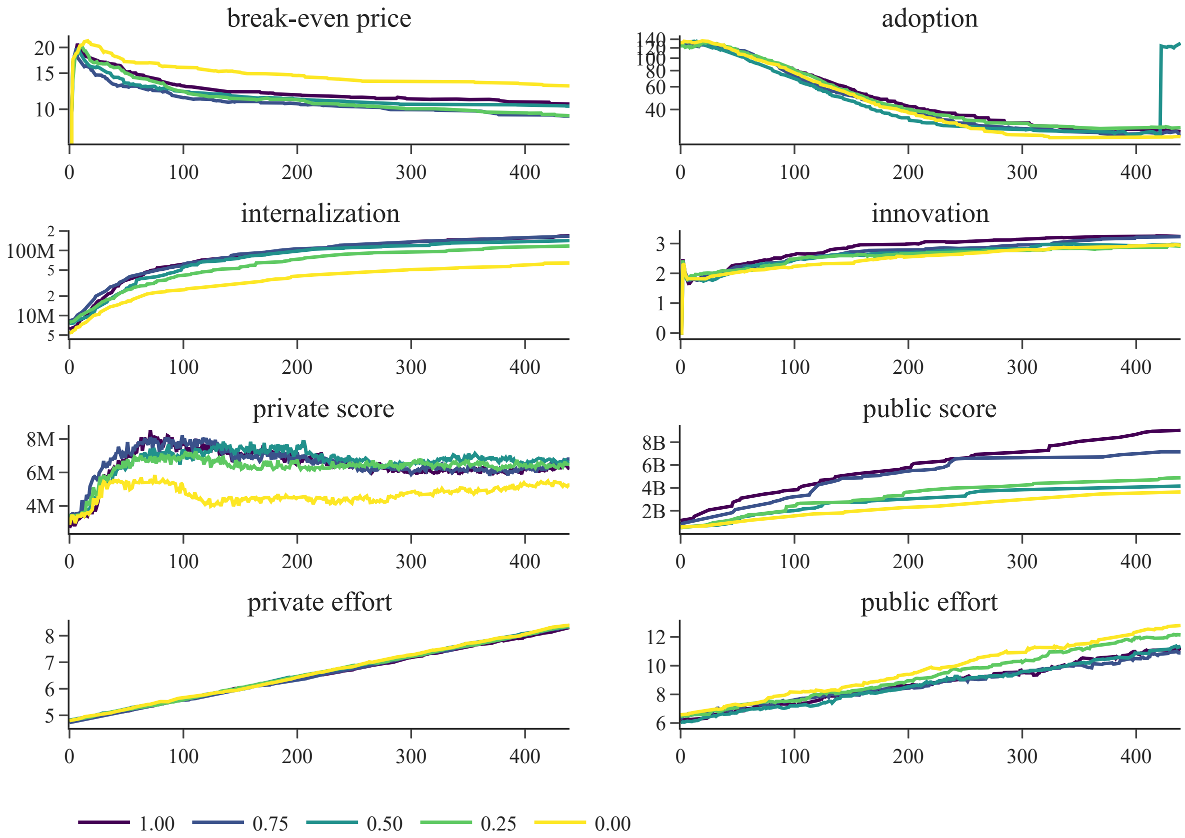

Figure C.8: Comparison between the 0.00, low intermediate, high intermediate and high scenarios regarding the trajectories of median absolute deviation of minimum price per MWh of renewables (in \$), of adoption of renewables (in MWs), of internalization (in \$), of innovation (in results of the innovation equation), of private scores, public scores, of private effort changes and public effort changes. Source: own elaboration.

ELEMENT	Total	5% p-value above	Ratio	tests	Share above	index
public_effort	13312	455	3.42%	10.36%	22.82%	2.2034
private_effort	14560	480	3.30%	11.33%	24.07%	2.1252
public_score	13312	312	2.34%	10.36%	15.65%	1.5109
internalization	14560	318	2.18%	11.33%	15.95%	1.4080
OPEX	14560	162	1.11%	11.33%	8.12%	0.7173
private_score	14560	108	0.74%	11.33%	5.42%	0.4782
adoption	14560	100	0.69%	11.33%	5.02%	0.4428
innovation	14560	39	0.27%	11.33%	1.96%	0.1727
CAPEX	14560	20	0.14%	11.33%	1.00%	0.0886
Mean	14282.7	221.556	0.016	0.111	0.111	1.016
Median	14560.0	162.000	0.011	0.113	0.081	0.717
Std	550.32	174.621	0.013	0.004	0.088	0.815
MAD	0.000	142.000	0.010	0.000	0.071	0.629

Table C.19: Tests below p-value, total number of tests, percentage of tests above p-value, share of tests regarding total number of tests, share of tests above p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of elements aggregated by element at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

SCENARIO	Total	5% p-value above	Ratio	tests	Share above	index
Tech	14976	422	2.82%	11.65%	21.16%	1.8165
0.25	14976	361	2.41%	11.65%	18.10%	1.5540
0.00	14976	273	1.82%	11.65%	13.69%	1.1752
Energy	14976	231	1.54%	11.65%	11.58%	0.9944
Baseline	8736	121	1.39%	6.80%	6.07%	0.8929
1.00	14976	192	1.28%	11.65%	9.63%	0.8265
0.50	14976	168	1.12%	11.65%	8.43%	0.7232
Bank	14976	114	0.76%	11.65%	5.72%	0.4907
0.75	14976	112	0.75%	11.65%	5.62%	0.4821
Mean	14282.7	221.556	0.015	0.111	0.111	0.995
Median	14976.0	192.000	0.014	0.117	0.096	0.893
Std	2080.00	111.682	0.007	0.016	0.056	0.454
MAD	0.000	78.000	0.004	0.000	0.039	0.282

Table C.20: Tests below p-value, total number of tests, percentage of tests above p-value, share of tests regarding total number of tests, share of tests above p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of elements aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

TIME LAG	Total	5% p-value below	Ratio	tests	Share below	index
3	8034	158	1.97%	6.25%	7.92%	1.2678
6	8034	156	1.94%	6.25%	7.82%	1.2518
0	8034	155	1.93%	6.25%	7.77%	1.2437
9	8034	147	1.83%	6.25%	7.37%	1.1795
18	8034	147	1.83%	6.25%	7.37%	1.1795
15	8034	145	1.80%	6.25%	7.27%	1.1635
12	8034	144	1.79%	6.25%	7.22%	1.1555
24	8034	132	1.64%	6.25%	6.62%	1.0592
21	8034	131	1.63%	6.25%	6.57%	1.0512
27	8034	120	1.49%	6.25%	6.02%	0.9629
30	8034	112	1.39%	6.25%	5.62%	0.8987
33	8034	107	1.33%	6.25%	5.37%	0.8586
36	8034	99	1.23%	6.25%	4.96%	0.7944
39	8034	91	1.13%	6.25%	4.56%	0.7302
42	8034	75	0.93%	6.25%	3.76%	0.6018
45	8034	75	0.93%	6.25%	3.76%	0.6018
Mean	8034.0	124.6	0.016	0.063	0.063	1.000
Median	8034.0	131.5	0.016	0.063	0.066	1.055
Std	0.00	28.416	0.004	0.000	0.014	0.228
MAD	0.000	21.500	0.003	0.000	0.011	0.173

Table C.21: Tests below p-value, total number of tests, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of elements aggregated by time lag at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

		Total	5% p-value above	Ratio	tests	Share above	index
TIME	**timeless**	39552	878	2.22%	30.77%	44.03%	1.4310
	1	29664	415	1.40%	23.08%	20.81%	0.9019
	12	29664	406	1.37%	23.08%	20.36%	0.8823
	48	29664	295	0.99%	23.08%	14.79%	0.6411
VECTOR	**STD**	9888	543	5.49%	7.69%	27.23%	3.5401
	MAD	9888	180	1.82%	7.69%	9.03%	1.1735
	acceleration	29664	512	1.73%	23.08%	25.68%	1.1127
	IQR	9888	121	1.22%	7.69%	6.07%	0.7889
	velocity	29664	312	1.05%	23.08%	15.65%	0.6780
	growth	29664	292	0.98%	23.08%	14.64%	0.6346
	QCP	9888	34	0.34%	7.69%	1.71%	0.2217
COUNCIL	**True**	41472	558	1.35%	46.60%	50.00%	1.0729
	False	47520	558	1.17%	53.40%	50.00%	0.9364
NUMBER	**0**	6048	87	1.44%	6.80%	7.80%	1.1471
	3	51840	720	1.39%	58.25%	64.52%	1.1075
	1	31104	309	0.99%	34.95%	27.69%	0.7922
DEGREE	**0.25**	10368	252	2.43%	11.65%	22.58%	1.9382
	0	10368	162	1.56%	11.65%	14.52%	1.2460
	1	10368	135	1.30%	11.65%	12.10%	1.0383
	None	37152	396	1.07%	41.75%	35.48%	0.8500
	0.5	10368	109	1.05%	11.65%	9.77%	0.8383
	0.75	10368	62	0.60%	11.65%	5.56%	0.4769

Table C.22: Tests below p-value, total number of tests, percentage of tests below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of elements aggregated by presence of council, number of policy makers, time frame, vectors and degree at a 5% p-value threshold. We also present mean, standard deviation, median and median absolute deviation per column. Source: own elaboration.

ELEMENTS	adopt.	CAPEX	innov.	intern.	OPEX	priv_effort	priv_score	pub_effort	pub_score	*mean*	*median*	*Std*	*MAD*
adopt.	0%	0%	0%	0.91%	0%	0.85%	2.24%	0%	1.32%	0.006	0.002	0.008	0.002
CAPEX	0%	0%	0%	0%	1.07%	0%	0%	0%	0%	0.006	0.002	0.008	0.006
innov.	0%	0%	0%	0.43%	0%	1%	0%	1%	0%	0.001	0.000	0.004	0.002
intern.	2.03%	0%	0%	0%	0%	3.37%	1.87%	1%	9.86%	0.002	0.001	0.003	0.008
OPEX	0%	8.65%	0%	0%	0%	0%	0%	0%	0%	0.020	0.011	0.032	0.006
priv_effort	1.44%	0%	0%	3.85%	0%	0%	2.72%	17.79%	2.04%	0.010	0.000	0.029	0.007
priv_score	1.71%	0%	0%	1.82%	0%	1%	0%	0.48%	1.44%	0.031	0.014	0.057	0.001
pub_effort	0.72%	0%	0%	1.20%	0%	21.94%	2.04%	0%	1.44%	0.007	0.005	0.008	0.002
pub_score	1.92%	0%	0%	9.92%	0%	3%	2.16%	2%	0%	0.030	0.007	0.071	0.014
mean	0.009	0.010	0.000	0.020	0.001	0.033	0.012	0.025	0.018				
median	0.005	0.000	0.000	0.007	0.000	0.006	0.010	0.003	0.014				
Std	0.008	0.031	0.000	0.013	0.004	0.076	0.012	0.062	0.033				
MAD	0.005	0.000	0.000	0.007	0.000	0.006	0.010	0.003	0.010				

Table C.23: Percentages of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between each pair of elements (except for innovation).

AGGREGATION	MAD
elements	0.62871
vector	0.32380
scenario	0.28226
degree	0.22599
time lag	0.17252
time frame	0.13039
council	0.09698
number	0.05928

Table C.24: Median absolute deviation of indexes per aggregation in the similar trajectory experiment.

SCENARIO	Total	5% p-value		Share		
		below	Ratio	tests	below	index
0.50	162	154	95.06%	11.39%	11.76%	1.0319
Energy	162	154	95.06%	11.39%	11.76%	1.0319
Baseline	126	118	93.65%	8.86%	9.01%	1.0166
0.25	162	150	92.59%	11.39%	11.45%	1.0051
0.00	162	150	92.59%	11.39%	11.45%	1.0051
0.75	162	148	91.36%	11.39%	11.30%	0.9917
Tech	162	148	91.36%	11.39%	11.30%	0.9917
1.00	162	144	88.89%	11.39%	10.99%	0.9649
Bank	162	144	88.89%	11.39%	10.99%	0.9649
Mean	158.0	145.6	0.922	0.111	0.111	1.000
Median	162.0	148.0	0.926	0.114	0.113	1.005
Std	12.00	10.944	0.023	0.008	0.008	0.025
MAD	0.000	4.000	0.012	0.000	0.003	0.013

Table C.25: Scores below p-value, total number of scores, percentage of scores above p-value, share of tests regarding total number of tests, share of tests above p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of time frames aggregated by element at a 5% p-value threshold. We also present mean, standard deviation, median and median average deviation per column. Source: own elaboration.

ELEMENTS	Total	5% p-value below	Ratio	tests	Share below	index
private__score	162	162	100%	11.39%	12.37%	1.0855
CAPEX	162	162	100%	11.39%	12.37%	1.0855
OPEX	162	162	100%	11.39%	12.37%	1.0855
adoption	162	160	98.77%	11.39%	12.21%	1.0721
internalization	162	156	96.30%	11.39%	11.91%	1.0453
public__effort	144	136	94.44%	10.13%	10.38%	1.0252
public__score	144	132	91.67%	10.13%	10.08%	0.9950
private__effort	162	132	81.48%	11.39%	10.08%	0.8845
innovation	162	108	66.67%	11.39%	8.24%	0.7237
Mean	158.0	145.6	0.921	0.111	0.111	1.0002
Median	162.0	156.0	0.963	0.114	0.119	1.0453
Std	7.937	19.36	0.113	0.006	0.015	0.1222
MAD	0.000	6.00	0.037	0.000	0.005	0.0402

Table C.26: Scores below p-value, total number of scores, percentage of scores above p-value, share of tests regarding total number of tests, share of tests above p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of time frames aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median average deviation per column. Source: own elaboration.

C.4 Time experiment

C.5 Vector experiment

		Total	5% p-value below	Ratio	Share tests	below	index
TIME	**48**	474	441	93.04%	33.33%	33.66%	1.0099
	1	474	440	92.83%	33.33%	33.59%	1.0076
	12	474	429	90.51%	33.33%	32.75%	0.9824
VECTOR	**velocity**	474	464	97.89%	33.33%	35.42%	1.0626
	acceleration	474	460	97.05%	33.33%	35.11%	1.0534
	growth	474	386	81.43%	33.33%	29.47%	0.8840
COUNCIL	**False**	774	714	92.25%	54.43%	54.50%	1.0013
	True	648	596	91.98%	45.57%	45.50%	0.9984
NUMBER	**0**	126	118	93.65%	8.86%	9.01%	1.0166
	3	810	746	92.10%	56.96%	56.95%	0.9997
	1	486	446	91.77%	34.18%	34.05%	0.9962
DEGREE	**0.5**	162	154	95.06%	11.39%	11.76%	1.0319
	0.25	162	150	92.59%	11.39%	11.45%	1.0051
	0	162	150	92.59%	11.39%	11.45%	1.0051
	None	612	564	92.16%	43.04%	43.05%	1.0004
	0.75	162	148	91.36%	11.39%	11.30%	0.9917
	1	162	144	88.89%	11.39%	10.99%	0.9649

Table C.27: Scores below p-value, total number of scores, percentage of scores below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of time frames aggregated by presence of council, number of policy makers, time frame, vectors and degree at a 5% p-value threshold. We also present mean, standard deviation, median and median average deviation per column. Source: own elaboration.

DESEGREGATION	MAD
elements	0.04020
scenario	0.01340
vector	0.00916
degree	0.00670
number	0.00357
time	0.00229
council	0.00148

Table C.28: Median absolute deviation of indexes per aggregation in the time experiment.

SCENARIO	Total	5% p-value below	Ratio	Share tests	below	index
Baseline	714	704	99%	8.86%	8.92%	1.0072
1.00	918	904	98%	11.39%	11.46%	1.0060
Bank	918	904	98.47%	11.39%	11.46%	1.0060
0.75	918	902	98.26%	11.39%	11.44%	1.0037
0.50	918	898	97.82%	11.39%	11.38%	0.9993
0.25	918	898	97.82%	11.39%	11.38%	0.9993
0.00	918	896	97.60%	11.39%	11.36%	0.9971
Tech	918	894	97.39%	11.39%	11.33%	0.9948
Energy	918	888	96.73%	11.39%	11.26%	0.9882
Mean	895.3	876.4	0.979	0.111	0.111	1.000
Median	918.0	898.0	0.978	0.114	0.114	0.999
Std	68.00	64.867	0.006	0.008	0.008	0.006
MAD	0.000	4.000	0.004	0.000	0.001	0.004

Table C.29: Scores below p-value, total number of scores, percentage of scores above p-value, share of tests regarding total number of tests, share of tests above p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of vectors aggregated by element at a 5% p-value threshold. We also present mean, standard deviation, median and median average deviation per column. Source: own elaboration.

SCENARIO	Total	5% p-value below	Ratio	Share tests	below	index
innovation	918	918	100%	11.39%	11.64%	1.0216
adoption	918	918	100%	11.39%	11.64%	1.0216
CAPEX	918	912	99%	11.39%	11.56%	1.0149
OPEX	918	910	99%	11.39%	11.54%	1.0126
internalization	918	908	98.91%	11.39%	11.51%	1.0104
public_score	816	806	98.77%	10.13%	10.22%	1.0090
private_score	918	904	98.47%	11.39%	11.46%	1.0060
public_effort	816	768	94.12%	10.13%	9.74%	0.9615
private_effort	918	844	91.94%	11.39%	10.70%	0.9392
Mean	895.3	876.4	0.979	0.111	0.111	1.000
Median	918.0	908.0	0.989	0.114	0.115	1.010
Std	44.978	56.319	0.028	0.006	0.007	0.029
MAD	0.000	10.000	0.004	0.000	0.001	0.004

Table C.30: Scores below p-value, total number of scores, percentage of scores above p-value, share of tests regarding total number of tests, share of tests above p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of vectors aggregated by scenario at a 5% p-value threshold. We also present mean, standard deviation, median and median average deviation per column. Source: own elaboration.

		Total	5% p-value below	Ratio	Share tests	below	index
TIME	**12**	2370	2360	99.58%	29.41%	29.92%	1.0172
	48	2370	2354	99.32%	29.41%	29.84%	1.0147
	1	2370	2350	99.16%	29.41%	29.79%	1.0129
	timeless	948	824	86.92%	11.76%	10.45%	0.8879
VECTOR	**growth**	1422	1412	99.30%	17.65%	17.90%	1.0144
	acceleration	1422	1408	99.02%	17.65%	17.85%	1.0115
	QCP	948	938	98.95%	11.76%	11.89%	1.0108
	velocity	1422	1407	98.95%	17.65%	17.84%	1.0108
	STD	948	909	95.89%	11.76%	11.52%	0.9795
	MAD	948	908	95.78%	11.76%	11.51%	0.9784
	IQR	948	906	95.57%	11.76%	11.49%	0.9763
COUNCIL	**True**	3672	3602	98.09%	45.57%	45.66%	1.0021
	False	4386	4286	97.72%	54.43%	54.34%	0.9983
NUMBER	**0**	714	704	99%	8.86%	8.92%	1.0072
	3	4590	4498	98.00%	56.96%	57.02%	1.0011
	1	2754	2686	97.53%	34.18%	34.05%	0.9963
DEGREE	**1**	918	904	98.47%	11.39%	11.46%	1.0060
	0.75	918	902	98.26%	11.39%	11.44%	1.0037
	0.5	918	898	97.82%	11.39%	11.38%	0.9993
	0.25	918	898	97.82%	11.39%	11.38%	0.9993
	None	3468	3390	97.75%	43.04%	42.98%	0.9986
	0	918	896	97.60%	11.39%	11.36%	0.9971

Table C.31: Scores below p-value, total number of scores, percentage of scores below p-value, share of tests regarding total number of tests, share of tests below p-value regarding total number of tests below p-value and share-index for Kolmogorov–Smirnov tests between each possible pair of vectors aggregated by presence of council, number of policy makers, time frame, vectors and degree at a 5% p-value threshold. We also present mean, standard deviation, median and median average deviation per column. Source: own elaboration.

AGGREGATION	MAD
elements	0.0246
scenario	0.0126
time	0.0076
number	0.0060
vector	0.0043
council	0.0037
degree	0.0019

Table C.32: Median absolute deviation of indexes per aggregation in the vector experiment.

VECTOR	velocity	acc.	growth	STD	MAD	IQR	QCP
velocity	0%	96.20%	97.47%	100%	100%	100%	100%
acc.	96.20%	0%	99.58%	99.16%	100%	99.58%	99.58%
growth	97.47%	99.58%	0%	100%	100%	100%	98.73%
STD	100%	99.16%	100%	0%	77.22%	77.22%	98.73%
MAD	100%	100%	100%	77.22%	0%	74.68%	97.47%
IQR	100%	99.58%	100%	77.22%	74.68%	0%	96.20%
QCP	100%	99.58%	98.73%	98.73%	97.47%	96.20%	0%
Mean	0.848	0.849	0.851	0.789	0.785	0.782	0.844
Median	0.987	0.994	0.998	0.882	0.886	0.884	0.987
Std	0.403	0.404	0.406	0.386	0.387	0.387	0.014
MAD	0.013	0.004	0.002	0.114	0.114	0.116	0.011

Table C.33: Percentages of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between each pair of vectors.

VECTOR	velocity	acc.	growth	STD	MAD	IQR	QCP	*Median*
velocity	*	0.9716	0.9816	1.0429	1.0441	1.0464	1.0107	1.027
acc.	0.9723	*	1.0028	1.0341	1.0441	1.0419	1.0064	1.020
growth	0.9851	1.0057	*	1.0429	1.0441	1.0464	0.9979	1.024
STD	1.0107	1.0014	1.0071	*	0.8062	0.8079	0.9979	1.000
MAD	1.0107	1.0099	1.0071	0.8053	*	0.7815	0.9851	0.996
IQR	1.0107	1.0057	1.0071	0.8053	0.7797	*	0.9723	0.989
QCP	1.0107	1.0057	0.9943	1.0297	1.0176	1.0066	*	1.009
MAD	0.000	0.002	0.002	0.011	0.013	0.022	0.011	*

Table C.34: Indexes (percentage of tests below threshold over percentage of tests performed in the column) of Kolmogorov-Smirnov tests that reject the null hypothesis a 5% significance level between each pair of vectors.