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SEQUENTIAL COORDINATION OF POWER GENERATION AND NETWORK INVESTMENTS : THE ROLE OF RENEWABLE INCENTIVES

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Abstract

The development of renewable, variable and decentralized electricity production raises many challenges for all the electricity system stakeholders. The massive introduction of renewable and variable sources requires a rethinking of network operators' business models. In this paper, we therefore address the central issue of coordinating investments in the electricity network and in renewable energies in a context of unstable subsidies. Through a three-stage strategic game, we develop a benchmark model where the operator is proactive and then confront it with an alternative model where the operator is reactive. We use dynamic stochastic modeling to formalize actors' choices as a mathematical program with equilibrium constraints. The study's major result is to show that a proactive operator may cause a loss of welfare compared to a reactive operator. This depends mainly on the weight of network costs and time periods, the intensity of support measures towards renewable energy and the maturity of renewable technologies.

Keywords: coordination, proactive, reactive, premium, modeling, investment, power network, renewable energy

I. Introduction

The development of renewable, variable and decentralized electricity production – and changes in consumption patterns, in particular the development of electric mobility – raise many challenges for all players in the electricity system. The energy transition will require a profound transformation of the energy system to facilitate the massive integration of renewable and intermittent energies and to make electricity and hydrogen the central vectors of this transformation. Access to energy is currently operated through a centralized management mechanism by power system operators ensuring the integration of new technologies, so-called flexibility; with a security paradigm strictly ensuring the balancing of the network, historically adapted to conventional technologies and unidirectional energy flows. The massive introduction of renewable and variable energy sources requires of network operators to rethink their business models.

With the opening of the electricity markets to competition, generation investment decisions are made by generation companies to maximize their profits. In contrast, planning for the expansion of power systems still remains regulated transmission companies' responsibility, almost entirely. Indeed, in many network industries such as rail, gas and electricity, liberalization has led to the "unbundling" of the network as a monopolistic bottleneck for potentially competitive parts. The rationale for network unbundling is to prevent a vertically integrated company from using network access to discriminate against potential downstream competitors. This vertical separation has introduced a new problem, namely how to coordinate investment in the network with the competitive parties' investments. Investment coordination is becoming increasingly relevant in countries that are restructuring their industries toward a greater share of renewable electricity generation.

This raises the important question of how these sunk investment decisions should be coordinated. Indeed, the electricity sector, which has long been organized around an integrated generation-transportation monopoly, sometimes including distribution, is experiencing coordination problems that need be addressed through implementing adequate mechanisms.

In addition, in order to achieve the energy transition's ambitious objectives, many countries have put in place, over the last two decades, support mechanisms for renewable energies aimed at speeding up investments. That way, governments want to encourage investment and ensure renewable energy production's competitiveness. As of 2017, 128 countries had regulatory mandates and incentives for renewable energy[1]. However, in recent years, many support schemes have been revised or retracted suddenly and unexpectedly. For example, in 2014, the amounts of subsidies paid to generators was retroactively adjusted in Bulgaria, Belgium, the Czech Republic, Spain, and Greece (Boomsma and Linnerud, 2015). In the same year, feed-in tariffs were reduced in Germany, Bulgaria, Greece, Switzerland, and Italy and (REN21, 2015). In addition, Ukraine removed a tax exemption for companies selling renewable energy (REN21, 2015). In 2018, China also made a sudden revision in its feed-in tariff making new solar power projects less likely to be eligible for subsidy (The Economist, 2018). Thus, there is uncertainty surrounding the continuation of renewable energy support schemes. The likelihood of support schemes being withdrawn is bound to change producers' investment behavior (Roel et al., 2021).

The regulatory instability associated with renewable energy support is partly the result of technological advances. Indeed, a subsidy's purpose is to ensure renewable energy production's competitiveness. Thus, when there is such a technological advance that the technology is profitable on its own, the subsidy is no longer needed and can be withdrawn. It can also be withdrawn when the original renewable energy capacity target has been met or the budget exhausted. In addition, a policy can be revised or withdrawn due to a depleted budget, as was the case in Italy regarding their support of solar photovoltaics (PV) in 2013 (Karneyeva and Wüstenhagen, 2017). However, in some places, green technologies still cannot survive without subsidies (Institute for Energy Research, 2017).

This paper is structured around the central issue of coordinating investments in the electricity network and renewables in a context of regulatory instability in renewable energy support mechanisms. We explore the coordination of the network operator's investment choices, in a regulated monopoly situation but with an increasingly performance-based regulation, and decentralized actors' investments. Indeed, these decentralized productions can create an availability gap between the new network infrastructures and the energy supply development, as well as technical overloads linked to network congestion and overvoltage problems. It is also important to analyze renewable energy producers' investment behaviors. To do so, we consider a benchmark model where the network operator is proactive, which we then confront with an alternative model where the operator is reactive. In the proactive case, the operator is the leader of the game, he anticipates the behavior of producers and invests accordingly to integrate new productions. But in the reactive case, the operator first observes the producers'

[1] https://www.ren21.net/gsr-2018/

investment decisions before making his investment decisions. It is also important to analyze the investment behavior of renewable energy producers who face a double constraint: the instability of support mechanisms and the unavailability of the network. They must therefore make an arbitration of their investment choices taking into account the likely evolution of support mechanisms and the present and/or future availability of the network.

In the economic literature, our paper contributes to the analysis of regulation's effect on the infrastructure sector in an uncertain environment (Dobbs, 2004; Guthrie, 2006; Evans and Guthrie, 2012; Broer and Zwart, 2013; Willems and Zwart, 2018; Guthrie, 2020; Azevedo et al., 2020). Most of these studies acknowledge the importance of uncertainty in regulatory capital investment analysis. Adopting a real options approach, they focus specifically on welfare effects in a game between the regulated monopolist and the social planner. They assume that the regulated monopolist not only provides infrastructure but also makes production decisions. As a result, they generally do not take into account the interactions between regulated entities and deregulated private firms. In practice, this assumption does not hold, given the deregulated nature of most infrastructure industries in OECD countries. In the example of the electricity sector, the energy regulator is responsible for policy, the DSO (the regulated monopoly) provides the necessary network infrastructure, while generation decisions are made by market stakeholders. All these decisions shape the evolution of the electricity sector. It is therefore necessary to take them into account to achieve socially desirable outcomes. Through a three-stage strategic game, this paper determines system actors' optimal coordination that maximizes societal welfare. We consider that only renewable resource operator and producers are active players in the game. We develop a benchmark model where the operator is proactive and then compare it to an alternative model where the operator is reactive.

In contrast to these studies, in our paper we consider a regulated monopoly that maximizes social welfare and strategic producers that maximize their profits. Similarly, to Sauma and Oren (2006), Biggar and Hesamzadeh (2014), we distinguish between two sequential approaches to coordinating network and generation investments: The proactive approach on the one hand and the reactive approach on the other. In the proactive approach, the network operator announces its future plans for network expansion and then leaves it to generators to decide where to expand their generation capacity. In the reactive approach, however, generators act first. They decide on their investments and then the network operator reacts and plans the network expansion accordingly. Madrigal and Stoft (2011) explain both approaches and focus on the benefit of proactive coordination to build transmission capacity that will allow for timely integration of new renewable generation, given the longer lead time of network investment projects than of generation.

Hesamzadeh et al., (2011) model proactive coordination in a context of strategic generator investments. They model the problem faced by a network planner using the social welfare concept of economics. Moreover, producers' behavior is modeled as the Nash equilibrium of a strategic game. The concept of the Nash solution is then reformulated as an optimization problem and a new concept – the Stackelberg-Worst Nash equilibrium – is introduced to solve the multiple equilibrium problem. The proposed structure can take into account the effects of the transmission network expansion on market power and strategic investments in production.

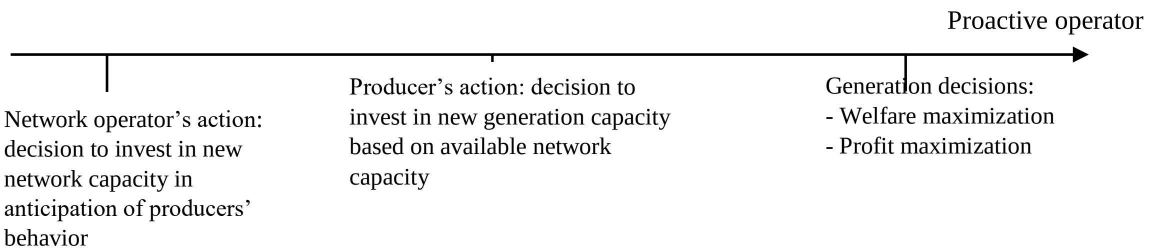
In addition, Sauma and Oren (2006, 2007) propose mathematical models for both reactive and proactive approaches. They show that proactive coordination leads to greater social welfare compared to reactive coordination. According to Hesamzadeh et al., (2016) this inaccurate assumption of continuous variables invalidates their evidence of higher social welfare in proactive coordination because decisions are discrete. Rious et al., (2011) and Lavrutich et al., (2022) consider a proactive network operator and show, through a dynamic game, how the conflicting goals between a profit-maximizing private firm and a welfare-maximizing network operator affect social welfare through their decisions about investments timing and size. As an extension of these three papers that have inspired our model, we bring elements of analysis based on different parameters and actors. Indeed, these papers do not distinguish between conventional and renewable producers, which have different characteristics. One of this work's main originality consists in evaluating the good timing of network investments compared to investments in production units according to two major issues of the energy system at hand. On the one hand, the regulatory context in terms of incentives for renewables, formalized by two parameters: the expected renewable premium level, as well as the signals on its sustainability over time and its stability. On the other hand, we take into account the weight of the time period in new networks operation as a determinant in evaluating the opportunity costs that can be generated by proactive network planning. We therefore study both how the subsidy (the premium) and the operator's investment trajectory affect the renewable's investment decisions (time and size) and, in turn, the social planner's objectives. Finally, unlike the literature where modeling is primarily based on numerical simulation approaches (Sauma and Oren, 2007; Hesamzadeh et al., 2016), we provide evidence for a comparison between proactive and reactive operators by developing a model that solves a three-stage dynamic game, offering tractable analytical results. In contrast to the literature evaluating proactive network operator (Sauma and Oren (2006), Biggar and Hesamzadeh (2014), Lavrutich et al., (2022)), we show that a proactive operator may cause a loss of welfare compared to a reactive operator. This mainly depends on the weight of network costs and time periods, the intensity of support measures towards renewable and the maturity of renewable technologies.

The paper also contributes to the literature that studies the effects of subsidies on green investments. For example, some papers focus on carbon pricing and study how policy uncertainty affects price volatility (Yang et al., 2008; Fuss et al., 2008; Kang and Letourneau, 2016). Others focus on the combination of carbon tax rate reduction and subsidy (Bigerna et al., 2019; Abrell et al., 2019; Danielova and Sarkar, 2011). In addition, recent papers related to renewable energy consider policy uncertainty related to random withdrawal, revision, and granting of a subsidy (Boomsma and Linnerud, 2015; Ritzenhofen and Spinler, 2016; Eryilmaz and Homans, 2016; Adkins and Paxson, 2016; Chronopoulos et al., 2016). They study how uncertainty in the availability of a certain type of subsidy affects investment behavior. The effect of uncertainty as regards the availability of a subsidy on investment behavior highly depends on the type of subsidy in place, as well as the uncertainty level. Nagy et al., (2021) study a lump-sum investment subsidy and the role of the subsidy size and the risk of potential subsidy withdrawal on investment. They also study the effect of political risk on social welfare and social planner goals. They conclude that a higher probability of investment subsidy withdrawal harms both the policymaker's ability to increase renewable energy capacity and welfare. We contribute to this literature by introducing the effect of coordination between the network operator and renewable generators on green investment behavior.

The remainder of this paper is organized as follows. We introduce the model and its features in Section 2. In this section, we detail the game that is our study's subject, by presenting the main actors, the main assumptions and notations. In Section 3, we present our model's main theoretical results. The last section concludes the paper with the main results.

II. Model

We develop a three-stage stochastic dynamic game model to evaluate the long-term optimal coordination between the main active players in the system i.e., the network operator, the new conventional and the renewable. This is a 3-stage sequential game (Figure 1) where the network operator can be proactive (baseline model) or reactive. In the proactive case, the network operator is the leader of the game, he anticipates the behavior of producers and invests accordingly to integrate new productions. But in the reactive case, the network operator first observes the producers' investment decisions before making his investment decisions. The proactive model's first step concerns the network operator's investment decisions, the second producers' investment decisions and the last the generation decisions. But in the reactive case, the first step concerns the investment decisions of the generators, the second concerns the investment decisions of the network operator and the last concerns the generation decisions. When we are in the proactive case the new network capacities and the new renewable generation capacities are operational at the same time. However, in the reactive case, the new network capacities will be operational with a delay of d years due to the longer network update times. In the rest of our work, we will focus on the proactive case to which we will later make modifications to formulate the reactive case. Following the two cases analysis, we will make a comparative study to find the socially optimal case. The model is formulated as a mathematical program with equilibrium constraints and we use the mixed complementarity problem technique to solve the subproblems of the game and find the equilibrium at each stage (Gabriel and Smeers, 2005; Clastres and Khalfallah, 2021). This model's main objective is to analyze the different actors' strategic behavior and find the optimal situation for the company as a whole.



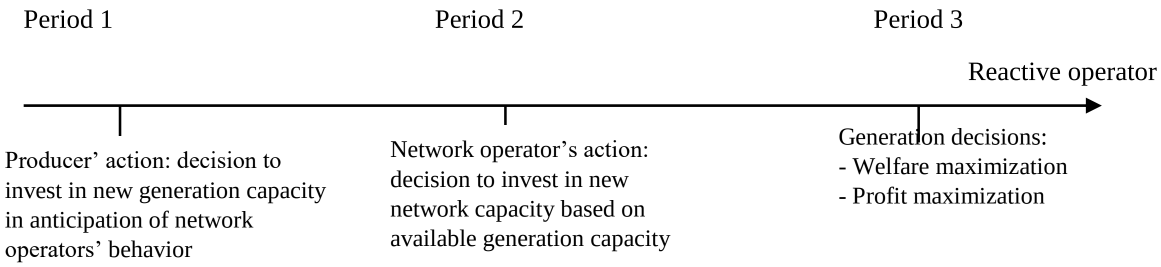


Figure 1: schematic representation of the game

1. Model assumptions

The system is a zonal one where the system operator is in charge of balancing the network and providing the network infrastructure. Faced with a growing projected demand, the network operator balances the system by anticipating producers' reactions who make decisions in a competitive environment by maximizing their individual profits. In this competitive market, two types of operational producers interact: the producers already present on the mainly conventional and old technologies market; and the new entrants on the market that can be renewable or new conventional with more efficient technologies. We consider that only the network operator and the new entrants are active players.

Furthermore, the model is dynamic and stochastic because one of the parameters (the renewable premium level) is uncertain and can change from one year to another. The market is repeated N times and it is assumed that when premium ($\boldsymbol{Pr_i}$) is zero in a given year, then it will not be renewed in future years. The renewable premium is one of this model's key elements. It will enable us to analyze renewable generators' strategic investment behavior.

Furthermore, we assume that the projected demand is higher than the existing capacity, hence the need for new generation capacity to meet the additional demand. These investments will come from renewable or new conventional. We assume that only renewable investments require network extensions to be undertaken by the network operator. New conventional is the extension of existing capacity with more efficient technologies. Moreover, we consider the investment in the network as inefficient when the infrastructure is available but not used, due to lack of coordination. Moreover, this model only considers congestion due to the unavailability of the network infrastructure.

The model developed is a 3-period strategic game. We assume that in each period, all the previous periods actions are observable by the players who base their current decisions on this information and on their "correct" rational expectations about all the other players' behaviors in the current period, and the next period's outcomes. We now explain the model starting from the last stage. The last period corresponds to generation decisions. In this stage, producers make rational generation decisions that maximize their individual profits. We therefore calculate the quantities produced for given production and network capacities. Indeed, we model these generation decisions by maximizing the profit of each producer (the renewable and the new conventional) under the constraint of the available production and network capacities. As in Sauma and Oren (2005) and Yao et al., (2004), generators compete in a Nash-Cournot fashion by simultaneously deciding on their production quantities so as to maximize their individual profit, while taking into account their competitors' production decisions and network availability.

We assume that the pricing mechanism used in the electricity market is the merit order. Thus, the generation units are requested in order of increasing marginal cost and the market price is equal to the marginal cost of the last unit accepted to cover the electricity demand. The equilibrium price ($\boldsymbol{P_i}$) will therefore be equal to the marginal cost of existing capacity (c_{ex}), otherwise it is equal to the Voll (Value of Lost Load) when supply cannot meet demand. The VoLL is a socio-economic indicator that measures the monetary damages resulting from the loss of economic activity due to a power outage or, in other words, the maximum price of electricity that customers are willing to pay to avoid an outage. (European Commission, 2017).

In the second period, each generator invests in new generation capacity to meet the projected demand. For convenience, we assume that generators' generation decisions are not constrained by physical capacity limits. Instead, we let producers' marginal cost curves rise steadily so that generation quantities will be limited only by economic considerations and network constraints. The return on generation capacity investments made in period 2 occurs in period 3 (energy markets repeated N times). We assume that, when making their investment decisions in period 2, generating firms are aware of the network expansion in period 1 and form rational expectations about the investments made by their competitors and the expected market equilibrium in period 3. Thus, competing producers' investment and production decisions are modeled as a perfect subgame Nash equilibrium.

Finally, in the first period, we consider that the program of the network operator represents the welfare. The regulator maximizes welfare through the network operator's program. The network operator, which we model as a Stackelberg leader in our three-period game, evaluates different network expansion projects, while anticipating generators' response and the regulator in periods 2 and 3. In this paradigm, since the network operator anticipates the generation firms' response, optimizing the network investment plan will also determine how best to incentivize generation investment to maximize the objective function set by the system operator (typically social welfare). Therefore, we will use the term "proactive planner/planning" to describe such a planning approach. Moreover, we assume that the production cost functions and the investment costs in production capacity and network capacity are linear.

2. Model notations

Decision variables

K_{Ren}: new renewable capacity

X_{Ren} : renewable generation

T_{Ren}: new network capacity for renewable

K_{con} : new conventional capacity

X_{con} : conventional generation

Parameters

D: projected demand

K_{ex} : existing capacity

C_{ex} : variable production cost of existing capacity

c_{ex} : marginal cost of the existing capacity

C_{con} : variable cost of new conventional generation

c_{con} : marginal cost of new conventional

I_T : unit investment cost of the network

d : network operational time in the reactive case

I_{con} : unit investment cost of new conventional

I_{Ren}: unit investment cost of renewable energy

$Voll$: Value of Lost Load

θ: renewable load factor; $0 \leq \theta \leq 1$

P : competitive price of electricity

Pr_i = {0, Pr}: premium of renewable according to the state of nature i

$E_n(.)$: mathematical expectation

Set

$i = \{0, 1\}$: state of nature

- if i = 0 then Pr = 0
- if i = 1 then Pr > 0

$N = \{1, 2, 3, \dots, 10\}$: time horizon of the study

3. Mathematical formulation

- *The 3rd period of the model*

We start by formulating the 3rd period of the model, which concerns the generation decisions period. During this period, each producer maximizes his profit under production capacities' and network's constraints. At this stage of the game, demand D is fulfilled. Then, electricity price P, the renewable premium Pr_i and the generation and network capacities are known. Therefore, generators decide on the generation quantities that maximize their profit, given the available generation and network capacities.

Therefore, the renewable decides on his profit-maximizing output $\boldsymbol{X_{Ren}}$ under the constraint of his generation capacities $\boldsymbol{K_{Ren}}$ and the new network capacities $\boldsymbol{T_{Ren}}$. Indeed, we assume that the renewable needs new lines for connection to the network. We add a load factor θ to the generation capacity to avoid possible oversizing of the network capacity. In our model, we use a load factor only for renewables because the model is only interested in the new network capacities needed to integrate renewables. The load factor[2] of an electrical generation unit is the ratio between the energy it produces over a given period and the energy it would have produced during that period if it had been operating constantly at nominal power. The load factor is between 0 and 1 depending on the state of nature. In addition to market price, the renewable producer receives a premium on each unit sold and its variable costs are zero. Their objective function is therefore formulated as follows:

$$\max_{XRen\ i,n} (P_i + Pr_i) X_{Ren,i,n} \tag{1}$$

Under constraint of:

$$X_{Ren,i,n} \leq \theta K_{Ren} \quad (\lambda_1) \tag{2}$$

$$X_{Ren,i,n} \leq \boldsymbol{T_{Ren}} \ (\lambda_2) \tag{3}$$

λ_1 and λ_2 are the dual variables of constraints (2) and (3) that represent the opportunity cost of the lack of renewable generation capacity and the opportunity cost of the lack of network capacity, respectively.

The conventional utility maximizes their profit under the constraint of its generation capacity K_{con} and the level of demand minus the generation capacity K_{Ren} of the renewable utility that has priority on the market. They also take into account the existing capacities K_{ex} in the system. Conventional power has non-zero variable costs C_{con} (price of uranium, oil, gas, etc.). Their unit profit will therefore be equal to the market price P_i minus their marginal production cost c_{con}. Moreover, conventional power does not necessarily need new network capacity to connect its production. It is therefore assumed that, unlike renewables, it is not subject to a network capacity constraint. Thus, their objective function is formulated as follows:

$$\text{Max}_{\ X_{con,i,n}} \ (P_i - c_{con}) X_{con,i,n} \tag{4}$$

Constrained by:

$$X_{con,i,n} \leq K_{con} \quad (\lambda_3) \tag{5}$$

$$X_{con,i,n} \leq D_i - \theta K_{Ren} - K_{ex} \quad (\lambda_4) \tag{6}$$

The assumptions of the previously specified model guarantee that (1-3) and (1-6) are convex programming problems, which implies that the first-order conditions are sufficient for optimality (Gabriel and Smeers, 2005;

[2] https://www.connaissancedesenergies.org/questions-et-reponses-energies/quest-ce-que-le-facteur-de-charge-dune-unite-de-production-electrique

Clastres and Khalfallah, 2021). Therefore, to solve the game in period 3, we can simply formulate an MCP program that can be solved as discussed in Appendix 1.

- *The 2nd period of the model*

In the second period, only new producers, active players in the game, invest by maximizing their total expected profits over the N market years. At this stage, demand is unknown, only the new network capacities are known. And, the renewable premium, at this stage, is uncertain. Here, the decision variables are the generation capacities (K_{Ren} of renewable and K_{con} of conventional). This period's constraints are formulated from the resolution of the 3rd period's programs.

The renewable decides in a more favorable but uncertain regulatory environment and maximizes their total expected profit. They base their investment decisions on rational expectations formulated on market parameters (price, premium and demand). Their program is a Bellman function (1954) that can be formulated as follows:

$$\max_{KRen} \sum_{n=1}^{N} E_n \left[(P_i + Pr_i) X^*_{Ren,i,n} \right] - I_{Ren}.K_{Ren} \tag{7}$$

Constrained by the results of the previous step

Premium Pr_i is uncertain and tends to zero. It is likely to change from year to year depending on the state of nature i. For simplicity, we assume two states of nature: $i = \{0, 1\}$. When the state of nature is 0 then the premium is zero, otherwise it is greater than 0. Also, when it is zero in a given year n, it is assumed that it will not be rolled over in subsequent years. Therefore Pr_i obeys a stochastic process (the Markov chain) as shown in Figure 2.

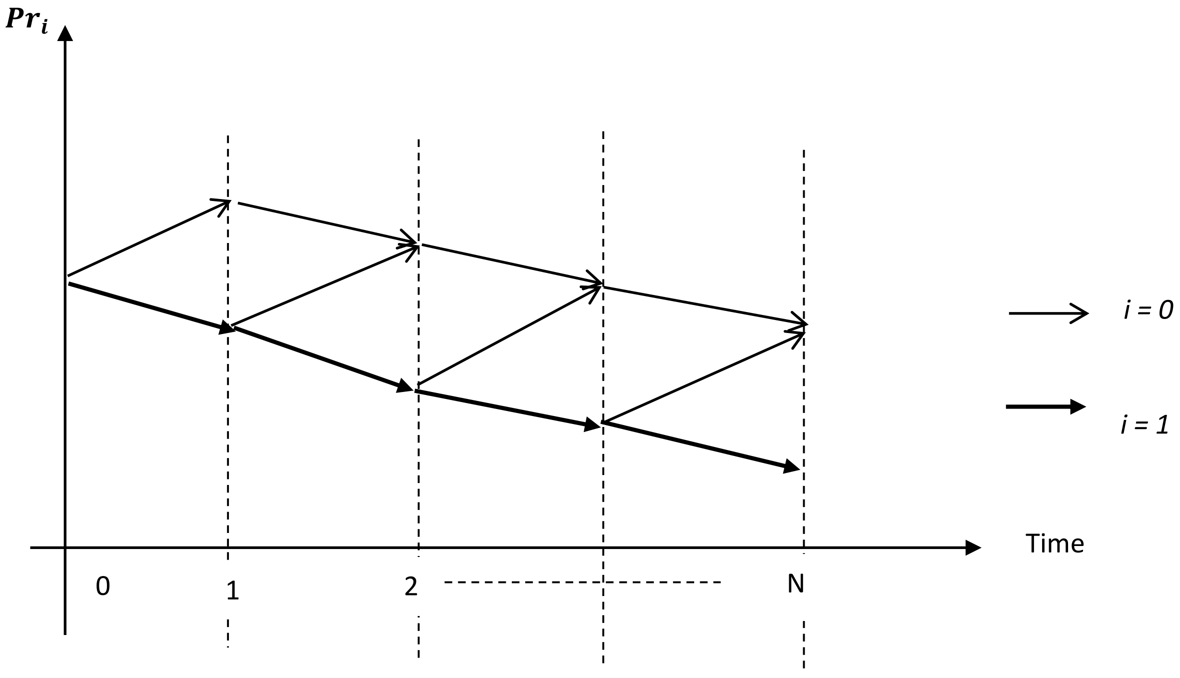


Figure 2: Stochastic evolution of the variable Pr_i

When for a given year *i=0* then the premium is zero and will not be renewed the following year. And when *i*= then the premium is non-zero and may or may not be zero the following year. Let p be the probability that the state of nature is favorable (*i=1*) in a given year n, we will have:

$$\max_{KRen} \sum_{n=1}^{N} \left[p(P_i + Pr_i) X^*_{Ren,i,n} + (1-p) P_i \,.\, X^*_{Ren,i,n} \right] - I_{Ren}.K_{Ren} \tag{8}$$

Constrained by the results of the previous step

The analysis of the probability distribution (see appendix) gives the following probability function: $p_n = p^n$. Then the Bellman function is rewritten as follows:

$$\max_{KRen} \sum_{n=1}^{N} \left[p^n (P_i + Pr) X^*_{Ren,i,n} + (1 - p^n) P_i \, . X^*_{Ren,i,n}\right] - I_{Ren} . K_{Ren} \quad (9)$$

Constrained by:

$$\theta K_{Ren} \leq T_{Ren} \ (\lambda_5) \quad (10)$$

The new conventional decide in a competitive environment and also maximize their total expected profit. They are a strategic actor that anticipates their competitors' decisions before making a decision that they consider optimal for maximizing their profit. As the network is traditionally adapted for this type of generation technology, the new conventional operator need not build new network capacity to connect their generation (there may be a need to reinforce the network). However, in their investment decisions, they must take into account existing capacity and renewable energy, which is much more favored for energy transition reasons.

$$\text{Max}_{Kcon} \ \sum_{n=1}^{N} E_n \left[(P_i - c_{con}) X^*_{con,i,n}\right] - I_{con} . K_{con} \quad (11)$$

Constrained by

$$K_{con} \leq D - \theta K_{Ren} - K_{ex} \quad (\lambda_6) \quad (12)$$

- *The 1st period of the model*

In the first period, the demand, the premium and the new generation capacities are unknown. The network operator, a regulated monopoly, maximizes his program that we consider as the total expected social welfare and makes investment decisions based on producers' strategic behaviors. He therefore decides on the levels of investment in the network in order to maximize the welfare of society as a whole. Thus, his program maximizes both consumer surplus and producer surplus. The decision variable in this step is T_{Ren}, which represents new network capacity. The proactive operator anticipates the producers' investment decisions and invests accordingly. In this type of coordination, the network is operational at the same time as the new generation capacities. However, the operator bases their investment decisions on rational expectations and under the constraint of previous programs possible scenarios. His program is formulated as follows:

$$\text{Max}_{TRen} \sum_{n=1}^{N} E_n \left[CS_n + PS_n\right] - I_{Ren} . K_{Ren} - I_{con} . K_{con} - I_T . T_{Ren} \quad (13)$$

$$\text{Max}_{TRen} \sum_{n=1}^{N} E_n \left[(P_i^* - c_{con}) X^*_{con,i,n} + (P_i^* + Pr_i) X^*_{Ren,i,n} + (P_i^* - c_{ex}) \left(D_i - X^*_{Ren,i,n} - X^*_{con,i,n}\right) + (Voll - P_i^*) D_i\right] - I_{Ren} . K^*_{Ren} - I_{con} . K^*_{con} - I_T . T_{Ren}$$

Constrained by

$$T_{Ren} = f(K^*_{Ren}) \quad (15)$$

$$D - T_{Ren} - K_{ex} = f(K^*_{con}) \quad (16)$$

The reactive case

In the reactive case, the network operator first observes generators' behaviors before making investment decisions in network capacities. Producers are therefore the game leaders. They anticipate the network operator's reaction and are the first to make investment decisions given a projected demand that is greater than the existing generation capacity. We also have 3 periods, as in the proactive case. In the 3rd period, we calculate the generation decisions (see proactive case). In the 2nd period, the network operator invests in new network capacities by maximizing the total expected social welfare. In this period, the network operator is aware of the new generation capacities and therefore makes their investment decisions accordingly. Producers (renewable in particular) are modeled as leaders in Stackelberg.

The reactive case specificity is that the network operator decides to invest only when they have some information on producers' investment choices (1st period). He can then invest in new capacities that will be at most equal to the new production capacities. Compared to the proactive case, the network operator avoids an investment cost per unit of capacity for *d* years that can be expressed as $d\left(\frac{I_T}{N}\right)$, where $\frac{I_T}{N}$ represents the annual unit investment cost. However, unlike the proactive case, the new lines will not be operational at the same time as the new generation capacities. Indeed, the new lines will only be available after *d* years due to their longer construction time. We will therefore have *d* periods during which the renewable producer will not be present on the market due to the lack of availability of the network infrastructure. We formulate this case as follows:

- ***3rd period* (same as proactive case)**
- ***2nd period (the program of network operator):***

$$\max_{T_{Ren}} \sum_{n=d}^{N} E_n \left[(P_i^* - c_{con}) X_{con,i,n}^* + (P_i^* + Pr_i) X_{Ren,i,n}^* + (P_i^* - c_{ex}) \left(D_i - X_{Ren,i,n}^* - X_{con,i,n}^* \right) + (Voll - P_i^*) D_i \right] - I_{Ren}.K_{Ren}^* - I_{con}.K_{con}^* - I_T.T_{Ren} + d\left(\frac{I_T}{N}\right).T_{Ren}$$

Constrained by:

$$T_{Ren} \leq \theta K_{Ren} \,(\lambda_7) \quad (18)$$

$$D_i - T_{Ren} - K_{ex} = K_{con} \;\; (\lambda_8) \quad (19)$$

- ***1st period (the programs of generators):***

  - **The renewable**

$$\max_{K_{Ren}} \sum_{n=d}^{N} \left[p^n (P_i + Pr_i) X_{Ren,i,n}^* + (1 - p^n) P_i . X_{Ren,i,n}^* \right] - I_{Ren}.K_{Ren} \quad (20)$$

Constrained by:

$$K_{Ren} = f(T_{Ren}^*) \;\; (\lambda_9) \quad (21)$$

$$K_{Ren} \leq D_i - K_{ex} \;\; (\lambda_{10}) \quad (22)$$

  - **The conventional**

$$\max_{K_{con}} \sum_{n=d}^{N} E_n \left[(P_i - c_{con}) X_{con,i,n}^* \right] - I_{con}.K_{con} \quad (23)$$

Constrained by

$$K_{con} \leq D_i - \theta K_{Ren} - K_{ex} \quad (\lambda_{11}) \quad (24)$$

I. Theoretical results

To analyze producers' and the network operator's investment decisions, the complex solutions presented in the appendices are rearranged to give more tractable and subtle results. A sensitivity analysis to the model's main parameters is undertaken, all other things being equal. We first consider the level of the renewable premium (Pr_i), as its level constitutes a strong signal to induce renewable investments. Also, the probability of the premium, which is a key parameter to capture the intensity of the regulatory signals' continuity in favor of renewable.

We also consider the renewable (I_{Ren}) unit investment cost and transmission (I_T) which represent the decision variables of the main active players in the game (renewable and network operator). Finally, we consider the role of network operationalization time (*d*) in comparing *welfare* in the proactive and reactive settings.

Proposition 1: Producers offer all their available capacity to the market

Optimizing the market stage as demonstrated in appendix 1 gives us the following results:

$$X^*_{Ren} = \text{Min}\{\theta K_{Ren}, T_{Ren}\} \tag{25}$$

and

$$X^*_{con} = D_i - X^*_{Ren} - K_{ex} \tag{26}$$

The results of (1-3) indicate that, at market equilibrium, generators (renewable and conventional) offer quantities at the limit of available capacity and demand. According to (1), the renewable offers a quantity X^*_{Ren} to the market such that X^*_{Ren} equals the minimum of the available capacities in generation K_{Ren} and transmission T_{Ren}. Rationally, the latter would like to produce all their available production capacity. However, they must ensure that the available network capacity enables them to transmit the entire amount produced. Therefore, the renewable is forced to produce an amount at most equal to the available distribution capacity even if their generation capacity allows them to produce more. Renewable energy still has priority on the market because it has a zero marginal production cost, unlike conventional energy.

According to the different scenarios on network and generation investments, the resolution of the market steps leads to three possible situations: two sub-optimality situations (induced by the network constraint or the renewable generation constraint) and one optimality situation.

- **Network constraint** means the network capacity does not allow the renewable to produce all their available capacity. They therefore produce the quantity that the network allows them to transport. In this situation, its unit profit is equal to the opportunity cost of the lack of network capacity λ_2. Since renewable is not flexible, when weather conditions are favorable, then they will produce all of their available generation capacity. If the network capacity does not allow for this amount of generation to flow, some of this energy will be lost (disconnection) or the network will be congested (overload). The network constraint is therefore the most sub-optimal situation for the system and society. The network capacity must therefore be at least equal to the generation capacity.
- **Generation constraint** means that the renewable's generation capacity does not enable them to fully utilize the available network capacity. In this case, their unit profit is equal to the opportunity cost of the lack of generation capacity λ_1.
- **Optimality situation** indicates the system optimum. It corresponds to the situation where these two constraints are both lifted: the generation and network capacities are at the same level. In this case, renewable energies produce all their available capacity and fully use the available network capacity. Their unit profit is then optimal and equal to the sum of the two opportunity costs.

As for the conventional, they produce the quantity demanded D_i minus the quantity produced by the renewable (which have priority in the market thanks to these zero variable costs) and the existing capacity K_{ex} as shown in program (4-6).

Proposition 2: Renewable investments are conditioned on the one hand by the stability of price signals related to renewable-specific regulatory incentives and on the other hand by the availability of the new network.

The renewable capacity optimization program yields the following result for the baseline model (Appendix 2):

$$K^*_{Ren} = \begin{cases} T_{Ren} \; si \; R_m > I_{Ren} \\ 0 \; si \; R_m < I_{Ren} \end{cases} \tag{27}$$

Where,

$$R_m = \sum_{n=1}^{N} [p^n(P_i + Pr_i) + (1 - p^n)P_i] \; avec \; N = (1,2, \dots, 10) \tag{28}$$

Not surprisingly, results show the decision to invest or not from the renewable depends on the level of their total expected marginal revenue relative to their unit investment cost. They decide to invest if their marginal revenue R_m is greater than their unit investment cost I_{Ren} and they do not invest if it is less. If beneficial, the renewable invest as much as the available network capacity ($K^*_{Ren} = T_{Ren}$). Note that its marginal revenue depends strongly on the premium Pr_i et de sa distribution rationnelle de probabilité p. These two parameters internalize the renewable-specific incentives as well as their sustainability predictability. They are positively correlated with the marginal revenue and its rational probability distribution p. The higher they are the higher the marginal revenue. To better observe the effect of the changing premium on the renewable's investment decision, we analyze the impact of key parameters I_{Ren} et Pr_i .

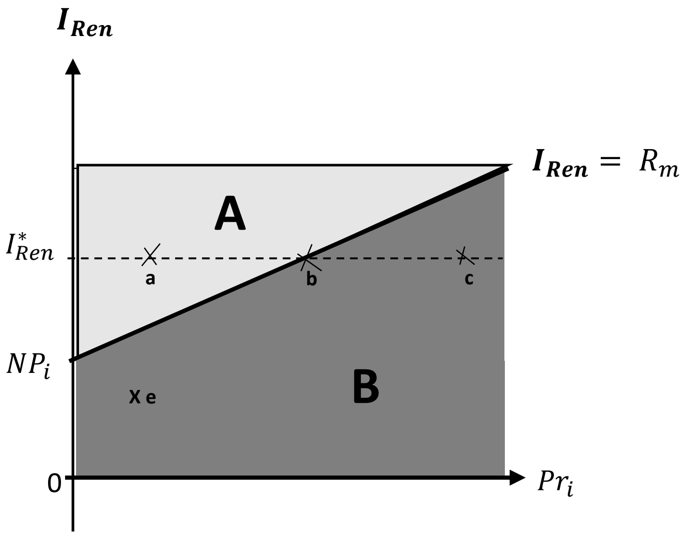
The simplified expression for R_m gives:

$$R_m = \sum_{n=1}^{N} p^n Pr_i + NP_i \tag{29}$$

We start with a baseline situation that we call the indifference situation, where the marginal revenue equals the unit investment cost ($R_m = I_{Ren}$). This represents the producer's indifference between "investing" or "not investing". Thus, we will have:

$$I_{Ren} = \sum_{n=1}^{N} p^n Pr_i + NP_i \tag{30}$$

I_{Ren} is a linear and increasing function of $Pr_i$and has the ordinate at the origin NP_i. The slope of the curve can be interpreted as the probability index of the sustainability of the renewable premium, i.e. $\sum_{n=1}^{N} p^n$.

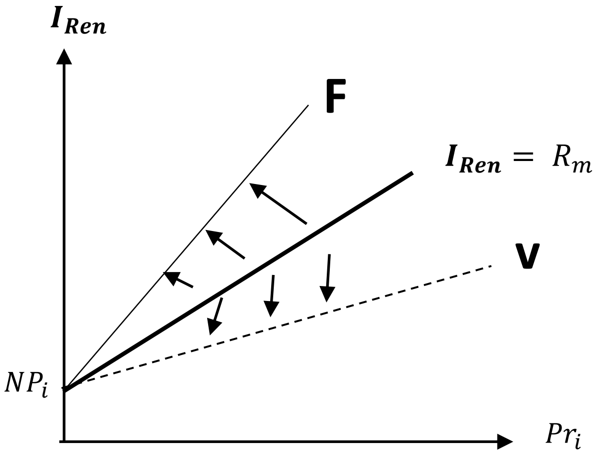


Graph 1: Sensitivity of Renewable Investment to the Premium

Graph 1 shows us two zones, A and B. Zone A shows all combinations of $\{I_{Ren}, Pr_i\}$ where the renewable refrains from any investment decision. Indeed, for any point in zone A, the unit investment cost is higher than the marginal revenue. On the other hand, when we move to zone B, the conditions become favorable to investment because the marginal revenue exceeds the unit investment cost in this zone. The two zones are delimited by the indifference line. This line rotates around the y-intercept as we vary probability *p* (see graph 2).

For a unit investment cost I^*_{Ren}, we end up with three *a*, *b* and *c*, depending on the level of the premium. Point *a* is in the "non-investment" zone and point *b* is on the line of indifference with a higher level of premium than at point *a*. On the other hand, point *c* is in the investment zone but with a much higher premium. This situation enables us to deduce that, for very low premium levels, the renewable refrain from investing or invest very little (point *e*).

Graph 2 shows how the probability distribution impacts the indifference situation. When probability *p*, i.e. the regulatory signals on the sustainability of renewable incentives are high, the indifference curve shifts upwards (curve F); and it shifts downwards (curve V) when this probability decreases. We deduce that, when the producer is optimistic about the premium evolution, the "no investment" zone is reduced and increases inversely, or if the regulatory signals are weak.



Graph 2: Sensitivity of Renewable Investment to the Probability of Premium

Proposition 3: Renewable-related network investments are only effective if the renewable regulatory price signals are sufficient.

We now turn to the network operator's decisions. We recall that they take the decision at the beginning of the game. They anticipate the producer's reaction and invest accordingly, while maximizing the total expected surplus. Their program (see Appendix 3), when simplified, gives the following formula:

$$\mathbf{Max}_{TRen}\ \boldsymbol{A.T_{Ren} + B} \qquad (\mathbf{31})$$

With,
$A = \sum_{n=1}^{N}[p^n(P_i + Pr_i) + (1-p^n)P_i] - \sum_{n=1}^{N}(P_i - c_{con}) - I_{Ren} - I_T + I_{con}$

Thus, the optimal welfare is achieved when T_{Ren} tends to infinity, subject to A>0. The optimal network investment plan would therefore be the maximum amount of capacity that the renewable can make, given the existing demand and capacity. The new network capacity that therefore optimizes the system for the whole society would be equal to the projected demand, minus the existing capacity.

$$T_{Ren} = \begin{cases} D_i - K_{ex}\ si\ A > 0 \\ 0\ si\ A < 0 \end{cases} \qquad (32)$$

To better interpret this result, we consider a basic situation that we call the indifference situation, where $A = 0$. This is the situation when the operator is indifferent between "investing" or "not investing" in the network. The simplified expression for A gives:

$$A = \sum_{n=1}^{N}[p^n Pr_i + c_{con}] - I_{Ren} - I_T + I_{con} \qquad (33)$$

Here we consider, I_{Ren}, I_T and Pr_i as our key parameters. Let $I = I_{Ren} + I_T$: the social investment cost of renewable, incorporating the power plants' direct cost and the related network costs.

$$A = 0\ \rightarrow\ I = \sum_{n=1}^{N} p^n Pr_i + Nc_{con} + I_{con} \qquad (34)$$

$A = 0$ can be seen as the threshold for triggering renewable-specific network and generation investments. We find that without renewable-specific incentives ($Pr_i = 0$), the operator is indifferent as to investing or not investing as soon as the social investment cost of renewable I is equal to the opportunity cost of no new renewables, which can be valued by the cost of conventional technology ($Nc_{con} + I_{con}$) brought in to make up for the lack of renewable.

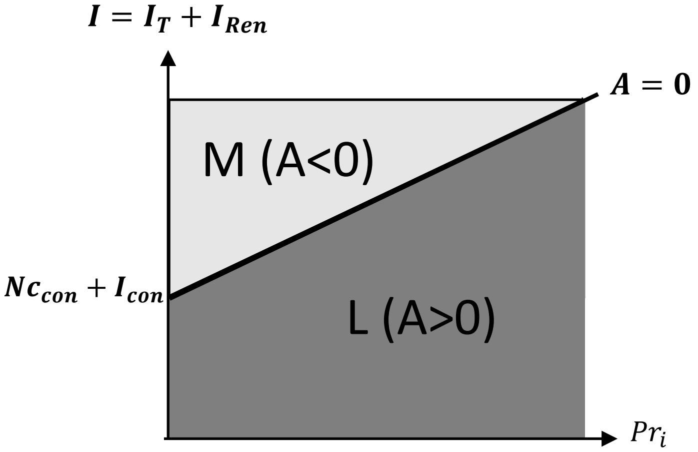
Investments are only triggered when the cost I is lower than this opportunity cost (A>0). However, if the regulatory incentives are powerful ($Pr_i > 0$), this indifference threshold is less constraining to trigger the network investments necessary to accompany the investments in renewable plants. Indeed, this threshold increases with expected renewable premiums ($\sum_{n=1}^{N} p^n Pr_i$),

We can see the price signal from renewable-specific regulation must offset the gap between the social investment cost of renewable and the opportunity cost of not having renewable, to trigger the necessary investments. Rearranging the above equation yields the following efficiency condition:

$$\sum_{n=1}^{N} p^n Pr_i \geq I - (Nc_{con} + I_{con}) \qquad (35)$$

When the social cost of renewable is higher than the opportunity cost of not using renewable, regulatory incentives are needed to compensate for lack of competitiveness.

We now look at the relationship between I and the renewable premium. I is an increasing linear function of Pr_i and has the intercept $Nc_{con} + I_{con}$. The slope of the curve for I is $\sum_{n=1}^{N} p^n$.



Graph 3: Relationship between Social Investment Cost of Renewable and Renewable Premium

Graph 3 shows us two zones, zone M and zone L, which respectively represent the non-investment zone and the investment zone of the renewable network. The two zones are delineated by the operator's indifference line or the renewable investment trigger point. For higher investment costs, the premium signal triggers more expensive network investments (larger I) and a larger investment zone.

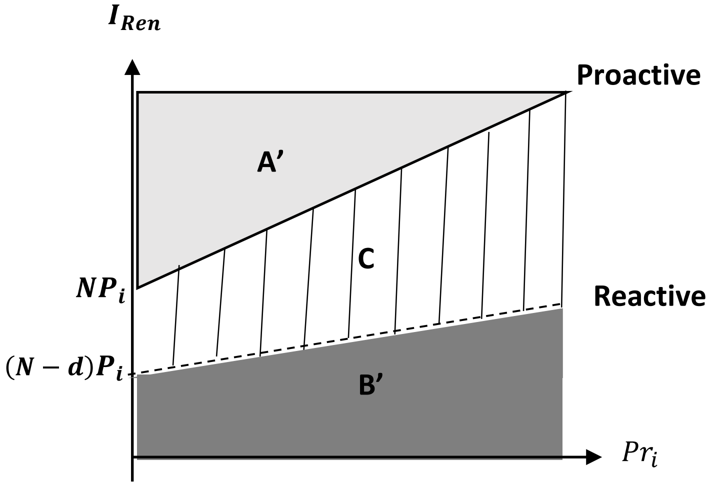
On the other hand, the premium predictability measured by the probability (p) shifts the zone boundary along the indifference line upwards. This increases the investment zone.

Proposition 4: With a reactive operator, low investment costs or strong regulatory incentives are needed to trigger efficient renewable investments

If the operator practices reactive investments, the indifference situation between investing and not investing in renewable is now represented by the following equation (see Appendix 4):

$$I_{Ren} = \sum_{n=d}^{N} p^n Pr_i + (N - d)P_i \qquad (36)$$

Compared to the proactive scenario, the slope is reduced because the time horizon is decreased by d years: $\sum_{n=d}^{N} p^n < \sum_{n=1}^{N} p^n$. Also, the intercept is decreased by dP_i.



Graph 4: Investment in renewable energy: Reactive VS Proactive.

Graph 4 represents to us the loss of efficient renewable investment potential when moving from the proactive to the reactive case (hatched area C). Two effects can explain this loss. A direct network effect due to the number of years d that the new network has not been operational. A market effect with a loss of revenue expressed by dP_i. We note that the time of network operationalization d in the reactive case leads to a reduction of the investment area. We see that, for the same unit investment costs between $(N-d)P_i$ and NP_i, the amount of the premium, which the renewable needs to make its investment profitable, is higher in the reactive case. On the other hand, renewable investments are only triggered for very low unit investment costs. However, when unit investment costs rise above $(N-d)P_i$, the operator must make proactive network investments to induce renewable investments and avoid the need for high renewable subsidies.

Proposition 5: When network costs are significant, a reactive network operator is not socially harmful in the presence of fairly mature renewable technologies (low premiums) and/or when network operational lead times are short.

We now compare the surpluses associated with the two scenarios on the network operator's planning mode. First, we determine the threshold network investment T^*_{Ren} for which the two scenarios provide an identical surplus. This involves solving the following equation:

$$AT_{Ren} + B = A'T_{Ren} + B' \quad (37)$$

With,

$A = \sum_{n=1}^{N}[p^n Pr_i + c_{con}] - I_{Ren} - I_T + I_{con}$

$A' = \sum_{n=d}^{N}[p^n Pr_i + c_{con}] - I_{Ren} + I_{con} + I_T\left(\frac{d}{N} - 1\right)$

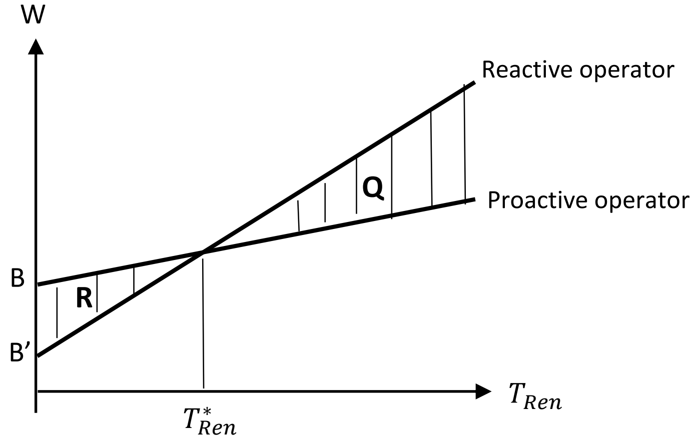
$B = \sum_{n=1}^{N} E_n\, [D_i(Voll - c_{con}) + K_{ex}(c_{con} - c_{ex})] - I_{con}(D_i - K_{ex})$

$B' = \sum_{n=d}^{N} E_n\, [D_i(Voll - c_{con}) + K_{ex}(c_{con} - c_{ex})] - I_{con}(D_i - K_{ex})$

The resolution gives the following result:

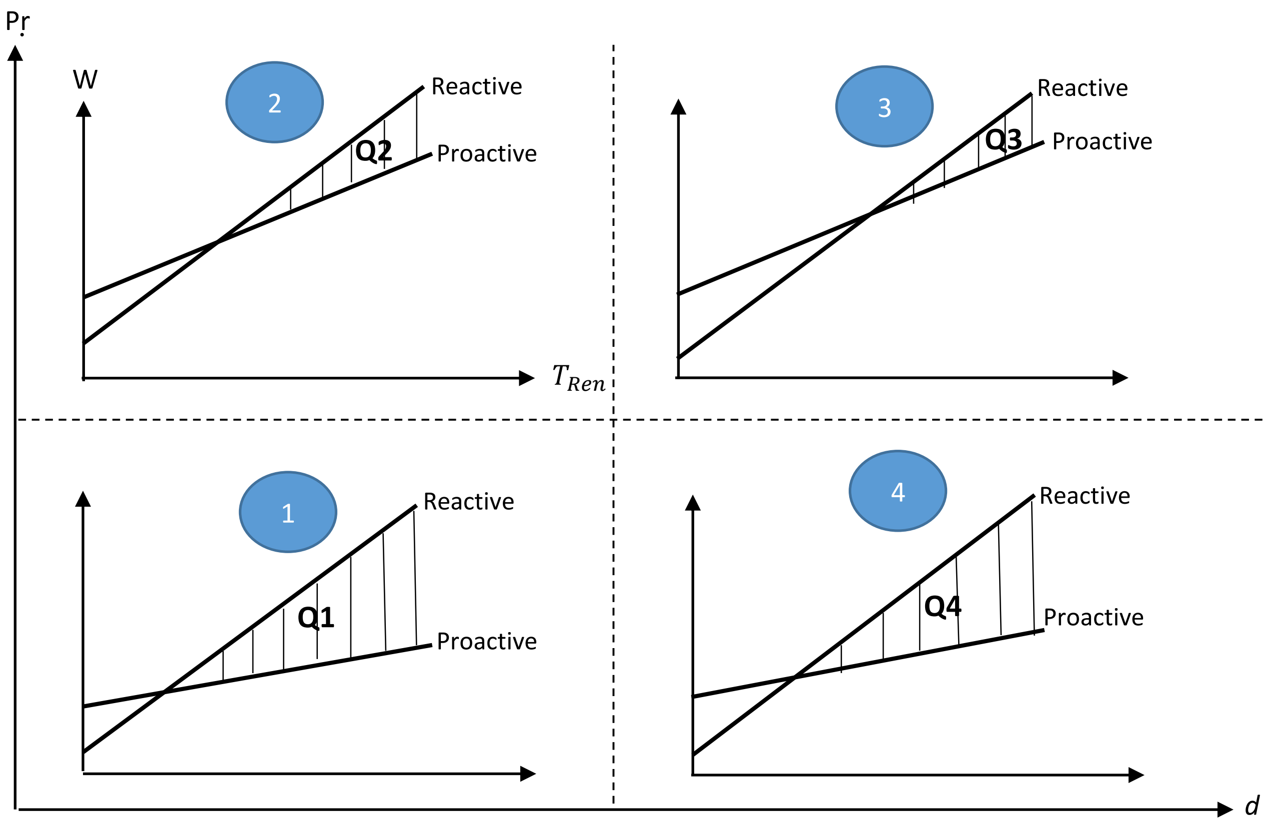
$$T^*_{Ren} = \frac{d[D_i(Voll - c_{con}) + K_{ex}(c_{con} - c_{ex})]}{I_T\frac{d}{N} - (\sum_{n=1}^{d} p^n Pr_i + dc_{con})} \quad (38)$$

T^*_{Ren} is only positive if $I_T\frac{d}{N} > (\sum_{n=1}^{d} p^n\, Pr_i + dc_{con})$. This compares the network cost avoided by the reactive operator ($I_T\frac{d}{N}$) to the renewable generator's lost revenue during periods of network unavailability ($\sum_{n=1}^{d} p^n\, Pr_i + dc_{con}$). In this situation, i.e., the avoided network cost is higher, comparing welfares yields the following result:



Graph 5: Proactive operator efficiency threshold.

The above graph shows an original result of the study, which consists in highlighting a threshold level of the network extension specific to the renewable energy at which a reactive operator is more beneficial for welfare than a proactive operator. Indeed, always under the condition that the network cost avoided by the reactive operator is higher than the loss of revenue induced for the renewable, substantial and proactive network investments would be costly for welfare. Being proactive, building a substantial network early enough in relation to the expected renewable investments (zone Q in graph 6) would imply an opportunity cost that would be too high for welfare, if renewable investments do not follow in an optimal way. This risk is important when renewable incentives are insufficient or may disappear in future (low $\sum_{n=1}^{d} p^n \, Pr_i$). However, it will be more appropriate to invest moderately in the network under a proactive operator (zone R in Figure 6). To better analyze the parameters that can significantly influence this result, we evaluate the sensitivity of this threshold network extension with respect to two key parameters: network operationalization time d and level of the renewable premium Pr_i. The following graph shows us the evolution of T^*_{Ren} for possible situations on the relationship between d and Pr_i.



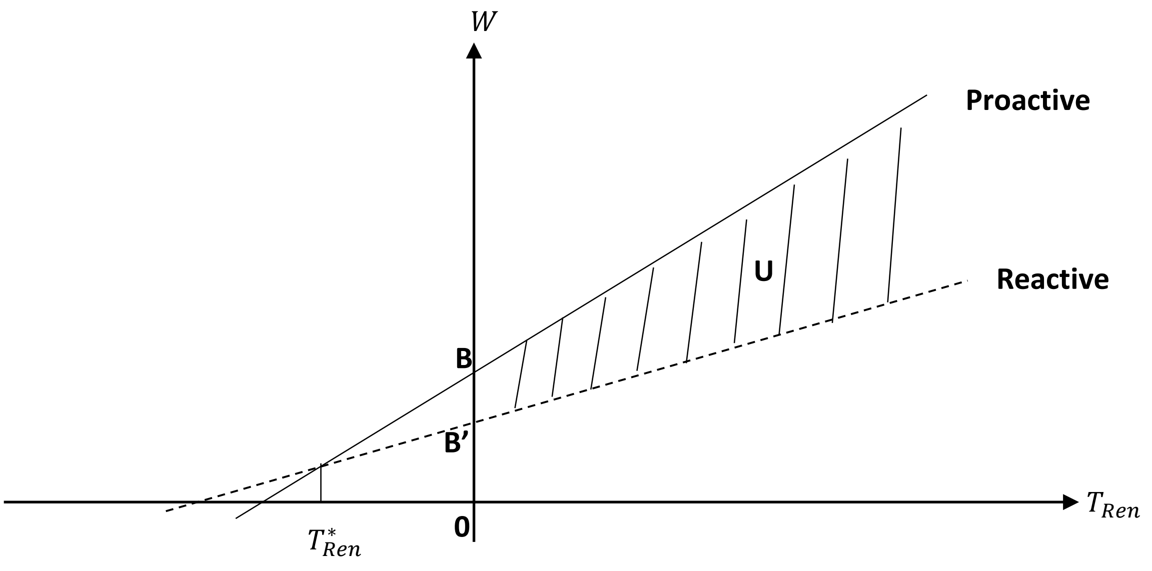
Graph 6: Sensitivity analysis of T^*_{Ren} with respect to Pr_i and d

The graph above shows us how T^*_{Ren} varies as a function of Pr_i et d. The graphs on the left (1 and 2) are in an area where d is low. They show the level of T^*_{Ren} for the same time period d but with a higher level of premium in 2 than in 1. The graphs on the right (3 and 4) are in an area where d is high. They show the level of T^*_{Ren} for the same time period d with a higher premium level in 3 than in 4.

Analyzing these graphs, we can see the following two observations: i) when the network operational delay d is short, it is not necessary to opt for a proactive operator, i.e., because it is more expensive for the company. Indeed, this is not necessary since, in this case, the operator will have a relatively short lead time to set up the necessary network to accommodate potential new renewables. This observation is less valid when incentives for renewables are strong, i.e., the level of the premium is high (moving from subgraph 1 to subgraph 2), with a reduction in the area of social profitability of the reactive compared to the proactive (Q2<Q1). ii), when time period d is high, all other things being equal, T^*_{Ren} increases, which means that high network extensions are required for the reactive to be more socially beneficial than the proactive. Indeed, the loss of revenue for renewable actors increases considerably with time period d, which requires network investments, well in advance, to improve welfare. However, from a certain threshold, admittedly high, the reactive is better since the trade-off between the network cost avoided by the reactive and the shortfall of the renewable is in favor of the proactive. The reactive categorically deteriorates the welfare compared to the proactive when the renewable premium is significant (from subgraph 4 to subgraph 3). With a considerable d time-period, combined with strong renewable incentives, network investment needs, well in advance, to accompany the strongly expected renewable investments due to a very incentive regulation and a consequent shortfall for the renewable, if the operator practices reactive planning[3]. We can admit that when network costs are significant, reactive planning is not socially harmful when renewable technologies are mature enough (low premiums) and/or when the network operationalization time is short.

Proposition 6: When network costs are moderate or low, a proactive network operator is more socially beneficial.

We recall that the T^*_{Ren} obtained in equation (38) is only positive if $I_T \frac{d}{N} > (\sum_{n=1}^{d} p^n \, Pr_i + dc_{con})$. Otherwise, T^*_{Ren} is negative, which means a proactive operator is socially better than the reactive one, regardless of actors' topology. This is achieved when the network cost avoided by the reactive operator ($I_T \frac{d}{N}$) is less than the renewable generator's lost revenue during periods of network unavailability ($\sum_{n=1}^{d} p^n \, Pr_i + dc_{con}$), as shown in the following graph:



Graph 7: Network Investment: Reactive VS Proactive.

Graph 7 represents the *welfare* deadweight loss when moving from the proactive scenario to the reactive scenario (zone U).We can admit that, when the renewable deadweight loss due to network operationalization time periods are large or larger than the avoided network cost potentially avoided by a network operator who prefers to wait

[3] The sensitivity of the results to the probability of the premium has the same consequences on the comparability between reactive and proactive. Indeed, playing on the level of the premium or its probability acts in the same way as an incentive on the strategies of actors in terms of investment in renewable and network.

before investing, the network operator must bring the necessary network to effectively accompany the arrival of renewable, regardless of the maturity of the technologies in question. This is more the case when renewable technologies are quite immature and strong renewable incentives are offered (high Pr_i and/or p). With fairly mature technologies and – or when – the renewable shortfall is moderate, a reactive network operator is desired if network costs are low. Which would mean low value for the option to wait for the operator, valued by the avoided cost $I_T \frac{d}{N}$, which would not create a social gain from waiting before investing.

II. Conclusion

We have explored the coordination of the network operator's investment choices in a regulated monopoly situation and decentralized actors' investments. In this paper, through a three-stage strategic game, we have determined the optimal coordination of the system actors that maximizes the welfare of society. Considering that only the operator and the producers of the renewable energy are the active actors of the game, we have developed a benchmark model where the operator is proactive, which we have then confronted with an alternative model where the operator is reactive. A dynamic stochastic modeling was used to formalize actors' choices. We find a proactive operator is socially the most beneficial only when the time-periods in making new networks available are significant. We also find that, when future signals on renewable incentives are high, renewable investments are increasing despite high investment costs. A similar effect is observed when we increase the level of premiums that generators receive. Furthermore, we find that the reactive operator is socially beneficial when renewable technologies are mature enough or the network operationalization time is short. The reactive operator is also socially beneficial when the network costs are very significant. Finally, we find that when the renewable deadweight loss due to network operationalization time is larger than the avoided network cost potentially avoided by a reactive network operator, the network operator must bring the necessary network to effectively accompany the arrival of renewable, regardless of the maturity of the technologies.

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Appendix 1. Use of the MCP method to find the equilibrium at generation decisions stage

At each period n and nature state i, the renewable maximizes its profit (1) subject to constraints (2-3). The decision variable is the produced quantity $X_{Ren,i,n}$. To state themodel as a MCP problem we need to reformulate the renewable optimization problem as follows:
To calculate the optimality conditions of each program, we first define the Lagrangian function of the corresponding optimization problem:

$$\mathcal{L}(X_{Ren}, \lambda_1, \lambda_2) = (P_i + Pr_i)X_{Ren,i,n} + \lambda_1(\theta K_{Ren} - X_{Ren}) + \lambda_2(T_{Ren} - X_{Ren}) \quad (38)$$

Then, we calculate the gradient of the Lagrangian function with respect to the decision variable $X_{Ren,i,n}$.

$$\mathcal{L}'_{XRen} = (P_i + Pr_i) - \lambda_1 - \lambda_2 \quad (39)$$

Optimality conditions of the renewable are:

$$\mathcal{L}'_{XRen} = (P_i + Pr_i) - \lambda_1 - \lambda_2 = 0 \quad (40)$$

$$\lambda_1(\theta K_{Ren} - X_{Ren}) = 0 \quad (41)$$

$$\lambda_2(T_{Ren} - X_{Ren}) = 0 \quad (42)$$

At each period n and nature state i, the new conventional maximizes its profit (4) subject to constraints (5-6). The decision variable is the produced quantity $X_{con,i,n}$

Optimality conditions of the new conventional are :

$$\mathcal{L}'_{Xcon} = (P_i + c_{con}) - \lambda_3 - \lambda_4 = 0 \quad (43)$$

$$\lambda_3(K_{con} - X_{con}) = 0 \quad (44)$$

$$\lambda_4(D_i - K_{Ren} - K_{ex} - X_{con}) = 0 \quad (45)$$

This set of equations consists of the first-order conditions multiplied by their corresponding decision variables and the inequality constraints multiplied by their corresponding dual variables, all equal to zero; next the inequality constraints themselves; and finally, the explicit statement of the dual variables.

Grouping all these conditions together leads to an MCP problem. Eqs. (25)–(26) are therefore the solutions to this MCP problem. Existence and uniqueness of the solution : Given that the maximization objective function is concave and continuously differentiable, the KKT conditions presented above are necessary and sufficient for optimality since the feasible region is polyhedral (Bazaraa et al., 1993).

Appendix 2. Use of the MCP method to find the equilibrium at the investment stage in production capacities

The producers decide their generation capacities by maximizing their total expected profits over the N market years. The stochastic MCP model in second period of the model is detailed as following:

- Renewable producer : the decision variable is K_{Ren}

Bellman function (1954):

$$\max_{K_{Ren}} \sum_{n=1}^{N} E_n \left[(P_i + Pr_i) X^*_{Ren,i,n} \right] - I_{Ren}.K_{Ren} \quad (46)$$

Subject to :

$$\theta K_{Ren} \leq T_{Ren} \quad (\lambda_5) \quad (47)$$

Let p be the probability that he has premium Pr in a given year n, we will have :

$$\max_{K_{Ren}} \sum_{n=1}^{N} \left[p(P_i + Pr_i)X^*_{Ren,i,n} + (1-p)P_i \,.X^*_{Ren,i,n}\right] - I_{Ren}.K_{Ren} \quad (21)$$

Pr_i obeys a stochastic process: the Markov chain

When the premium is zero in a given year n, then it is assumed that it will not be renewed in future years. Let's write the probability function:

At n=1, $p_1 = \frac{1}{2} = p$

At n=2, $p_2 = \frac{1}{4} = p^2$

At n=3, $p_3 = \frac{1}{8} = p^3$

At n=4, $p_4 = \frac{1}{16} = p^4$

At n=5, $p_5 = \frac{1}{32} = p^5$

. . .

. . .

. . .

. . .

$p_i = p^i$

. . .

. . .

. . .

. . .

$p_n = p^n$

Let's rewrite the Bellman function :

According to the results of the generation decision stage, we have :

$$\max_{K_{Ren}} \sum_{n=1}^{N} [p^n(P_i + Pr_i)K_{Ren} + (1-p^n)P_i \,.K_{Ren}] - I_{Ren}.K_{Ren} \quad (48)$$

$$\mathcal{L}(K_{Ren}, \lambda_5) = \sum_{n=1}^{N} [p^n(P_i + Pr_i)K_{Ren} + (1-p^n)P_i \,.K_{Ren}] - I_{Ren}.K_{Ren} + \lambda_5(T_{Ren} - \theta K_{Ren})$$

Optimality conditions of the renewable are :

$$\mathcal{L}'_{KRen} = \sum_{n=1}^{N} [p^n(P_i + Pr_i) + (1-p^n)P_i] - I_{Ren} - \lambda_5 = 0 \quad (49)$$

$$\lambda_5(T_{Ren} - \theta K_{Ren}) = 0 \quad (50)$$

$$\lambda_5 = \sum_{n=1}^{N}[p^n(P_i + Pr_i) + (1-p^n)P_i] - I_{Ren} \quad (51)$$

$$\lambda_5(T_{Ren} - \theta K_{Ren}) = 0 \quad (52)$$

- Conventional producer : the decision variable is K_{con}

$$\max_{K_{con}} \sum_{n=1}^{N} E_n \left[(P_i - c_{con})X^*_{con,i,n}\right] - I_{con}.K_{con} \quad (53)$$

Subject to :

$$K_{con} \leq D_i - \theta K_{Ren} - K_{ex} \ \ (\lambda_6) \quad (54)$$

Optimality conditions of the new conventional are :

$$\mathcal{L}'_{Kcon} = \sum_{n=1}^{N}(P_i - c_{con}) - I_{con} - \lambda_6 = 0 \quad (55)$$

$$\lambda_6 = \sum_{n=1}^{N}(P_i - c_{con}) - I_{con} \quad (56)$$

$$\lambda_6(D - \theta K_{Ren} - K_{ex} - K_{con}) = 0 \quad (57)$$

Appendix 3. A mathematical program with equilibrium constraints to find the solutions to the overall game

The operator bases their investment decisions on rational expectations and under the constraint of previous programs possible scenarios. Their program is formulated as follows:

$$\text{Max}_{T_{Ren}} \sum_{n=1}^{N} E_n\ [CS_n + PS_n] - \ I_{Ren}.K_{Ren} - \ I_{con}.K_{con} - \ I_T.T_{Ren} \quad (58)$$

$$\text{Max}_{T_{Ren}} \sum_{n=1}^{N} E_n \left[(P_i^* - \ c_{con})X^*_{con,i,n} + (P_i^* + Pr_i)X^*_{Ren,i,n} + (P_i^* - \ c_{ex})\left(D_i - \ X^*_{Ren,i,n} - X^*_{con,i,n}\right) + (Voll - P_i^*)D_i\right] - \ I_{Ren}.K^*_{Ren} - \ I_{con}.K^*_{con} - \ I_T.T_{Ren}$$

Subject to:

$$T_{Ren} = f(K^*_{Ren}) \quad (59)$$

$$D_i - T_{Ren} - K_{ex} = f(K^*_{con}) \quad (60)$$

To solve this non-linear MCP model, we now develop and rearrange the objective function (58) by integrating best-reply quantities for the second and third periods given by equilibrium constraints, we obtain the following new objective function :

$$\max_{T_{Ren}} \sum_{n=1}^{N} E_n\ [(P_i^* - \ c_{con})(D_i - T_{Ren} - K_{ex}) + (P_i^* + Pr_i)T_{Ren} + (P_i^* - \ c_{ex})\ (D_i - \ T_{Ren} - D_i + T_{Ren} + K_{ex}) + (Voll - P_i^*)D_i] - \ I_{Ren}.T_{Ren} - \ I_{con}(D_i - T_{Ren} - K_{ex}) - \ I_T.T_{Ren}$$

$$\max_{T_{Ren}} A.T_{Ren} + B \quad (61)$$

Where

$$A = \sum_{n=1}^{N} E_n[(P_i^* + Pr_i) - (P_i^* - \ c_{con})] - I_{Ren} - I_T + I_{con} \quad (62)$$

$$A = \sum_{n=1}^{N} [p^n Pr_i + c_{con}] - I_{Ren} - I_T + I_{con} \tag{63}$$

And

$$B = \sum_{n=1}^{N} E_n \left[D_i(Voll - c_{con}) + K_{ex}(c_{con} - c_{ex})\right] - I_{con}(D_i - K_{ex}) \tag{64}$$

Apendix 4 : equilibrium in reactive case

Compared to the proactive case, the network operator avoids an investment cost per unit of capacity for d years that can be expressed as $d\left(\frac{I_T}{N}\right)$, where $\frac{I_T}{N}$ represents the annual unit investment cost:

$$\max_{T_{Ren}} \sum_{n=d}^{N} E_n \left[(P_i^* - c_{con})X_{con,i,n}^* + (P_i^* + Pr_i)X_{Ren,i,n}^* + (P_i^* - c_{ex})\left(D_i - X_{Ren,i,n}^* - X_{con,i,n}^*\right) + (Voll - P_i^*)D_i\right] - I_{Ren}.K_{Ren}^* - I_{con}.K_{con}^* - I_T.T_{Ren} + d\left(\frac{I_T}{N}\right).T_{Ren}$$

$$\max_{T_{Ren}} A'.T_{Ren} + B' \tag{65}$$

Where

$$A' = \sum_{n=d}^{N} [p^n Pr_i + c_{con}] - I_{Ren} + I_{con} + I_T\left(\frac{d}{N} - 1\right) \tag{66}$$

And

$$B = \sum_{n=d}^{N} E_n \left[D_i(Voll - c_{con}) + K_{ex}(c_{con} - c_{ex})\right] - I_{con}(D_i - K_{ex}) \tag{67}$$

Appendix 5 : Reactive vs. proactive case

$$A = \sum_{n=1}^{N} [p^n Pr_i + c_{con}] - I_{Ren} - I_T + I_{con}$$

$$A' = \sum_{n=d}^{N} [p^n Pr_i + c_{con}] - I_{Ren} + I_{con} + I_T\left(\frac{d}{N} - 1\right)$$

$$A' = A - \sum_{n=1}^{d} p^n\, Pr_i - dc_{con} + I_T\frac{d}{N}$$

$$A' = A - \left(\sum_{n=1}^{d} p^n\, Pr_i + dc_{con}\right) + I_T\frac{d}{N}$$

We have $: A' \begin{cases} > A\ si\ \left(\sum_{n=1}^{d} p^n\, Pr_i + dc_{con}\right) < I_T\frac{d}{N} \\ < A\ si\ \left(\sum_{n=1}^{d} p^n\, Pr_i + dc_{con}\right) > I_T\frac{d}{N} \end{cases}$

$$B = \sum_{n=1}^{N} E_n \left[D_i(Voll - c_{con}) + K_{ex}(c_{con} - c_{ex})\right] - I_{con}(D_i - K_{ex})$$

$$B' = \sum_{n=d}^{N} E_n \left[D_i(Voll - c_{con}) + K_{ex}(c_{con} - c_{ex})\right] - I_{con}(D_i - K_{ex})$$

$$B' = B - d[D_i(Voll - c_{con}) + K_{ex}(c_{con} - c_{ex})]$$

$$B' < B$$

$$W = W'$$

$$AT_{Ren} + B = A'T_{Ren} + B'$$

$$T^*_{Ren} = \frac{d[D_i(Voll - c_{con}) + K_{ex}(c_{con} - c_{ex})]}{I_T \frac{d}{N} - (\sum_{n=1}^{d} p^n \, Pr_i + dc_{con})}$$

$$T^*_{Ren} \begin{cases} > 0 \; si \; I_T \frac{d}{N} - \left(\sum_{n=1}^{d} p^n \, Pr_i + dc_{con}\right) > 0 \\ < 0 \; si \; I_T \frac{d}{N} - \left(\sum_{n=1}^{d} p^n \, Pr_i + dc_{con}\right) < 0 \end{cases}$$