Polycentric governance of energy transitions

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Short Abstract

Policies may be aligned in order to increase their effects. We analyze three policiesrelated to the transition towards low carbon energy systems: energy policy, technology policy and public financing, each executed by a different policy maker. Policy makers interact with technology producers, energy providers and private banks. We simulate wind, solar and a fossil electricity source. Private agents desire satisfactory profits. Public agents may desire to increase the penetration of renewable sources, to increase the R&D or investment into local productive capacity. We observe the implications of the convergence or divergence of goals among policy makers.

Key words: Agent-based model; Renewable energy; public policies; Policy mix; Transition to low-carbon energy systems

Área temática: 1. Economia

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1. Introduction

Climate change is a reality that we must face. Efforts to mitigate climate change require multiple fronts: from individual actions to large coordinated actions among different governments. In that sense, since there normally is a detachment between individual and collective rationalities (CARDIM DE CARVALHO, 1997), and given the inherit uncertainty of large transition processes (DEQUECH, 2011) it may not be enough to expect individuals and private agents to undertake the actions needed to mitigate climate change. In that sense, the lock-in of fossil fuels only increases the need for collective over individual reasoning (ARTHUR, 1989). As such, regulation may be able to coordinate agents towards the common goal of mitigating climate change[1](CHANG, 1997; GLACHANT; PEREZ, 2007; MAZZUCATO, 2015). One of the first attempts of such coordination was the Kyoto protocol, nevertheless it soon became clear that there should be more incisive, direct and technology-driven efforts (SCHMIDT; SEWERIN, 2017).

Moreover, it also became clear that just focusing on price mechanisms could not be enough. Technology and finance incentives then entered the stage: be it as part of a national policy of climate change mitigation (Germany) or as a policy to diversify a country's energy mix (Brazil) (FERREIRA; BLASQUES; PINHO, 2014; PODCAMENI, 2014; HOCHSTETLER; KOSTKA, 2015; GAWEL et al., 2017; VAZQUEZ et al., 2018). In that sense, multiple policies began to be aligned focusing on a policy mix that is suitable to foster change (CUNNINGHAM et al., 2016; SCHMIDT; SEWERIN, 2018). Policy is a measure that affects the comparative risks among sources (CASELLI; GATTI, 2017; GEDDES; SCHMIDT, 2018). We argue that an analysis of static cost-benefits should then be changed to a dynamic risk-opportunity analysis (MERCURE et al., 2020; SHARPE et al., 2020) in order to reflect the changing scenario that encompasses climate change mitigation technologies (NELSON, 1994; MITCHELL; WOODMAN, 2010).

In order to analyze the interplay of policy makers, we elaborate an agent based model (ABM): a computational model of simulation (TESFATSION, 2011). There are multiple examples of ABM on different areas, including the analysis of technology change (FAGIOLO; DOSI, 2003), financial systems (EHRENTREICH, 2008), and transition processes (LAMPERTI et al., 2018). Our methodological stand-point is the Institutional Analysis and Development framework (OSTROM, 2005). Such methodology is already used on ABM (IYCHETTIRA; HAKVOORT; LINARES, 2017). Our model consists of three classes of private agents: energy providers, technology producers and private banks. Technology producers invest in productive capacity or into R&D and manufacture energy provision assets, focusing on either wind or solar. Energy providers acquire assets from technology producers in order to provide energy (electricity or molecules). Private banks finance asset acquisitions. On top of those private agents we have three public agents: an energy policy maker which decides between auctions, carbon tax and feed-in tariffs; a technology policy maker which provides incentives to technology producers; and a public bank which decides between direct lending and guarantee provision.

Nevertheless, by diversifying the fronts of action, problems of discoordination of policies and initiatives may arise. Discoordination may especially arise from different goals that orient each policy maker (JANÉ, 2016). In terms of goals, there exist many possibilities, nevertheless we analyze three: to focus on the entry of renewable capacity (VAZQUEZ et al., 2018); to focus on the development of local productive capacity of renewables (MAZZUCATO; PENNA, 2015); and to focus on the development of R&D capabilities by innovative firms (GRÜBLER et al., 2014). Each public agent may choose one of those goals in order to orient their policymaking activities. Public agents may also change and revise their policies: changing the incentivized source, the policy in place or even internal

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[1] Joskow (2008) reviewed the large worldwide regulatory shift towards market liberalization in electricity markets. Such large regulatory change indicates the possibility of using regulation to steer significant change processes in energy systems.

decision-making characteristics (e.g. likelihood of revision).

2. Theoretical background

We understand policies as a set of rules: prescriptions of actions that agents must perform, must avoid or may do alongside related sanctions or benefits (CRAWFORD; OSTROM, 1995). Rules nevertheless are not constant and abstract notions that exist above agents, but rather constructs that emerge from interactions (NORTH, 1990). There exists a multitude of definitions of rules (DOPFER, 2004; POTTS, 2007), nevertheless we use Ostrom's (2005, 2011) definition, since it connects rules to a systematic description of a system's dynamic: the IAD framework.

The IAD framework connects variables and parameters[2]to outcomes through two structures: interactions that occur within action arenas, and evaluative criteria that act upon both interactions and outcomes. Outcomes affect exogenous variables in the next analyzed period, and outcomes affect the action situations themselves, thus emphasizing dynamics through feedback loops. Another feedback loop occurs from interactions to action situations.

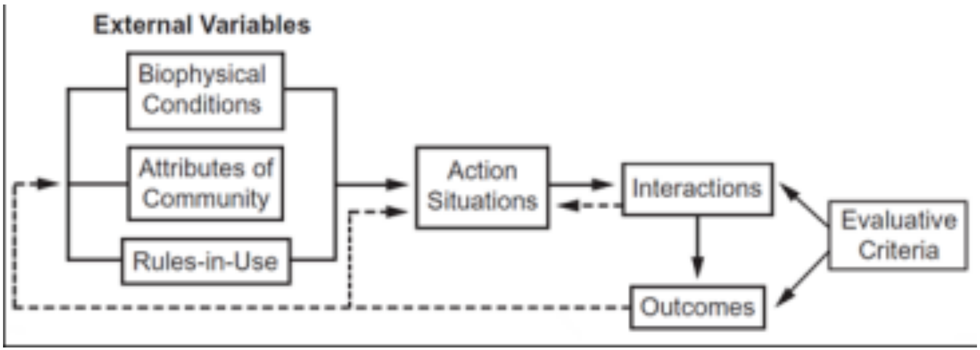

Figure 1 - A Framework for Institutional Analysis. Source: Ostrom (2011, p. 10).

The connection of rules with that framework goes beyond being an entry in the "external variable" category: action situations are the combination of actors and action arenas, and rules affect both. More importantly, there may exist multiple arenas and the rules that arise from each arena may affect the others: the rules that affect an action arena emerge from both it and other action arenas (MCGINNIS, 2011). Ostrom (2005) provides a taxonomy of rules in order to systematize the analysis:

- **Position rules** affect the relative positions of agents, ex.: incentivized vs. non incentivized firm;
- **Boundary rules** affect what actors may change from one position to another, ex.: what firms are eligible for incentives;
- **Choice rules** affect the choices that agents in certain positions have, ex.: incentivized firms must use certain source whereas non-incentivized firms are free to choose;
- **Information rules** control the information that flows from one agent to another, with the disclosed policy being an example and the undisclosed strategy of a private agent being another;
- **Aggregation rules** determine which agents may or must participate in certain

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[2] Both comprise, alongside the current set of rules, the exogenous variables in the terminology used.

action, ex.: what agents must pay for the amortization of power plants;

- **Payoff rules** affect the correlated benefits and sanctions assigned to each choice related to each position, ex.: a carbon tax increases the OPEX of carbon plants;
- **Scope rules** determine the possible outcomes of each action, for example, a PPA may be payed or not, there is no in between.

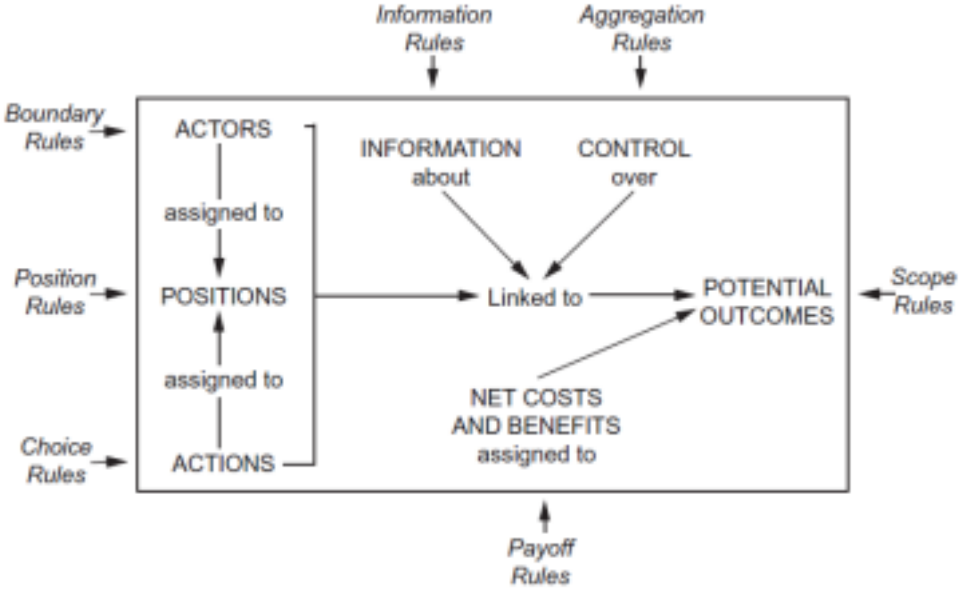

Figure 2 - The Internal Structure of an Action Situation. Source: Ostrom (2011, p. 10).

In that sense, the IAD framework may highlight the impacts that each instance of decision has over the others. In terms of climate change mitigation, the IAD opens up the possibility for interlinkage between multitudes of areas. Drawing from Nelson (1994, 2002), we highlight the relation between technology (innovation and adoption) and institutions (rules). Our focus in relation to rules is on policymaking, to be more specific, on the definition of new policies and revision of current policies. In other words, there is a focus on the debate of stability versus flexibility of policymaking (SILVA, 2015; CRAIG et al., 2017).

As such, it is important to discuss three aspects of policy: (1) what are the policies to be analyzed; (2) what is the measure applied to the policy; and (3) what the policy is measured to, i.e., what are its goals. In relation to (1), we emphasize policies that appear on the forefront of climate change mitigation and that are highlighted on green new deal initiatives. Those policies are: energy policy (MORENO et al., 2010; HELD et al., 2014;

GAWEL et al., 2017), technology policy (HELM; TANNOCK; ILIEV, 2014; TÕNURIST, 2017; GEDDES; SCHMIDT, 2018) and public financing (MAZZUCATO; PENNA, 2015; EGLI; STEFFEN; SCHMIDT, 2018; GEDDES; SCHMIDT, 2018). The option for the joint analysis of those three policy types draws from the debate of mixes of policy (CUNNINGHAM et al., 2016; SCHMIDT; SEWERIN, 2018), and from the necessity to analyze the combined effects of different policies on a system (PODCAMENI, 2014; FERREIRA, 2017; CAMILLO; FURTADO, 2018)[3].

In relation to the measure applied to the policy, we highlight the risk-opportunity analysis over the static cost-benefit analysis (MERCURE et al., 2020; SHARPE et al., 2020). Moreover, in relation to policy goals we highlight the debate over policies which targets are outcomes of the system (e.g. a reduction of 20% in emissions), versus policies which targets are the system itself (e.g. entry of a certain source in the mix) (BOSCHMA, 2013).

In terms of the IAD framework, the policy goal appears as its evaluative criteria (KÜNNEKE, 2008), whereas the measure applied to the policy appear as part of the monitoring action situation (WHALEY; WEATHERHEAD, 2014; NIGUSSIE et al., 2018).

According to Ostrom (2005), agents may engage in rule changing when the benefits (□□) of abandoning one rule (□□□□□□□□) for a new (□□□□□□□□) outweigh the costs of performing that change. In a sense, that rule-changing process is a sort of cost-benefit analysis that may be adapted to a risk-opportunity analysis. As such, we first assess the risks and opportunities of remaining in the old set of rules and, if the latter outweighs the first then the agent may engage in rule-changing. In order to reflect the criticality of the level shifting strategies and to internalize the costs of change, a certain threshold is established based on the difference between risk and opportunity and, if met, it adds or reduces the criticality of change for a new set of rules. In concrete terms, the further away from a goal or from the competition, the more willing to change the agent will be. When that criticality is met, the agent then assesses the risks and opportunities of each new set of rules and decides for the best[4], with the possibility of the old rule still being perceived as the best.

One important aspect that influences this whole process is the problem complexity boundary, i.e., the boundary for the agent to abandon the deductive status-quo process and to engage in an inductive changing process (ARTHUR, 1992, 1994). In terms of further thresholds, an agent's decision variable is a function of its past decision according to the costs of obtaining information regarding its evaluative criteria: how close or far from its goals the agent is.

Nevertheless, not all parts of the IAD have their dynamics in a similar time frame, i.e., there are different levels of situation in analysis. That statement becomes clearer when dividing between the two levels that co-evolve: the institutional and technological levels (Table 1). It is common to separate the everyday operation from routines, those two from technological trajectories and all from the technological paradigm, and to attribute a top down causality between them: the paradigm affects the trajectory that affects routines that end up affecting the operation management of firms. In a similar fashion, there is a top down causality in the institutional level: resource allocation is affect by governance structures that are affected by the institutional environment that is affected by embedded institutions in society (e.g. culture).

In that sense, Vazquez and Hallack (2018) divide each level by different situation types in terms of mutability and closeness to action: from the closest and most mutable operational level (resource allocation and operation management) to higher and less mutable levels, in order: collective-choice (governance and routines), constitutional (institutional environment and technological trajectory) and metaconstitutional (embeddedness and technological paradigm). Highlighting the dynamics in the causality process, change becomes a matter of time, with more time being necessary for change to happen to higher levels, e.g. a metaconstitutional change could take centuries to occur. What emphasizes the time aspect of change in the IAD framework is nevertheless the

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[3] In macroeconomics the analysis of policy interlinkages and spillovers is common, especially between monetary and fiscal policies (CARDIM DE CARVALHO, 1997).

[4] "Best" here is not regarded as the overall and all-encompassing best rule possible, but simply as the best one in terms of the agent's analysis. Such analysis is limited, both due to its own information and decision-making constraints (ARTHUR, 1994) and also due to the uncertainty inherent to the analysis (DEQUECH, 2011).

bottom-up change process: the level-shifting strategies. Sufficient change that endures for sufficient time in any lower level may affect a higher level if there is enough criticality: for example, a decrease in demand for a company's product may lead to change in routines that may lead such company into new markets. Nevertheless, through co evolution, a level-shifting strategy on the institutional or technology level may affect its counterpart: e.g., changes in routines may affect not only the technological trajectory but also the institutional environment itself. It is relevant to notice that level-shifting strategies are always active: they are not a deliberate decision to revise parts of the decision-making process; they emerge from the decision-making process itself.

Situation Type	**Institutional level**	**Technology level**
Operational level	Resource allocation	Operation management
Collective-choice level	Governance	Routines
Constitutional level	Institutional environment	Technological trajectory
Meta-constitutional level	Embeddedness	Technological paradigm

Table 1 -Relation between technology and institutional levels according to different situation types. Source: Vazquez (2018).

Level-shifting strategies are crucial for policies: through the changes in operational level variables caused by changes in payoff and choice rules, policymakers attempt to cause a chain reaction that end up affecting collective-choice and ultimately constitutional level variables. In that sense, time is crucial for that process: quick responses may not indicate level-shifted higher-level variables due to path dependency. As such, for change to occur there needs to exist level-shifting strategies for firms. Moreover, for change to occur there also needs to exist level-shifting strategies for the policy makers themselves: they must be able to adapt and revise their strategies according to the system itself.

Agents decide to engage in rule-changing activities when the opportunity of new rules exceeds the risks of changing. Policy makers may act on both ends of that comparison: by increasing the opportunities of new rules; and by decreasing the risks of changing. One example for that in energy systems would be the use of auctions with long term power purchase agreements (PPAs). On the other hand, they may also reduce the opportunities of using certain technologies. One classic example is the use of carbon taxes (HELD et al., 2014).

In that sense, we hypothesize that the key aspect for policy making processes in transition contexts are to provoke level-shifting strategies in the private agents. In order to do so, policy makers however must also be able internalize such level-shifting strategies into their policy-making processes. In turn, that means that debate of flexibility versus stability may not be on the forefront for such activities in, but rather how may policy makers foster co-evolutionary change in both institutional and technology levels on transition contexts.

As such, we advocate that policy mixes may be adequate for doing so, since they would act upon more action arenas, affect more agents and encompass more of the system. In that sense, we analyze how different policy mixes affect such co-evolution processes in terms of level-shifting strategies.

3. Overview of the model

We model co-evolution between technology and institutions in the context of energy transitions. The main relation between the multiple private agents is that technology producers manufacture the technology that is acquired by energy providers, financed by banks (or, less likely, as reinvestments), in order to produce energy to meet the established demand. At the same time, policy occurs: the development bank finances and provides guarantees; the energy policy maker does energy policy; and the technology policy maker does technology policy. Technology policy comes in the form of financial incentives to research and development (R&D) given to private technology producers. Energy policy however may come in three forms: carbon tax, feed-in tariffs and energy auctions. A carbon-tax increases the OPEX costs of fossil fuels, whereas a feed-in tariff increases the payment for a certain renewable source over its market price, thus actually being a feed in premium[5].

We streamline an economy to three aspects: financing, technology-related reinvestment and providing energy. In Ostrom's (2005) terms, each aspect represents an action arena. In each arena (Table 2), there is at least two different types of agents: one public and several private agents.

	Private agents involved	**Public agents involved**
Financing arena	**Private banks** competing for energy providers	**Public Bank**
Technology arena	**Technology producers** competing for energy providers	**Technology Policy Maker**
Energy arena	**Energy providers** competing for the demand	**Energy Policy Maker**

Table 2 - Agents that act within the different action arenas (apart from the monitoring arena). Source: own elaboration.

Each agent has a certain task that it performs according to certain effort: technology

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[5] Feed-in tariffs substitute the market price for a specific unrelated source price, whereas feed-in premiums increase that market price by a certain margin, thus being related to the clearance price (SCHALLENBERG-RODRIGUEZ; HAAS, 2012). Klein et al (2008) broadens the comparison between different types of feed-in tariffs.

producers reinvest into R&D or productive capacity, energy providers invest in capacity, banks finance assets, and policy makers decide their policy effort. Effort is decided on a satisficing basis (SIMON, 1979): agents attempt to catch up to their competition or to their goals, but lag behind when ahead of competition or goals.

Every agent performs a certain task with a certain effort. All tasks are goal-oriented, being such goal given by an agent's evaluative criteria. All effort occurs within a certain strategy that each agent possesses. Strategies may be static or have some dynamic parts. If more than one aspect is variable, there is a hierarchy of change: the strategy has a core and a rim. In a nutshell, a strategy is a vector of parameters and/or variables that provides the agent with a rulebook.

Situation Type	**Institutional level**	**Technology level**	**Variables and parameters**
Operational level	Resource allocation	Operation management	Effort
Collective choice level	Governance	Routines	Strategy
Constitutional level	Institutional environment	Technological trajectory	Meta-strategy
Meta constitutional level	Embeddedness	Technological paradigm	Evaluative Criteria

Table 3 – Variables and parameters associated with different situation types. Source: own elaboration based on Vazquez (2018).

In that sense, resorting to Ostrom's (2005) and Crawford and Ostrom's (1995) definition of rules, position and scope rules are given due to the scope of time and analysis of the simulation. Regarding the other rules, we highlight five relations: first, how energy policy affects payoff rules of the energy provision arena, i.e., the comparative prices of sources. Second, the effect of technology policy on boundary rules of the reinvestment arena: how much is available for a technology producer to reinvest? Third, how monitoring affects choice rules of all other arenas: should one revise its decision-making process? Fourth, how financing affects boundary rules of the financing arena: who may hold the position of financier and financed agents? Lastly, how technology producers' reinvestments affect scope rules of the energy provision arena, i.e., the risk-opportunity of a technology for the moment.

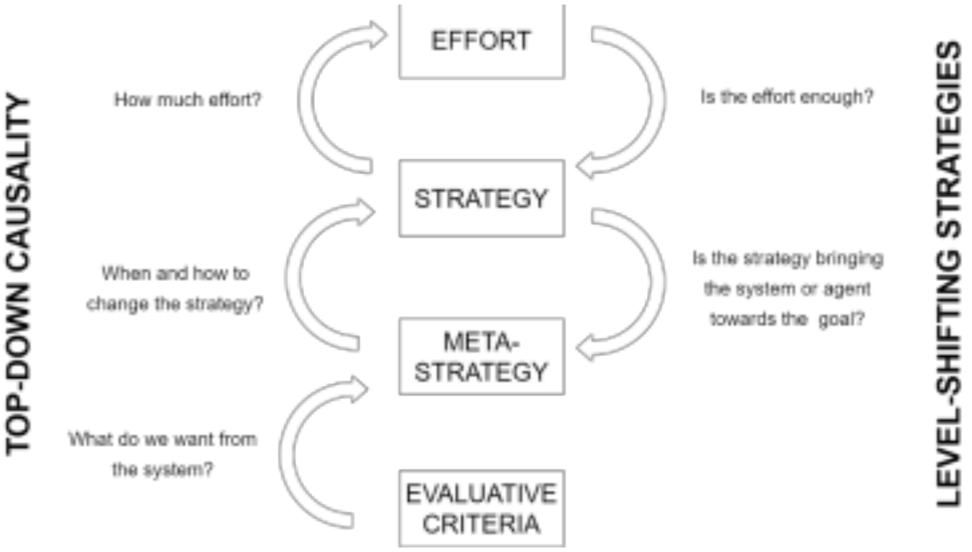

Figure 3 – Top down causality and level-shifting strategy for a generic agent in the system in relation to different situation types. Source: Own elaboration.

Figure 3 displays the difference between top-down causality and level-shifting strategies for an agent in the system. The effort that an agent puts on its activity is given by its strategies: e.g. the current policy. The strategy is given by its meta-strategy: e.g. which policy must the policy maker first attempt. The meta-strategy is given by its evaluative criteria: e.g. how will the policy maker evaluate sources and policies regarding one another in order to rank them in terms of most likely to be in force. The evaluative criteria itself does not change given the timeframe of the simulation.

The level-shifting strategies then change higher hierarchy variables if the necessary criticality is reached: if the effort is being consistently raised and the system is still far from reaching its goals, the likelihood of the policy maker changing its policy (or the incentivized source) increases. Subsequently, the system's response may also lead the policy maker into revising its revision-making process: how sources are ranked in relation to each other; or its own likelihood to change policies or incentivized sources.

4. Technology: progress and policy

Emissions of GHG come from multiple uses and sources, nevertheless, a significant portion of emissions come from electricity production, heating and transportation that use fossil fuels. For some uses and in certain conditions, some of those green technologies are competitive in relation to their fossil-based counterparts; nevertheless, more technological progress would be key for their diffusion. In fact, technological progress, innovation and diffusion were key factors for green technologies to come to their current stage. In that sense, innovation and diffusion are broad topics that encompass firms, universities, public research centers and more. For the model, we combine the agent who innovates with the agent that manufactures, delivers and installs the technology into the **technology producer**. Moreover, each sub technology may only have one technology

producer: we model competition among sources, not within producers of the same source[6].

The technology producer manufactures technology for producing energy, being goal oriented towards a satisficing behavior: it does not want to lag behind competition, but accommodates when far ahead of its competitors in terms of profits[7]. The technology producer connects to other agents by providing them with energy assets. In terms of its own behavior, a technology producer reinvests into either R&D or into productive capacity, separating part of its cash-flow according to its effort, i.e. its decision variable ($\square\square_{\square\square}$) is the percentage of how much of its cash-flow will be reinvested. The decision variable is given by the equation:

$$\square\square_{\square\square,\square\square} = \square\square_{\square\square} * (\square\square_{\square\square,[\square\square-\square\square,\square\square-1]} - \square\square_{\square\square,\square\square-1})' + (1 - \square\square_{\square\square}) * \square\square_{\square\square,\square\square-1} \quad (1)$$

In equation 1, $\square\square$ represents revenues in general, with $\square\square_{\square\square,[\square\square-\square\square,\square\square-1]}$ being the mean revenue of all $\square\square$ technology providers between the periods $\square\square - \square\square$ and $\square\square - 1$ of the simulation[8]. The variable $\square\square_{\square\square,\square\square-1}$ represents the revenue of the technology provider $\square\square$ at the period $\square\square - 1$. The higher its own revenues are in relation to its competition, the lower the result of their difference is, and vice versa. We use the normalized[9]value represented by $(\cdot)'$. The variable $\square\square_{\square\square,\square\square-1}$ represents the previous value for the decision variable for the technology provider $\square\square$ and the parameter $\square\square_{\square\square}$is a coefficient that controls how much of effort will be given by previous decisions and by the current state of affairs. As such, given the structure of equation 1 and the nature of the parameter $\square\square$, we highlight the relevance of path dependency in terms of decisions. Then, the technology provider reinvests $\square\square_{\square\square,\square\square}$ of its cash flow into either R&D or productive capacity. Innovation ($\square\square_{\square\square,\square\square}$) is given by the equation:

$$\square\square_{\square\square,\square\square} = \square\square\square\square\square\square\square\square\square\square\square\square\square\square\square(1) + \square\square(0,1) \quad (2)$$

The equation 2 is taken from Fagiolo and Dosi (2003). The first part $\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square(1)$ reflects disruptive innovation whereas the second part $\square\square(0,1)$ reflects marginal innovation. Innovation occurs when the amount put into R&D (in \$) reaches a certain threshold (a constant in \$) that is unknown to the firm itself. If the threshold is not reached at the current time, the total amount is carried over to the next period with a certain discount factor in order to reflect both loss of material and immaterial assets as well as overall technical progress in the economy. Different sources have different thresholds in order to reflect innovation differences among different technologies (HUENTELER et al., 2016).

A technology provider may innovate by reducing CAPEX or OPEX of its technology as well as by increasing the generation capacity of the minimum lump investment. Being $\square\square_{\square\square,\square\square}$the result of the innovation equation for the technology provider $\square\square$ at the period $\square\square$, it would reduce CAPEX or OPEX by $1/\square\square_{\square\square,\square\square}$ or increase capacity by $\square\square_{\square\square,\square\square}$. Values of $\square\square_{\square\square,\square\square}$ below one would be discarded, since they would reflect R&D that ended up with results

[6] In that sense we emphasize the heterogeneity between sources, not the heterogeneities between different companies that belong to the same source.

[7] We are aware of the importance of shares (LAZONICK; O'SULLIVAN, 2002), nevertheless, as the model only has a banking market and not a full fletched financial market, we opted to have companies decide in relation to their profits and not in relation to the shareholder value.

[8] Every value is discounted by time in order to reflect the higher importance of more recent events.

[9] Normalized by dividing it by the difference of the maximum and minimum revenues for the time between $\square\square - \square\square$ and $\square\square - 1$.

that fared worse than the already used techniques. The choice between CAPEX, OPEX or lump is uniformly random. The reduction of CAPEX or OPEX and the increase capacity of a single unit of investment reflects the changes in modern energy systems (JOSKOW, 2011; IEA, 2013, 2014; THE BRATTLE GROUP, 2015).

A technology provider that, on the other hand, reinvests into productive capacity may reduce CAPEX costs. Similarly to innovation it also has a threshold but in integer numbers. That thresholds represents how many times the investment into productive capacity must be for the CAPEX to lower.

□□□□□□□□□□□□□,□□ = □□□□□□ (1, □□□□□□□□□□□□□□□□ / □□□□* □□□□□□□)^{□□□□□□□□□□□□□□□□□□□□□□} * □□□□□□□□□□□□□□□□□□□□ (3)

On equation 3 the current value of CAPEX for a certain □□ technology producer is given by a fraction of its base CAPEX. Such fraction is given by how much the productive capacity of the □□ technology provider in the □□ − 1 period (□□□□□□,□□−1) is bigger than □□□□times its base CAPEX. Nevertheless, such process only occurs if the technology has significant transportation costs (□□□□□□□□□□□□□□□□□□□□□□□ = 1), if not (□□□□□□□□□□□□□□□□□□□□□□□ = 0), then the CAPEX remains at its base level regardless of the investment in productive capacity.

Equation 3 thus reflects the internalization efforts effects' of parts of productive chains for novel technologies, i.e., the increase in local manufacture items or parts of technologies that are still locally incipient. Such efforts in terms of policy are normally related to job creation and development (MAZZUCATO, 2015; MAZZUCATO; PENNA, 2015).

In that sense, in our model, technology is composed of CAPEX and OPEX, capacity factor and minimum plant size or minimum lump size investment (in MW). There is also time variables: time to build the infrastructure and lifetime of the investment. We also have the amount of CO2 that the source emits.

Technology producers affect their environment as much as they are affected by it. They are goal-oriented agents that, within their strategy, act towards their goals. As such, they monitor their environment and their insertion in it in order to evaluate their course of action. When some certain conditions are met, a technology producer may engage in changing the rules that guide their actions: if they reinvest into productive capacity or into R&D; how much time they take into account when analyzing past actions; or □□. Technology producers cannot change the source that they produce.

Technology producers may engage in rule changing activities when profits start to fall below their historic average:

□□□□□□□□□□□□□□□□□□□□ = {□□ℎ□□□□□□□□□, □□□□ □□□□,□□−1 < (1 − □□□□) * □□□□,[□□−□□,□□−1] (4)

□□□□□□□□□□□□□□□□□□□□□□, □□□□ □□□□,□□−1 > (1 + □□□□) *

$□□_{□□,[□□−□□,□□−1]}$

According to equation 4, when current revenues of a technology producer $□□$ at the previous)

period fall below the historic average between $□□ − □□$ and $□□ − 1$ periods ($□□_{□□,[□□−□□,□□−1]}$ discounted the costs of changing $(1 − □□_{□□})$, then the agent may engage in changing its strategy. It mainly follows Ostrom's (2005) rule-changing equation.

When the situation described in equation 4 is of change, then the agent runs a . If the distribution results

$□□(0,1)$ distribution with a threshold equal to $□□_{□□,□□−1}/□□_{□□,[□□−□□,□□−1]}$

are above the threshold, then the agent actively engages in changing the rules that it uses according to its strategy hierarchy. Normally a firm would have $□□$ variables that it changes in order to pursue a better strategy, nevertheless we bring it down to up to three variables: one that is changed when the distribution threshold is reached (as described) and two that are reached when its score is brought down to zero.

A variable's score is equal to, at the start, $10 * (1 − □□_{□□})$ for the scored variable of lower hierarchy and $10 * (10 − □□_{□□})$, i.e., the more prone to adapt the agent is, the more prone the agent is to revise its strategy. Moreover, they will change first variables that are of a lower hierarchy. The scores are affected when any situation described by equation 4 is true, decreasing the scores of the variables by 1 if the decision is to change or increasing those scores by 1 if the decision is to reinforce. Moreover, if the distribution threshold is reached, then the increase or decrease is changed to 3. With that we allow for the build up of criticality even with situations in which the decision, at first, was to keep the status quo (when the distribution threshold is not reached). When the score of a variable reaches zero and that variables suffers change, its score goes back to its starting value.

The technology provider is affected by its context and as such by the agents that acquire its technology (energy producers), the banks that finance such acquisition (private banks or the development bank) as well as by the energy policy maker that affects the relative prices per source. Nevertheless, one policy maker directly affects the technology provider: the technology policy maker.

The **technology policy maker**, as well as the other policy makers, has a fixed budget to use for its policies. There are multiple types of technology policy, nevertheless we focus on direct incentives to companies. In a nutshell, the technology policy then increases the cash flow for certain technology providers that focus on the incentivized source[10].

As such, the policy maker decides how to much use of its budget. Its decision variable is then a percentage. A policy maker wants to steer the private agents towards its goal with the least amount of effort possible, i.e., the technology policy maker wants to provide incentives that are just enough to incentive the diffusion of the incentivized source. Its goal may be given in terms of a certain target or in terms of the overall speed of the diffusion. In other words, the technology policy maker may have a specific target to guide its policies or just aim to increase the diffusion of the incentivized technology, avoiding a reduction in its rhythm of diffusion.

$$□□□□□□(□□□□□□_{□□□□□□□□□□□□□□□□□□□□□},$$

$$□□_{□□,□□□□□□} = □□_{□□□□□□□} * (1 −$$

$$□□□□□□_{□□□□□□□□□□□□□□□□□□□□□})−□□)$$

$$(□□□□□□_{□□□□□□□□□□□□□□□□□□□}−□□$$

$\square\square^{\square\square\square\square\square\square}) + (1 - \square\square_{\square\square\square\square\square\square\square}) * \quad \square\square_{\square\square-1,\square\square\square\square\square\square}$ (5)

If the policy maker’s goal is given in terms of a target, then its decision variable follows the equation $\square\square_{\square\square,\square\square\square\square\square\square} = \square\square_{\square\square\square\square\square\square\square} * \quad ^{\square\square\square\square\square\square_{\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square})-\square\square})}$ $(1 - (^{\square\square\square\square\square\square}{}_{\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square-\square\square} \quad \square\square^{\square\square\square\square\square\square}) + (1 -$

$\square\square\square\square\square\square(\square\square\square\square\square\square_{\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square},$

$\square\square_{\square\square\square\square\square\square\square}) * \square\square_{\square\square-1,\square\square\square\square\square\square}$ (55 Similarly to the previous decision variable equation, it is given in part by current events ($\square\square_{\square\square\square\square\square\square\square} * (\cdot)$) and by previous decisions ($(1 - \square\square_{\square\square\square\square\square\square\square}) * \square\square_{\square\square-1,\square\square\square\square\square\square}$). In that equation, its effort is given by the ratio between the accepted deadline for the target to be reached ($\square\square\square\square\square\square_{\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square}$) and the expected time it will take the system to reach that

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[10] If there is more than one company in the selected source, the division is equal.

target ($\square\square\square\square\square\square_{\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square}$). If the expected time is lower than the deadline, than that ratio becomes one and the decision variable is given exclusively by past decisions, i.e. the policy is going according to plans. Each deadline is discounted by the current period. With that, the numerator becomes the amount of time that the system may reach its target, and the denominator becomes the amount of time that the system will reach its target. In other words, it becomes a ratio between the accepted and expected time for the system to reach the pre-determined target.

With that equation, we are able to replicate three behaviors of policy makers: first, they are more eager to take action when deadlines approach. Secondly, policy makers are more eager to take action when there are signals that the system will not reach the target by the deadline, with the opposite side effect being that when it appears that the system is responding to its incentives then the policy maker reduces its effort. Lastly, that equation replicates the behavior that the more responsive to the system a policy maker is, the more eager to take action a policy maker is.

An important factor is that the policy maker changes its decision variable in chunks: the decision variable must trespass a certain threshold in order to become the disclosed variable. Without reaching that criticality, any new value for the decision variable will be internal to the policy maker: it indicates tendency but remains undisclosed. Essentially, it must be $1 - \square\square_{\square\square\square\square\square\square\square}$ or $1 + \square\square_{\square\square\square\square\square\square\square}$ times lower or bigger than the current disclosed variable. $- \square\square_{\square\square-1})' + (1 - \square\square_{\square\square\square\square\square\square\square}) * \square\square_{\square\square\square\square\square\square\square,\square\square-1}$ (6)

$\square\square_{\square\square\square\square\square\square\square,\square\square} = \square\square_{\square\square\square\square\square\square\square} * (\square\square_{[\square\square-\square\square,\square\square-1]}$

If however, the policy maker’s goal is given by the speed of diffusion of a certain source, then its decision is given by the equation 6. Similarly to the equation 1, the policy maker calibrates its effort in relation to how much better or worse the system is in relation to a certain score ($\square\square$).

The technology policy maker, similar to other policy makers has its goal related to a certain rationale that is one of three: green, development or innovation. A green rationale means that the policy maker wants to reduce emissions of the system. A development rationale means that the policy maker wants to increase investment into productive capacity. An innovation rationale means that the policy maker wants to increase the investment into R&D.

A policy maker’s rationale is also responsible for how it compares sources. A policy maker analyzes how the system is responding in terms of its rationale both in a backward looking fashion (what happened) and in a forward-looking fashion (what may happen).

$$[illegible]_{[illegible],[illegible]} = \frac{[illegible]^{[illegible]}_{[illegible],[illegible]-1} - [illegible]}{[illegible]-1}$$

$$\frac{\sum [illegible]_{[illegible]} + (1 - [illegible])^{[illegible]}_{[illegible],[illegible]-1} - [illegible]_{[illegible]-1}}{\sum [illegible]_{[illegible]} + [illegible]_{[illegible],[illegible]-1}} * (1 - [illegible]) \quad (7)$$

According to equation 7, the policy maker determines the score of a certain source at the current period ($[illegible]_{[illegible],[illegible]}$) in relation to how better or worse the score for that source is in relation to the policy maker’s rationale both regarding its backward-looking and forward looking variables. Moreover, it is accumulated over time, with the previous score, discounted by a factor [illegible], being part of what determines the current score. The parameter [illegible] determines how important the backward-looking portion of the analysis is.

Rationale	Green	Development	Innovation
Backward	Avoided emissions (how much would have to be emitted in order to produce the same GWh if using fossil)	Investment into productive capacity (in $, executed)	Investment into R&D (in $, executed)
Forward	Avoided emissions if the best technology in the source was used	Investment into productive capacity (in $, if all profits were reinvested)	Investment into R&D (in $, if all profits were reinvested)

Table 4 – Variables used to asses the scores for the backwards and forward parts of the total score, according to different rationales.

Similarly to the technology producer, it may change what it is currently doing when things go south. The technology policy maker analyzes how the policy is steering the system towards its goal. As such, it may engage in rule changing activities when certain criteria are met, according to equation 8. In that equation, [illegible] may either be the score (if the policy maker focuses on the speed of diffusion) or the expected vs. accepted deadlines for the target to be reached.

$$\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square = \{\square\square h\square\square\square\square\square\square\square\square\square, \square\square\square\square\ \square\square_{\square\square,\square\square-1} < (1-\square\square_{\square\square}) * \square\square_{\square\square,[\square\square-\square\square,\square\square-1]}$$

$$\square, \square\square\square\square\ \square\square_{\square\square,\square\square-1} > (1+\square\square_{\square\square}) * \square\square_{\square\square,[\square\square-\square\square,\square\square-1]} \quad (8)$$

If one of the two are true, then the policy maker runs a $\square\square(0,1)$ with the threshold being the ratio of the two sides of the inequality without the $\square\square_{\square\square}$. If the result of the distribution is above the threshold, then the policy maker follows a similar process to the rule changing activity of the technology producer. The exception is that if the policy maker is reinforcing its activity, it may add the current policy to a policy pool in order to be executed for $\square\square\square\square\square\square_{\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square}$ months. A portion of the budget ($\square\square\square\square\square\square\square\square\square\square\square\square * \square\square_{\square\square}$) is then separated for that policy to be executed until its deadline.

On the other hand, if the policy maker is changing policies, it may either change: the incentivized source; the policy being used; or even decision making variables ($\square\square_{\square\square}$ or its goal). What it may change depends on the score of the variable, in the same process of the technology producer with its hierarchy of change. If the policy maker changes sources, it runs a $\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square(1)$ in relation to its ranking of source according to each source's score.

5. Energy: provision and policy

Energy providers acquire assets from the technology providers in order to meet the assessed demand. Energy providers specialize into either providing electricity or molecules to the energy system. Such agents have to decide: 1) if they will invest, 2) if so, how much, 3) in which source, 4) in which technology within that source.

Both 1) and 2) are answered by its decision variable. Similarly to the technology providers it also follows the equation 1. The decision variable is then multiplied by the total demand for either molecules or electricity divided by the number of energy providers.

In relation to 3), the source that the energy provider will use depends on its strategy. If there is more than one technology producer within the chosen source, i.e., if the energy producer must choose between technologies, then it will rank them in terms of NPV and choose the one with the highest NPV. All the capacity that the energy provider is willing to contract and install is allocated to one single source.

Similarly to the technology producer, it may change or reinforce its strategy when revenues are above or below the expectations. When changing the source, it runs a $\square\square\square\square\square\square\square\square\square\square\square\square\square\square\square(1)$ over the ranked scores for each source. Similarly to the policy maker, it ranks each source based on two components: a backward-looking portion, that analyzes the *de facto* revenues for that source at the $\square\square - 1$ period; and a forward-looking portion, that analyzes the revenues that would occur if the whole demand was met by the best technology of that source. The two components are combined with an algebraic sum with a $\square\square$ factor that determines the relative weight of those components.

Nevertheless, there is an index that weights those decisions. Such index is given by how much of that energy producer's installed capacity is put into that source. That aims to reflect sunk costs and therefore the opportunity cost of swapping sources after so much has been invested into the first source. Energy producers may use the full index or 1-index, respectively reflecting homophily and preferential attachment.

Energy providers then decide which bank to ask for financing, ranking all banks in terms of their interest rates and starting with the bank with the lowest. If the financing does not come through, then the energy producer will change the attempted bank. If the bank is not willing to finance the asset acquisition and the energy provider has the necessary funds, it reinvests into the capacity.

The policy maker that directly affects energy producers is the **energy policy maker.** Much of its inner working are similar to that of the technology policy maker. What changes is the kind of policy that it performs: it may do carbon tax, feed-in tariff or auctions.

Carbon tax simply increases fossil's OPEX costs by $1 +$ [illegible]. In that sense, the policy maker may double the OPEX costs for fossil technologies. Carbon tax affects both old and new investments in fossil. FiT are essentially feed-in premium: it takes the current market price and multiplies it by $1 +$ [illegible] for the incentivized source.

Regarding auctions, first it announces that an auction will occur, collecting projects for it for a certain number of months. One important aspect is that when announced, energy producers add to their forward-looking part of their revision framework the NPV of a plant if they invest into that source. That occurs in order to reflect their analysis of the long-term possibilities of a PPA. During that time, all projects within the source (or sources) targeted by the auction will be put into the auction.

When the time for the auction comes, the energy policy maker collects all projects sent to the auction and contracts [illegible] $*$ [illegible] GWs. The policy maker then contracts projects ranked by their price until all projects are accepted or the cap capacity is reached. Cap capacity is basically a fraction of the max capacity for an auction.

Auction contracted projects are awarded a 20 year to 25 year PPA, replacing the market price. Moreover, for private banks there is no cash-flow risk, thus affecting their risk assessment for those projects

6. Financing: private and public

Banks finance the acquisition of capacity by energy providers. Banks can be broken down into **private banks** and a **development bank**. The decision variable of both banks determine their interest rate: private banks increase the minimum interest rate of the market by $1 +$ [illegible] and the development bank decrease the minimum interest rate of the market by $1 -$ [illegible]. The private banks assess risk for each source in terms of the relative weight of that technology in terms of the system's output of electricity or molecules in relation to the technology that produces the most, according to equation 9. For example, if wind and solar are respectively responsible for 35% and 15% of the electricity output, but fossil is responsible for 50%, then the risks would be 0%, 15% and 35% for fossil, wind and solar respectively.

[illegible] = [illegible] − [illegible] (9)

Having assessed risk, the bank then accepts to finance sources with a risk that is lower than its decision variable. In combination with its satisficing behavior that means that, banks that are lagging behind, would be more willing to finance riskier sources. Following the past example, if two banks have decision variables of 0.05 and 0.3, then the first bank would only finance fossil, whereas the second bank would also finance wind; and solar would be financed by any bank.

The decision variable for private banks follows the equation 1, but banks analyze its revenues in relation to the revenues of other banks. Having decided the risk, banks analyze projects that were sent to them at the previous period. They rank those projects in terms of the risk-assessed NPV: there is a cash-flow risk for each period and a financing risk. Essentially, they increase the CAPEX of the bank by $1 +$ [illegible] and decrease the earnings ([illegible] $*$ [illegible] $*$ [illegible]) by $1 -$ [illegible]. Nevertheless, if the investment has a guarantee, financing risk does not apply, the same happening to cash flow risk when the investment is auction-contracted. Moreover, when the investment is auction-contracted, the price that determines the NPV is the actual auction price. In relation to the average price of the source, it considers all active investments in that source: if they are contracted they have their price (be it market, auction-contracted or with the FiT). If there is no active investment in that source yet, it uses the lowest price. The price is a weighted average in terms of the output (GWh). The bank then accepts projects until a limit of net worth over receivables is reached. That limit reflects Basel III convections of leverage and net stable funding ratio (<10%).

The development bank focuses its efforts on certain sources. The development bank can either provide direct lending or guarantees to projects. When providing direct lending, the process is similar to that of private banks, but when providing guarantees, the development bank simply states that it will cover the remainder of the investment in case that the energy producer cannot pay their fees to the private bank that do accept to finance the investment. In the latter case, private banks would analyze the project without financing risk.

A distinction of the direct lending done by a development bank instead of private banks is that the development bank does not assess distinctive risks for each source. The decision variable is used to determine the minimum requirements of each technology in order to access incentives. The decision variable determines the requirements in terms of percentage.

Goal	An X% of requirements means that…
Green	The specific technology must be able to reduce emissions in X% in relation to its fossil counterpart
Development	The specific technology must have at least X% of the total investment in productive capacity
Innovation	The specific technology must have at least X% of the total investment in R&D

Table 5 – Meaning of a certain percentage of requirements by the Development Bank according to different rationales. Source: Own elaboration.

In order to accept to finance or give a guarantee to a certain operation, the development bank compares the distance between technologies in terms of their avoided emissions, investment into R&D and investment into productive capacity (Table 5). Depending on its current decision variable, it may or may not provide the incentive: the threshold for accepting to do so is equal to $1 - \text{[illegible]}_{\text{[illegible]},\text{[illegible]}-1}$ and the technology must be in the superior quantile determined by the threshold in terms of the observed variable.

For example, if a certain technology lies on the superior quartile in terms of the R&D expenditure and the development bank has a decision variable of 0.25, it will accept to finance that asset acquisition. On the other hand, a technology that lies on the superior half would not be incentivized. Each accepted source retains its current requirements, nevertheless they do not have a separated budget for perennial policies, and instead having to fit into the receivables/net worth ratio after all current incentivized sources have been analyzed.

The development bank may change or reinforce its policy, similarly to the other policy makers. The development bank does not have different policies per source, but rather will take into consideration all the different accepted sources, each with its correspondent threshold. One important aspect is that if all sources have been explored, then the development bank will reevaluate the policy with the highest risk.

7. Expected results, discussion and concluding remarks

In order to methodize and streamline the analysis, we analyze 24 indicators: the speeds of technology diffusion, technology innovation and development of local productive capacity for each renewable source (12); the standard deviation between the speeds among electricity, molecules and among all renewables (9); and the aggregate speeds for all renewables (3). By systematizing results, we allow for clearer comparison among cases: in general, the best possible result combines high speeds on all fronts with low standard deviations among sources. With those results, the system combines a high penetration of highly productive renewable technologies with a large development of local productive capacities for a widespread number of technologies. Worst-case scenarios are the opposite, in which there is no penetration of renewables and they remain underdeveloped both in R&D and in industrial terms. Nevertheless, the most interesting results occur between the two cases, mainly under two categories: difference among sources and/or differences among technology diffusion, technology innovation and development of local productive capacity. The three types of speeds that we analyze are the emergent phenomena of the model.

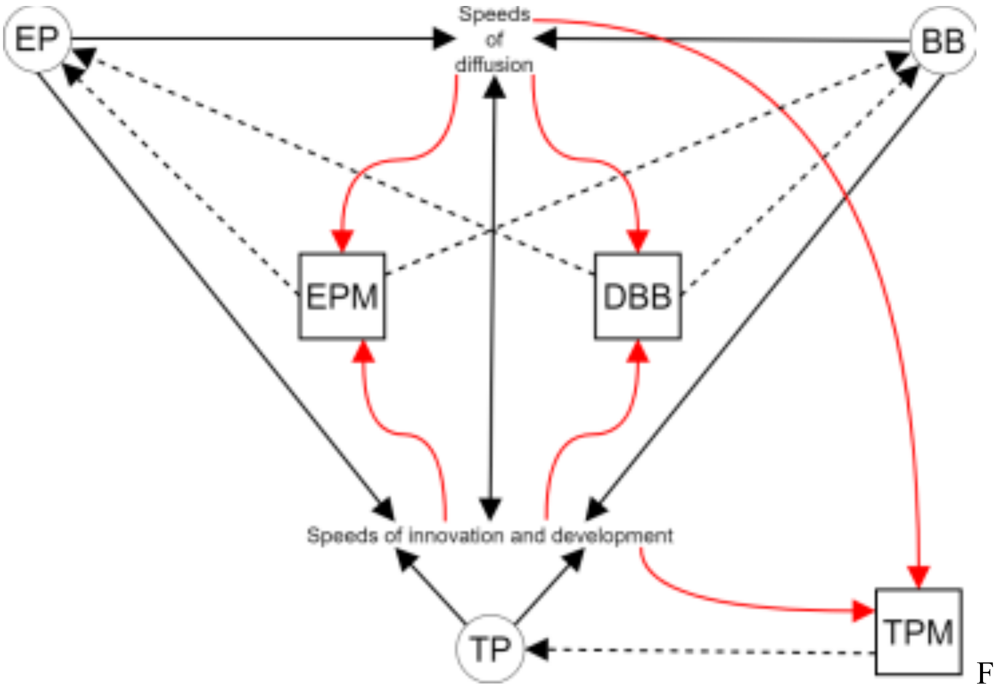

Figure 4 - Relations between agents and emergent phenomena. Source: Own elaboration

Figure 4 depicts the relations between agents and emergent phenomena in the simulation. Red arrows indicate revision based on a certain phenomenon. Black arrows indicate direct interactions. Dashed arrows indicate direct relations between public and private agents. With more assets being financed and built, there is an increase in cash flow for technology producers, which may lead to higher speeds of innovation and development. An increase in those speeds influence the speeds of diffusion by changing the NPVs of those technologies. On the other hand, the more diffused a technology is, the lower its risk perception is and the easier it is for that technology to be financed. Policy makers revise their policies according to the speeds and they influence those speeds through their policies: the EPM affects the NPV of new investments and may reduce risks with FiT and auctions; the DBB may reduce risks with guarantees or lend directly to EPs; and the TPM directly affect NPVs in future periods with its technology policies.

In conclusion, the emergent phenomena that we observe (the speeds of diffusion, innovation and development) and to the confluency or divergence of goals among the different policy makers involved. Higher speeds of diffusion are linked to closer-to-goal results and to goal-confluency among policy makers; whereas lower speeds of diffusion are linked to further-to-goal results and to some degree of goal-divergence. Full goal divergence, i.e., each policy maker focusing on one specific goal, tends to lead to undesirable results by the point-of-view of the policy makers themselves. If all policy makers agree on the same goal, they tend to focus on the same technology, giving it a lead over the competition, thus leading to a quicker diffusion, nevertheless, such winner picking may lead to the demise of prominent competitors and their technologies and also

may lead the picker-winner to reinvest less into productive capacity and R&D activities. As such, in this case, even though goals are fulfilled, technologies may be less developed (and thus more capacity is needed) and there may be less local development of industrial capabilities. On the other hand, with some degree of goal-divergence, the speed of diffusion may be slow at first, especially while competition is more fierce, but the end result tends to be more innovative technologies (and thus less capacity is needed) and more local development of industrial capabilities. As such, at first it may seem that the system is not going towards policy makers' goals, but it may soon pick up speed due to the fact that renewable technologies became more attractive than their fossil counterparts.

Moreover, one important aspect is that goal-divergence may lead to system results with more development and innovation, but goal-divergence may also lead to unwanted results. In other words, goal-divergence has more uncertainty as to what result will the system get. On the other hand, goal-confluency almost certainly leads the system towards less development and innovation, but leads the system towards goal-completion and avoids most unwanted results.

As such, we advocate that one cannot always recommend goal-divergence over goal divergence or vice-versa: it highly depends on the context, on the goals themselves and on the period. It also depends on the policymaking abilities of the policy makers, since goal-confluency appears to be more manageable than goal-divergence, with the latter requiring more rule-revisions and more policies in order to achieve goals, i.e., more active policymaking.

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