

Power Transmission Network Investment as an Anticipation Problem

Vincent Rious^{*}, Yannick Perez^{**}, Jean-Michel Glachant^{***}, Philippe Dessante^{****}

Abstract

Coordination of investment between generation and transmission of electricity has greatly complicated since the introduction of competition and vertical separation between competitive and regulated sectors (Joskow, 2006). Indeed, the reforms have pushed electricity investors in generation, in particular new entrants to build production units with short construction times (3 to 4 years). At the same time, because of local opposition, the Transmission System Operators have seen the time needed to build a power line increase considerably, reaching easily 10 years now (UCTE, 2008). This lag time between the construction of production units and network elements in new ways poses a coordination problem that leads to the creation of costly congestion on the network.

Rious et al. (2008, 2009) showed that the price signal alone cannot solve the problem of coordination between investments in power generation and transmission. Our idea here is to demonstrate that this coordination problem can be solved if the Transmission and System Operator implements a new coordination scheme where he anticipates the connection of these generation units and the congestion they can induce. For this, we develop an innovative model that compares in terms of social welfare a Transmission and System Operator that anticipates or not the connection of new potential generation units. This comparison is done by arbitrating between 1 ° the cost of anticipating network investment and 2 the cost of congestion that may occur over time as network elements are made when investments in generation facilities were not anticipated.

Our main result is established using realistic examples of the probability limit of connection of new generation units beyond which it is more effective that the Transmission and System Operator anticipates these connections. In conclusion, we make recommendations for the planning of power transmission to facilitate the entry of competitors into production. We also make recommendations for the incentives to the transmission owners to invest in crisis period despite their RPI-X regulation. Indeed, this period has seen a sharp decrease of revenue for transmission owner through the RPI term. Considering the time needed to build a power line, this effect if not well healed will have effect for the whole coordination of power system for a long time.

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I. Introduction

Power generation and transmission are complementary activities that must be coordinated to ensure an optimal use and development of the transmission network. The coordination between generation and transmission is more difficult in a liberalised power system, not only because these activities are unbundled but also because of the investors' freedom to choose their generation technologies (Joskow, 2006). The power reform has prompted the generation investors to build mainly power plants with short building time, such as Combined Cycle Gas Turbines (Glachant, 2006) or wind farms (ETSO, 2007). At the same time, the right of way of powerlines faces raising strong and diverse oppositions (ETSO, 2006). These conflicting trends increase the time needed to build transmission lines and leads sometimes to the point that the powerlines cannot be built.

The differences in investment time between generation and network create uncertainty for the network planning. Indeed, these differences in investment times are all the more detrimental that the generation capacities of these new plants are significant compared to the transmission lines capacities. The connection of these power plants can thus create congestion while the network is not upgraded yet.

Rious et al. (2009a & b) showed that the price signal alone cannot solve the problem of coordination between investments in power generation and transmission. First the locational signals are institutionally hard to implement because the TSOs that own the power transmission assets are poorly interested in it. Then the locational signals have a limited efficiency because of the intrinsic lumpy cost structure of network investment. Lastly generator has so many other locational constraints (access to water, primary energy, land, acceptability from local population, etc.) that the locational signals from power transmission network are then weakly operative.

Our claim is that a logical solution to this problem of differences in investment time between generation and network could be that the Transmission and System Operator (TSO) anticipates the connection of these new generation plants and the congestions that they may create. By anticipating the connection of generation plants, the TSO can adapt the network planning so that the network upgrade is operational when the generator is just built. To implement this process, the TSO must anticipate the administrative procedures required before the network upgrading. But if the network is not eventually upgraded, this anticipation is costly because of the administrative procedures and their cost. Logically, the cost-benefit analysis for the efficiency of anticipating the generation connection and of the required transmission investment thus depends on the anticipation cost and on the uncertainty on the effective generation connection and the required transmission investment.

This paper evaluates the efficiency of the strategy of anticipating the connection of power plants for the TSO in terms of the minimization of the network cost. The question is then to know if it is efficient for such a TSO to forecast the development of its network in advance of the request of connection so that there is sufficient planned transmission capacity to accommodate these new generation investments.

To our knowledge, the efficiency of anticipating generation investment has been little evaluated in the literature, either from an empirical or from a theoretical point of view. The paper of ETSO (2006) highlights the problem of coordination between transmission and generation investments on the European power system caused by the time needed to have the administrative authorization to build transmission upgrade. But ETSO proposes no solution to this problem, except claiming for reducing this duration. Brattle Group (2007), in a report done for the Dutch TSO, recommends that Tennet should anticipate transmission investment so that the connection of generator is shortened and there is less congestion on the network. The conclusion of Brattle Group is grounded on the experience of the California System Operator CAISO which plans to anticipate the transmission line to windy areas to ease and

accelerate the development of renewable projects (FERC, 2007). Even if Brattle Group and CAISO have noticed that anticipation can be costly, they have not clearly established if the proactive behaviour of the TSO is more efficient than the reactive one. In the economic literature, Sauma & Oren (2006, 2007) are the only ones to propose a model where they evaluate the efficiency of anticipating generation investment for more efficient network upgrades in the liberalised power system considering also potential use of market power. But they implicitly assume that anticipation is free. But as shown by Christiner (2007) anticipation is costly in reality and this cost can be quite high, up to 40% of the cost of investment project in the case of the Austrian 380kV-ring. And the cost of anticipation may then change the benefits of anticipating new connections of generators and the associated network development.

In our paper, we then evaluate if anticipation remains an efficient strategy from a social point of view even when taking into account the cost of anticipation. Our model has four characteristics, which makes it noticeable compared to the other references about the efficiency of TSO of anticipating generation investment.

1° The connection of a generator to the grid is a probabilistic event. Even in areas where there are primary energy sources, the connection of a generator remains uncertain because of the market uncertainty and because of the administrative agreements that the generator may not receive.

2° There is a difference between the time to build a power plant and the time to build the needed powerline to evacuate power. This difference can be quite high because of the lengthy administrative procedures for the right of way of powerline and because of the increasing local opposition for powerline. And this difference in the generation and transmission investment dynamics can create congestion while the generator is connected but the network is not upgraded.

3° Facing the uncertain connection of generators, the TSO can choose two strategies, the proactive one and the reactive one to anticipate the connections or not. If the TSO is reactive, he develops the network only once the generator is sure to invest in a precise location. But there is then generally a delay between the moment when the power plant can be operational and the moment when the network upgrade is operational. This creates congestion and is costly. Otherwise, the TSO can be proactive and anticipates the connection of generator. The network upgrade is then operational when the power plant is just operational.

But 4° if the TSO is proactive, anticipation is costly. This is because, if the power plant is eventually not built and then not connected to the network, the TSO has engaged some costs through the administrative procedures required to build powerline for nothing.

This paper is organised as follow. Section 2 will show that the need to coordinate generation and transmission varies with the considered generation technology. Section 3 will evaluate the efficiency of anticipating the generation connection and the required transmission investment. Section 4 will make an evaluation of the proactive TSO gains on realistic cases of connection with CCGT and wind farms. Section 5 will conclude and raise some implications of our work for academia, TSO managers and regulators.

II. Generation technology and the coordination of generation and transmission investments

In a liberalized power system where generation and transmission are generally unbundled, the need to coordinate these activities varies with the generation technology. Indeed, the time needed to build powerlines can be longer than the time needed to build some generation technologies. Our review on this problem show that it takes at least five years to build a powerline and on average seven to ten years in Europe (ETSO, 2006).

There are two steps to build a powerline. First the TSO must fulfil the administrative procedures to have the right to build the line. This step to obtain the administrative agreements lasts at least three years. But in practice, it can last five years on average. The second step consists in building the line. This step is quite short, about two years only, and faces few uncertainties. Getting administrative agreements is then the crucial step for the time between the investment decision and the completion of the project. The uncertainty on building the powerline comes from this period because of the local oppositions to the right of way of the transmission lines, which can result in postponing the line project or even in the impossibility to realise it.

The choice of generation technology also impacts the need of anticipation of network investment. Besides, some generation technologies have an important notional size while they can be more quickly built than the network requirement. The connection of these power plants can then create network congestion while the TSO has not yet upgraded his network to evacuate this new power. This can make the accommodation of these generators more difficult. This impact on the different generation technologies on the network is captured in table 1 by the third column that gives the notional size of an installation divided by the time to build it.

Table 1. Building time of different generation technologies (RAE, 2004; DGEMP, 2003)

Generation technology	Time needed to build (year)	Notional size (MW)	Notional size divided by time to build (MW/an)
<i>Combustion turbine</i>	1	40	40
<i>Coal</i>	4-5	150 to 1600*	30 to 400*
<i>Combined Cycle Gas Turbine (CCGT)</i>	2	800	400
<i>Nuclear</i>	5-7	1600	200 to 300
<i>Wind onshore</i>	2	25	12.5
<i>offshore</i>	2	100	50

*Depending on technologies

Here it is worth the cost to note that some generation technologies are easier to handle for TSO. For instance, coal and nuclear generation units face similar time horizon for construction than network investments. The TSO can then deal with their connection when required at the beginning of the project.

To the contrary, the Combined Cycle Gas Turbine (CCGT) and the wind farms can be built and connected faster than the network can be modified to accommodate them. The time to build CCGT is quite short since it is only about two to three years (RAE, 2004; DGEMP, 2003). The CCGT investors can then respond quickly to the power market needs. The notional size of CCGT is 800 MW. It cannot be neglected compared to the transmission capacity of powerlines between 1000 and 2500 MW for the voltage level where they connect (400 kV or 225 kV). Therefore, these new generation units can create important congestion

before the TSO can upgrade the network. A similar conclusion applies to the network where wind farm connect with capacity of powerlines around 100 MW.

This phenomenon becomes very important in liberalized markets worldwide because these two last technologies are actually the preferred ones in Europe and in the USA¹. For the CCGT, three elements account for this preference (Glachant, 2006). First of all, the investment cost of CCGT is small compared to those of other base or shoulder generation technologies, such as coal or nuclear. Besides, in the 90's, the CCGT had the smallest marginal cost because gas was cheap. Lastly, the CCGT investments are less risky than other base investments. Indeed, the CCGT investments induce and increase the correlation between the electricity prices and the gas prices. Therefore, the revenue of CCGT investors is all the more constant and all the less risky as this technology stands for an increasing share of the energy mix (Roques *et al.*, 2008). Consequently, the more the CCGT represents an important share of the energy mix, the more the investors are incentivised in investing in this technology, even if the increase of the gas price ends in making this technology less competitive compared to coal for instance.

The power reform has not only introduced competition in generation but also favoured the development of Renewable Energies because they generate electricity with less or without detrimental environmental effects. Various economic instruments support the development of wind technology because they are not competitive with conventional power sources otherwise². In a lot of countries, these mechanisms induce a quick and important development of wind electricity because they ensure a guaranteed profitability for a long period to the investors that choose this technology³. For instance, these last ten years, **three gigawatts of wind power installed in Denmark, ten in Spain and twenty in Germany**⁴. And other important developments of wind power capacity are planned in some countries as in Great Britain or in France.

Such massive connection of wind power to the transmission network is problematic for two reasons. Firstly, compared to the time to upgrade the network, the time to build wind farms is quite short, since it is about two to three years. Secondly, the network must adapt to the massive connection of such atypical power plants. This generation technology is atypical because its power delivery is intermittent and because they locate on network with small voltage level whereas these voltage levels were originally designed to supply load, not to accommodate decentralised generation. Besides, although the wind power is distributed generation, the wind farms are concentrated in geographical areas with wind (see figure 1).

Their massive connection can then require upgrading the transmission network to evacuate the power generated by all the wind farms in one area towards load centres. Therefore, the problem is the following one: CCGT and wind farm can require important network upgrading whose time to build is quite longer than the time to build these power plants. There may then be congestion between the moment when these generators connect to the network and the moment when the TSO upgrades the facilities.

The TSO can anticipate the connection of these plants and consequently plan the network investment to avoid these congestions. Then it can better deal with the uncertainty coming from the difference in time to build power plants and time to upgrade the network. But this

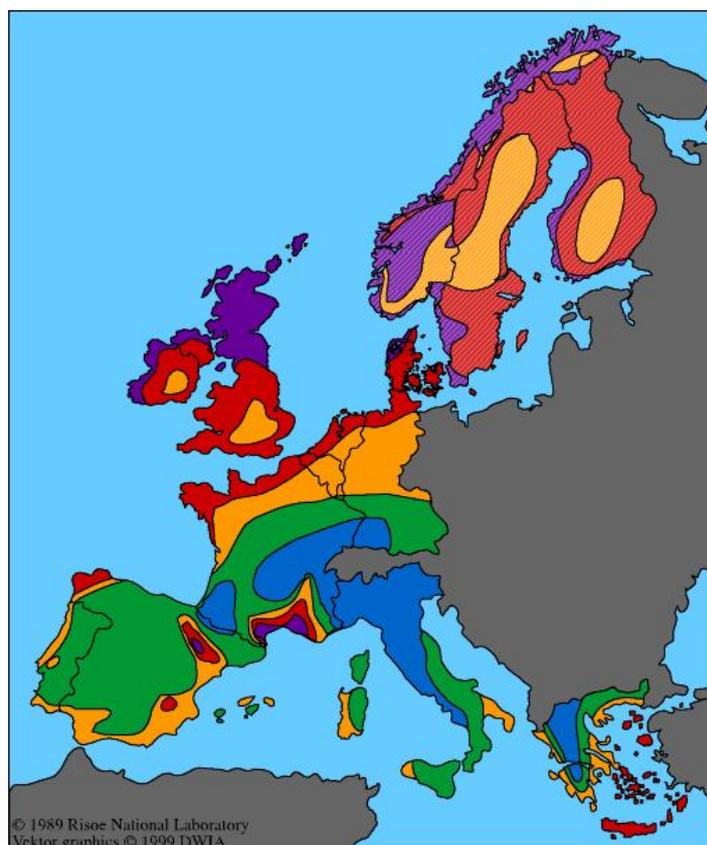
¹ To a lesser extent for the CCGT in the USA where coal is expected to be cheaper than gas to generate electricity in a few years, after 2010-2025 according to Glachant (2006).

² There exist three main subsidy mechanisms to promote the Renewable Energies: call for public tenders, price mechanisms (feed-in tariff), and quantity mechanisms with tradable property rights (green certificates) (Finon & Perez, 2007).

³ Despite the wind power investments are capital-intensive, about 1500 €/kW, that is to say similar to the investment cost of big coal power plants (RAE, 2004).

⁴ Source : www.ewea.org

work of anticipation is costly. As a consequence it is necessary to evaluate the efficiency of anticipating the network investment to accommodate new generators.



Colour	Sheltered terrain	Open plain	At a sea coast	Open sea	Hills and ridges					
	m/s	W/m ²	m/s	W/m ²	m/s	W/m ²	m/s	W/m ²	m/s	W/m ²
Red	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
Orange	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
Yellow	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
Green	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
Blue	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400
Purple			>7.5							
Red			5.5-7.5							
Orange			<5.5							

Figure 1. Wind Resources at 45 m Above Ground Level
(Source: <http://www.windpower.org/en/tour/wres/euomap.htm>)

III. A model to evaluate the efficiency of anticipating network investments

There is a noticeable difference in time to build CCGT and wind farm and in time to upgrade the network to accommodate these power stations. In order not to limit and even to facilitate the development of these generation technologies, it can be efficient to anticipate their connections. The network can then have sufficient capacity to accommodate them. The TSO can anticipate the connection of these generators and can so study in advance the opportunity of upgrading the network.

For the CCGT, this anticipation can be done at the same time as the gas network upgrading. The development of new entry points or new Liquefied Natural Gas (LNG) entry points can attract CCGT investors and modify the location of these generators on the electricity network. For windfarm, this anticipation can be done in the framework of a regional development

planning to identify areas to locate these generators⁵. More generally, this approach can be done identifying an available primary energy source that requires the upgrading of the transmission electricity network to be exploited⁶. For instance, this is the approach adopted for the *National Transmission Congestion Study* of the United States Department of Energy (USDoE, 2006) and for the development plan of the Norwegian transmission network (Statnett, 2005), for the study to increase the capacity of the interconnectors in the Nordel electricity network (Nordel, 2004).

Not only anticipating the connection of these power plants compensates for the time lag between generation and transmission investments, but also it leads to other benefits. If the TSO made this process public, it gives better information to the market participants. In particular it can signal new opportunities to locate and to access primary energy sources. It can also reveal some problems linked to security of supply. Some generation technologies are very concentrated, whereas the transmission network cannot evacuate all their cumulated production toward the load centres when it is necessary.

Such anticipation does not commit the TSO to invest if it eventually reveals unnecessary. Because, once the TSO has obtained the administrative agreements required before building the power line, the TSO can decide to upgrade the network effectively only after the relevant assumptions of the investment project become true or extremely certain. To the contrary, a TSO whose objective is to maximise the social welfare can decide to cancel a planned investment if the relevant conditions does not eventually happen. The administrative steps needed before the building of the transmission line have then an appreciable option value if the TSO can implement various planning strategies to invest (Boyle et al., 2006).

The TSO can implement two strategies to anticipate transmission reinforcements. 1° The TSO can be proactive and anticipates the change in the generation mix and location. 2° The TSO can be reactive and upgrades the network only once he knows where and when the power plants connect. Sauma and Oren (2006, 2007) show that the proactive TSO is always more efficient⁷ than the reactive one⁸ in an uncertain environment. But they implicitly assume that anticipation has no cost while it is costly in reality and this cost can be quite high (Christiner, 2007).

The essential parameters to evaluate the efficiency of the anticipating the generation and transmission investment are then the three following ones: 1° the cost of anticipating investments, 2° the difference between the time to build power plants and the time to upgrade the network, and 3° the probability of connection of the generators. Our model allows us to measure the influence of these different elements on the opportunity for the TSO to be proactive. Next, we will illustrate our results on two representative cases of connection, respectively of a CCGT and a wind farm.

⁵ It is the case of the Wind Development Areas (*Zones de Développement Éolien*) in France (loi de programme du 13 juillet 2005 fixant les orientations de la politique énergétique).

⁶ In the case of gas, energy can be transmitted without converting it. Therefore, the process of TSO for anticipating is part of a general approach to minimise the cost while arbitrating between the cost of transmitting gas and the cost of transmitting electricity.

⁷ From the point of view of the minimisation of the expected social cost.

⁸ Sauma and Oren (2006, 2007) assume also that the generators can use their market power. Here we do not consider that assuming that the generators can use market power in transmission planning is not relevant. Indeed, less costly measures can regulate this behavior.

A. A necessary condition for anticipation to be optimal

We present here a model where the congestion cost is assumed given and sufficient to require a transmission investment⁹. In our modelling, we search for the conditions when it is efficient from the point of view of the minimization of the expected social cost to anticipate the connection of power plants whose building time is shorter than the time needed to upgrade the network.

We consider the two TSO behaviours *-proactive and reactive-* that we described just above.

- To anticipate the connection of new power plants, a *proactive TSO* realizes in advance the study of the transmission investment project and the administrative procedures that are required to have the agreements to build the powerline.
- A *reactive TSO* does not study the project nor does he make the administrative procedures in advance. He realizes these steps only once the generators have effectively asked to connect to the network.

We assume that in a step before the application of our modelling, an expert has highlighted the nodes or areas where generators are more likely to connect and the lines that may experience congestion. It is similar to the approach used in the *National Electric Transmission Congestion Study* of the *U.S. Department of Energy* (USDoE, 2006). This phase consists in determining where it will be needed to upgrade the network taking into account the primary energy sources and the areas where the generators will be able to locate. The goal of our modelling is then not to find where to upgrade the network. Our modelling finds the lines whose forecasted constraints are such that it is efficient to anticipate their upgrading and especially to anticipate the long administrative procedures. Anticipating can result in accommodating the considered generation technologies more efficiently and more quickly¹⁰.

1) Definitions and assumptions

For each year y , we define two types of congestion cost that we note CU_y and CW_y , respectively with and without network reinforcement. Then, whatever the year y , the congestion cost without reinforcement is greater than the congestion cost with reinforcement, that is to say $CW_y \geq CU_y$. For a year y , the congestion cost CW_y or CU_y depends only on reinforcing the network, and not on the moment when the network is upgraded.

We define two functions of discounted and cumulative congestion cost over several years d with a discount rate a .

- The first function, $CW(d)$ is the total congestion cost discounted during d years before upgrading the network.
- The second function, $CU(d,T)$ is the total congestion cost discounted during T years after the network being upgraded the year d . We will use the parameter T so that the congestion cost as a whole (either with or without transmission investment) is evaluated over the same duration whatever the moment of network upgrading¹¹.

$CW(d)$ and $CU(d,T)$ can be expressed as functions of CW_y and CU_y as follow:

⁹ The problem of calculating the congestion cost is dealt with further details in this paper with the realistic case of connection of a CCGT and a wind farm (see paragraph IV).

¹⁰ Our model can also test the robustness of an already decided transmission investment against the connection of new CCGT or windfarms.

¹¹ If CU was evaluated over a fixed duration, for instance 10 years, whatever the moment when the network is upgraded, this would mean that congestion costs (without then with upgrade) would be assessed for 10 years if the investment was made at once, and for 10+d years if it is delayed. This would normally inflate the costs of a delayed investment, and bias the calculations towards recommending immediate investment.

$$CW(d) = \sum_{y=1}^d \frac{CW_y}{(1+a)^y} \quad \text{and} \quad CU(d,T) = \sum_{y=d+1}^{d+T} \frac{CU_y}{(1+a)^y} \quad (1)$$

Figure 2 exemplifies the two sums $CW(d)$ and $CU(d,T)$ with $T=10$ years on this example¹². For illustrative reasons, we assume that the terms $CW_y / (1+a)^y$ and $CU_y / (1+a)^y$ increase linearly with time¹³. $CW(d)$ corresponds to the grey trapezoid and $CU(d,T)$ corresponds to the black trapezoid.

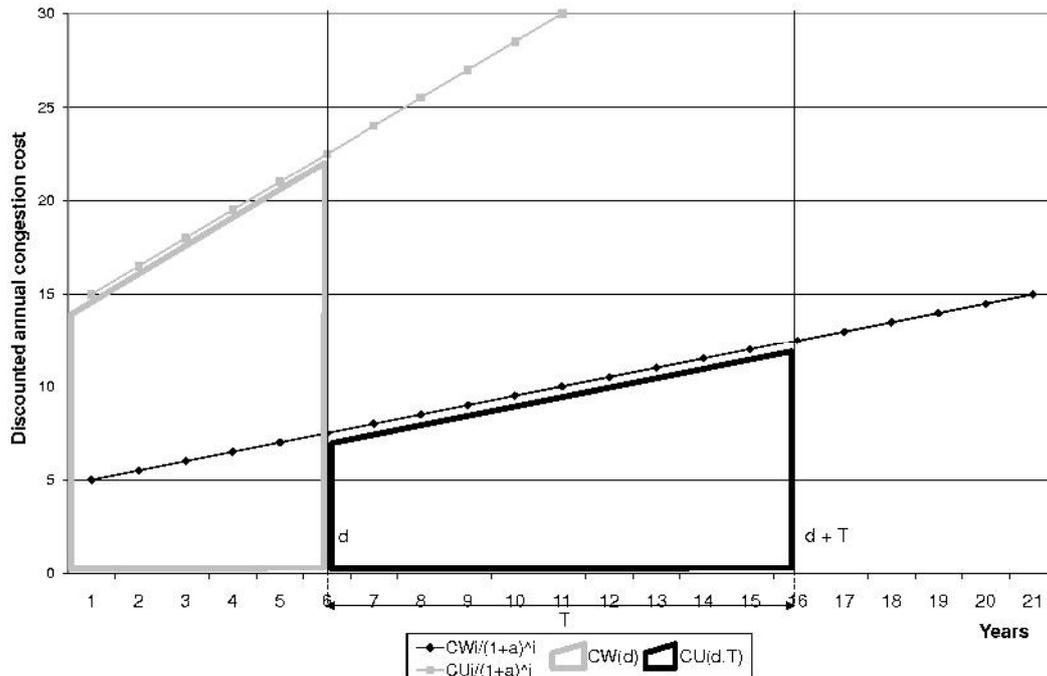


Figure 2. Definition of $CW(d)$ and $CU(d,T)$

We assume that the network must be reinforced as soon as a power plant connects. That is to say that the cost saved by the network upgrading as soon as the generator connects is greater than the related transmission investment cost. Figure 3 illustrates the cost saved by upgrading the network as a function of $CW(10)$ and $CU(0,10)$. The greyed area stands for this saved cost.

¹² The avoided costs thanks to the reinforcement of the network are generally evaluated at most only over ten years sometimes over twenty years for two reasons. First it is difficult to know accurately the state of the power system beyond ten years. Second discounting considerably decreases the costs beyond this duration.

¹³ This may not be the case in reality.

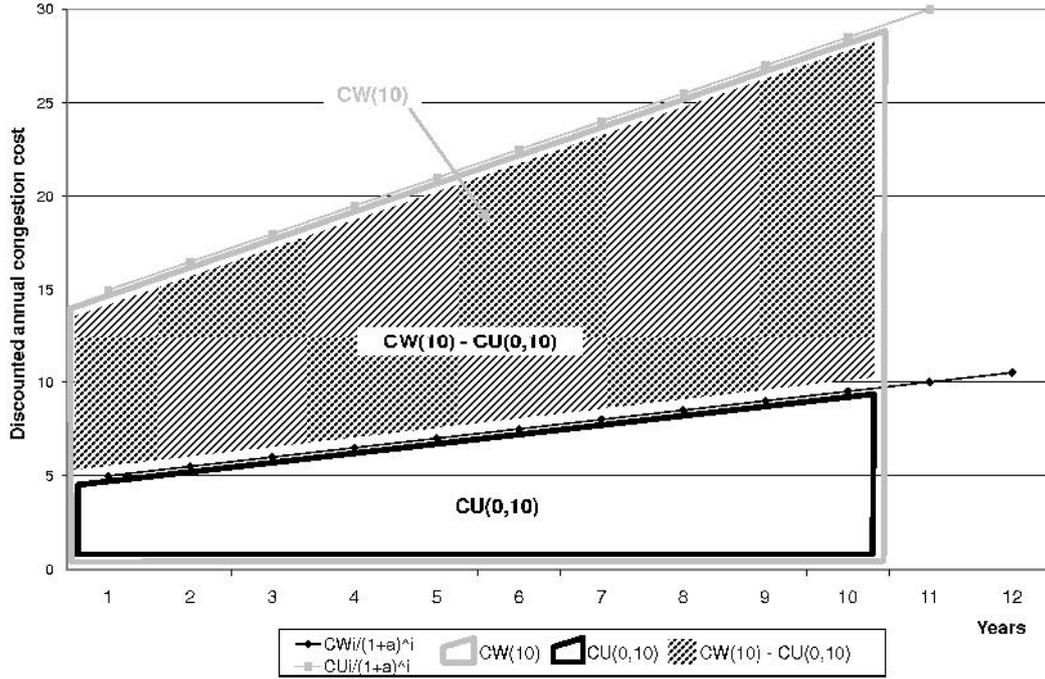


Figure 3. Cost saved by upgrading the network as a function of $CW(10)$ and $CU(0,10)$.

The equation (2) links $CW(10)$, $CU(0,10)$ and the investment cost I .

$$CW(10) - CU(0,10) \geq I \quad (2)$$

$$\text{With } CW(10) - CU(0,10) = \sum_{i=1}^{10} \frac{CW_i - CU_i}{(1+a)^i}$$

The moment of reference for discounting the cost over time is chosen so that the most conservative condition about the efficiency of a *proactive TSO* is obtained. This instant is then the moment when the generation investment begins to produce power. This convention degrades the advantage of discounting for the strategy of anticipating compared to the strategy of not anticipating. Indeed, if the beginning of the administrative procedures has been chosen as the instant of reference for discounting, the discounting of cost would have mechanically decreased the cost of network investment. By taking the beginning of production of the power plant as a time reference for discounting, this effect is avoided.

2) Expected social cost for a reactive TSO

A *reactive TSO* does not anticipate the connection of generators. It studies the network upgrading only once the generator has invested. The network investment to evacuate this power is ready to serve only d years after the connection of the generation unit, where d is the difference between the time to build a power plant and the time to upgrade the network. Figure 4 exemplifies this sequence of the generation and transmission investments. The timeframe of generation is in grey while the timeframe of transmission is in black. While the power plant has already connected and the network has not yet been upgraded, there is congestion for d years.

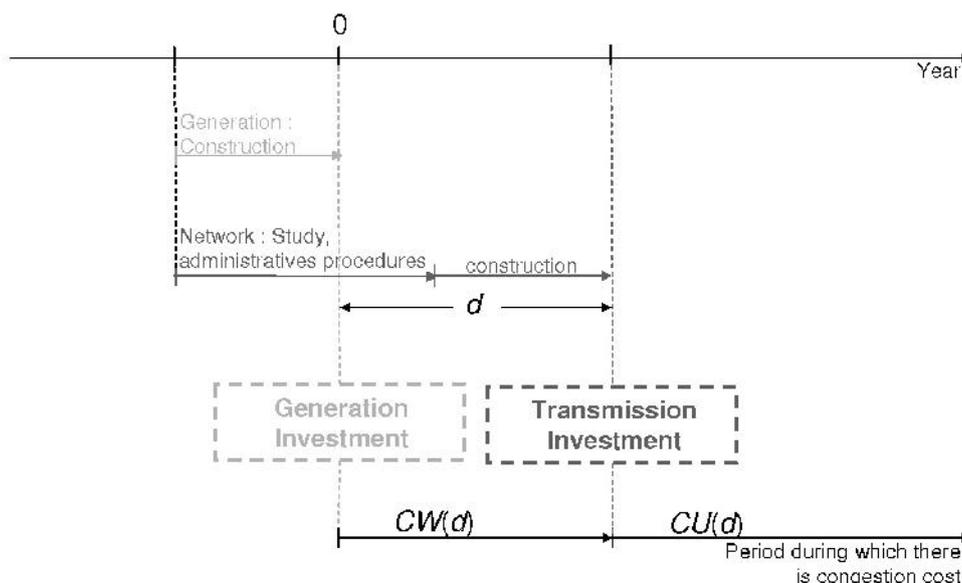


Figure 4. Sequence of the generation and transmission investment with a reactive TSO.

The generator can connect to the network with a probability p (and so does not connect with a probability of $1-p$). This uncertainty is not intrinsically quantifiable. However it is possible to attribute it a subjective value to evaluate the robustness of assumptions of a study for network investment.

If the generator connects, the system must successively support:

- $CW(d)$, the total congestion cost discounted for d years, while the TSO is upgrading the network
- $CU(d,10)$, the residual total congestion cost discounted for ten years¹⁴ after upgrading the network, that is to say d years after the connection of the generator,
- $I(1+a)^{-d}$, the discounted cost of this upgrading d years after the beginning of our study (corresponding to the moment when the generator is ready to generate power).

If the generator does not connect, the network investment cost and the congestion cost to the TSO are null. The table 2 summarises these two cases.

Table 2
Costs faced by the reactive TSO depending on the effective connection of the generator

Generator	invests Probability p	does not invest Probability $1-p$	Expected social cost
<i>waits for the connection of the power plant before studying and upgrading the network</i>	$CW(d) + CU(d,10) + I(1+a)^{-d}$	$0 + 0$	$E[C_{reactiveTSO}(p)] = p \left[CW(d) + CU(d,10) + I/(1+a)^d \right]$

3) Expected cost for a proactive TSO

A *proactive TSO* anticipates the connection of the generator. He studies the network upgrading and asks for the administrative agreements to build the powerline (without building it) before the connection of the power station. The network is upgraded only once the power

¹⁴ See footnote 12.

plant is being effectively connected. Figure 5 illustrates the sequence of the generation and transmission investments. The new transmission line and the new power plant begin to serve at the same time because the TSO has anticipated the network upgrading.

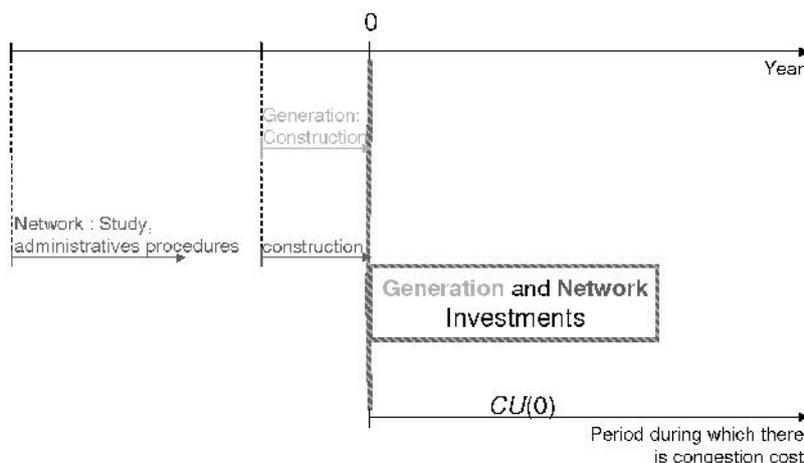


Figure 5. Sequence of the generation and transmission investment with a proactive TSO.

The generator can connect with a probability p (and so does not connect with a probability $1-p$). If the generator connects to the network, the system must successively support:

- $CU(0,10 + d)$, the residual total congestion cost discounted for $10 + d$ years after the power plant connecting and the network upgrading so that we evaluate congestion costs over the same duration whatever the moment when the network is effectively upgraded,
- and I , the upgrading cost.

In case of the generator not connecting, the congestion cost is null and the cost of anticipation linked to the non realization of the anticipated event is a share α of the total investment transmission cost. Indeed, the transmission investment is not done but the preliminary steps are however realized. The cost $\alpha.I$ includes not only the cost to anticipate to the TSO but also the cost born by the local authorities involved in the process of administrative agreements. Moreover, the cost $\alpha.I$ takes into account the *a posteriori* discounting of the cost to anticipate. We assume the cost to anticipate $\alpha.I$ is proportional to the investment cost because a power line faces all the more oppositions that it is longer and goes through a wider area. Table 3 summarises these costs.

Table 3

The costs faced by a proactive TSO depending on the effective connection of the generator

<i>TSO</i> \ Generator	Invests Probability p	Does not invest Probability $1-p$	Expected social cost
<i>Studies beforehand the installation of the power plant and invests at the same time as the generator</i>	$I + CU(0,10 + d)$	$\alpha.I + 0$	$E[C_{proactive\ TSO}(p)]$ $= \left(\begin{array}{l} p(I + CU(0,10 + d)) \\ + (1 - p)\alpha I \end{array} \right)$

4) General condition for a proactive TSO to be efficient

We are searching for the necessary and sufficient condition for the *proactive TSO* to be more efficient than the *reactive one* from the point of view of the minimization of the expected social cost. This condition links the cost α to anticipate, the probability p to connect

a power plant and the difference d in time to build a power plant and a power line such that the equation 3 is respected.

$$E[C_{proactive\ TSO}(p)] \leq E[C_{reactive\ TSO}(p)] \quad (3)$$

The equation 4 equivalently expresses this relation.

$$\alpha \leq p \left[(1+a)^{-d} + \alpha - 1 + \frac{CW(d) + CU(d,10) - CU(0,10+d)}{I} \right] \quad (4)^{15}$$

To interpret this formula, we consider the case of equality of the equation 4 and then define the limit of probability of “probability limit” p_{lim} to connect a power plant.

$$p_{lim} = \frac{\alpha}{(1+a)^{-d} + \alpha - 1 + \frac{CW(d) + CU(d,10) - CU(0,10+d)}{I}} \quad (5)$$

If the probability to connect a power plant is greater than p_{lim} , then the *proactive TSO* is more efficient than the *reactive one*¹⁶. The equivalence between the equations 3 and 4 then shows that the strategy of anticipation is all the more efficient that the probability p_{lim} is small. The interpretation of the equation 4 also consists in evaluating how the probability limit p_{lim} varies with the cost α for anticipating and the difference d in time to build a generation investment and a transmission one. For a given cost α for anticipating, p_{lim} decreases when the difference d between the time to build a power plant and a power line increases. This is because the congestion cost generally increases more quickly than the gain from postponing the network investment and its discounting. For a given difference d , p_{lim} increases when the cost α to anticipate increases.

5) A conservative evaluation of conditions for a proactive TSO to be efficient

The study of partial derivatives of p_{lim} versus α and d shows the following relationships between these variables and p_{lim} . p_{lim} increases when α increases. And p_{lim} decreases when d increases under the assumption that the derivative of $CW(d) + CU(d,10) - CU(0,10+d)$ is high enough (higher than the derivative of the term $(1+a)^{-d}$, which is very low). Table 2 shows some values of p_{lim} for a set of values of d and α . We also make a conservative assumption on the level of the term $CW(d) + CU(d,10) - CU(0,10+d)$. We assume that there is no congestion after investment (and therefore that $CU = 0$) and $CW(d)/I$ follows a linear law with a value of $CW(d)$ close to the discounting for d years of the annualized cost of investment over 20 years. This means that congestion exists and that it justifies the development of the network without inducing excessive congestion cost.

With the above assumptions, we show that the efficiency of the anticipation strategy is not obvious in all the possible situations. To be efficient, the strategy of anticipation of connections of new generators by the TSO requires appropriate conditions. Indeed, when the cost of anticipation is very high, 50% of the investment cost, and the difference of dynamics

¹⁵ The term $CW(d) + CU(d,10) - CU(0,10+d)$ can also be calculated as follows

$$CW(d) + CU(d,10) - CU(0,10+d) = \sum_{y=1}^d \frac{CW_y - CU_y}{(1+a)^y}$$

¹⁶ To the contrary, if the probability of connection p is less than p_{lim} , then the reactive TSO is more efficient than the proactive TSO.

between generation and transmission investments is moderate (4 years), we notice that the anticipation of generation investments would be efficient only when their connection has an extremely high probability (90%). However once the cost of anticipation decreases, anticipation becomes a more efficient strategy with lower probabilities of connection (until less than 50%). When the difference in dynamics between generation and transmission investments increases, the anticipation strategy becomes more efficient in just over one in four cases with a cost of anticipation of 50% and in more than one in two with a moderate cost of anticipation of 15%.

Table 4
Evaluation of the limit probability for some values of d and α

Difference in dynamics d in years	4			7		
Ratio congestion cost before network investment over the network investment cost $CW(d)/I$	0,3			0,6		
Cost of anticipation α in %	50	15	3	50	15	3
Limit probability p_{lim} in %	93	81	46	73	45	14

These results must be moderated because it is assumed that the congestion cost before the network upgrade is just sufficient to justify that the network be upgraded. Considering the expression of p_{lim} , we understand that a higher value of the congestion cost, before (CW) or after (CU) the grid reinforcement leads to lower values for the limit probability than the ones previously calculated. Our results are thus rather conservative. Even if they clearly show that the efficiency of the anticipation of new connections and of the associated network reinforcement is uncertain, but asks to consider specific situations where administrative costs are low or moderate or when the potential of new connection is not negligible.

IV. Evaluation of the proactive TSO on realistic cases of connection

To expand our first analysis, we now illustrate equation 4 on concrete cases of connection of a Combined Cycle Gas Turbine (CCGT) and then on a windfarm. We can determine the combinations of parameters where the *proactive TSO* is more efficient than the *reactive one*.

A. Investment and connection of a CCGT

We apply the criterion of the equation 4 on the simple case of the connection of a CCGT on a two node network. Figure 5 is realistic because the connection of CCGT raises problems mainly when these power plants are far from the load centres because they locate then in areas where there were previously no or few power plants and so where the network is not very developed.

In the example of figure 6, the load and most of generation are to the east. These power stations to the east are quite expensive, 40 €/MWh for the first 3000 MW and 100 €/MWh after. The power plants to the west are less expensive, only 35 €/MWh.

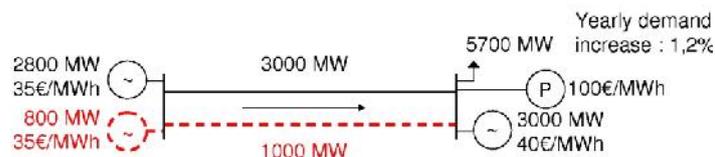


Figure 6. System to test the strategy to anticipate the connection of a CCGT.

A new generator is wishing to connect a 800 MW CCGT to the west. To evacuate the power of this new power plant, it is necessary to add a 1000 MW network upgrading that costs 100 million euros. We assume that the situation of figure 6 is representative of the 8760 hours of the year. The dashed lines on this figure stand for the investments.

First of all, we draw p_{lim} the probability “limit” to connect a CCGT. When the effective probability is above the probability, the *proactive TSO* is more efficient for a given cost α to anticipate (equal to 10% of the considered network investment). The probability “limit” can be defined as a function of the difference d between the time of building a power plant and the time of building a powerline. This function is drawn on figure 7.

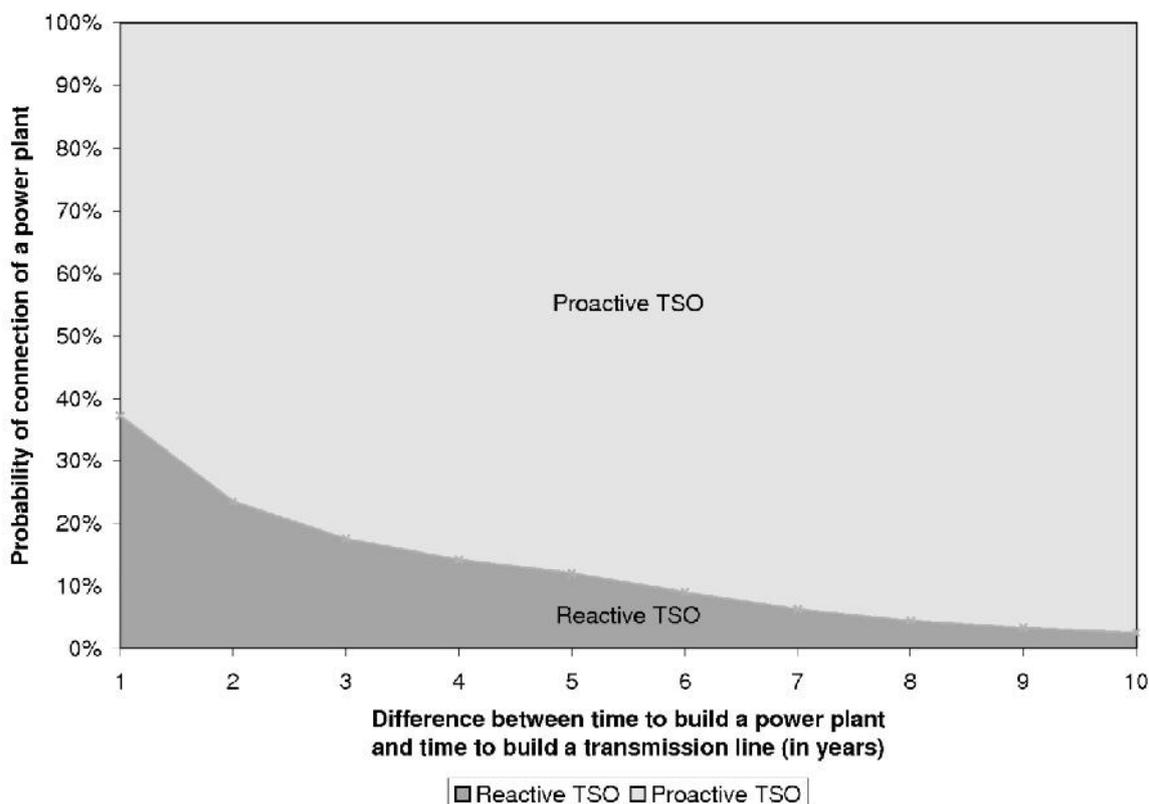


Figure 7. Probability limit of connection beyond which the TSO must be proactive depending on the difference of temporal dynamics d between the network investments and a CCGT

Above the curve associating the probability limit with the difference in dynamics of investments, proactivity is the optimal behaviour for a TSO. Below this curve, reactivity is the optimal behaviour for a TSO. On figure 7, we notice that the probability limit decreases as the difference in dynamics increases. We find again that the TSO has little interest in anticipating the connection of a generator if the temporal rhythms of these two complementary investments are close (that is to say that if the time of building a network investment is short or if the time of building a generation investment is long). For the connection of a CCGT, this difference in time is at least of three to four years. For such a difference, the probability limit of connection is around 15 to 20%. This weak value is already significant to justify the anticipation of the network reinforcement.

The planner does not know in advance the cost of anticipating the reinforcement, that is to say the cost of the administrative agreements needed to build the reinforcement¹⁷. The cost of anticipating is *a priori* weak compared to the whole cost of powerlines. The environmental

¹⁷ Indeed, it is difficult to rely on historical data for the cost of anticipation, because the powerlines face more and more local oppositions.

impact study is the core of the administrative procedures needed to build overhead powerlines (ETSO 2006). The cost of this study is at the maximum only 3% of the total cost of the network investment¹⁸. However, when the opposition to the way of a powerline is strong, the lawsuits and the judicial recourses follow the administrative procedures, which can considerably increase the cost of anticipation. Such data of cost being inaccessible to our knowledge, we take 50% of the whole cost of the study as an upper bound¹⁹. Moreover, in an approach that aims at minimizing the social cost, it is necessary to consider the cost of administrative procedures for all the stake holders: the TSO of course, administration, but also the non governmental organizations, etc.

It is then useful for the TSO and the regulator to know the sensibility of the limit between the reactive TSO and the proactive one to the different parameters that define this limit. All the more that there is no available information on the whole cost of the administrative procedures either for the TSO or for the other stake holders of the power system.

Figure 8 describes the limit of efficiency between the *proactive TSO* and the *reactive TSO* as a surface parameterized by the relationship linking α , p and d . For the combinations of these parameters above these surfaces, it is more efficient for the TSO to be proactive.

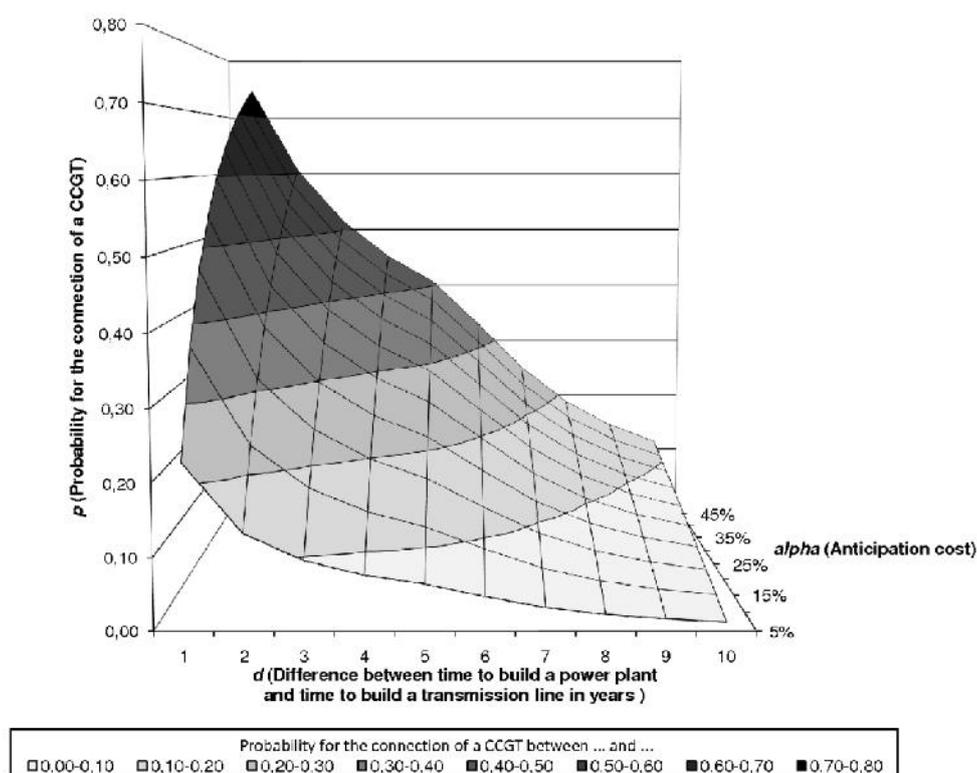


Figure 8. Combination of the parameters α , d et p that set the limit of efficiency of the proactive TSO for the connection of a CCGT

We can draw three main lessons from figure 8.

First the sensitivity for the probability limit of the cost of anticipation is all the more weak that the difference in temporal dynamics between the network and generation investments is important. Then the probability of connection delimiting the reactive and proactive behaviours for the accommodation capacity is robust for moderate variations of the cost of anticipation. For instance, for a cost of anticipation estimated at 10% whereas the real cost reaches 20% of the total investment cost, the probability limit reactive/proactive vary only

¹⁸ <http://ec.europa.eu/environment/eia/eia-studies-and-reports/eia-costs-benefit-en.htm>

¹⁹ This is the case for one of the two lines needed to make the 380 kV ring in Austria (Christiner, 2007).

from ten to twelve points for differences of dynamics between generation and transmission investments that justify such an anticipation (that is to say beyond four years).

Therefore and secondly, for all the simulated cases, for differences in time of building that can justify an anticipation (beyond four years), we notice that it is on average advantageous to anticipate the network investments. Of course, this advantage may be limited. For instance, for a cost of anticipation of 50%²⁰ and a difference in time of building of five years, the probability limit of connection beyond which the TSO must be proactive is 45%. That is to say that for our example, the strategy to anticipate is more efficient than the reactive strategy for a little bit more than a connection over two.

Lastly, in the representative example of realistic situations, the anticipation of connection of CCGT by the TSO is on average the best strategy for two reasons. First the probability of connection favourable to an efficient *proactive TSO* decreases quickly with the difference in temporal dynamics between the network and generation investments. This probability limit then becomes quickly significant for the differences in dynamics where the anticipation of connection of generators is interesting, that is to say beyond three to four years. Second this probability limit remains quite robust for moderate variations (the most realistic one) of the cost of anticipation linked to administrative procedures needed before the building of connection.

Now we realise a similar analysis for the case of the connection of a windfarm in a load pocket.

B. Connection of windfarm

We apply the criterion of equation 4 on a simple but realistic case of the connection of a windfarm in a load pocket thanks to the following two-node network (figure 9). The connection of windfarms indeed raises difficulties because they are decentralized generation and so are mainly connected on distribution networks that generally accommodate no or few power plants, but where load exists.

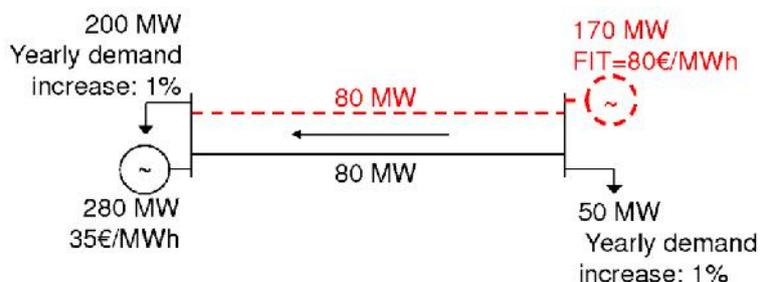


Figure 9. Test network with the connection of windfarms

Contrary to the previous case, we assume now that there is consumption to both nodes of the network, in particular to the node where a new wind power plant connects. The load to the east is 50 MW whereas it is 200 MW to the west. The increase in load is 1% for the two nodes of the network. The generation to the west is conventional power plants whose generation cost is 35 €/MWh. The two nodes are linked by a medium voltage network whose initial capacity is 80 MW, and a reinforcement of 80 MW can be added.

The wind generation with a capacity of 170 MW wishes to connect to the east. We assume that the distribution function of the power P generated by this generator is the following one:

²⁰ This value is maybe excessive but we use it as an upper bound for the cost of anticipating network investments.

Table 4 Distribution function of a wind generator

P is less than	10%	of the installed power capacity during	50%	of time
P is equal to	40%		40%	
P is more than	80%		10%	

For simplicity reason, we assume that the wind generators are remunerated by a feed-in tariff of 80 €/MWh. To evacuate the power of this new generator, it is possible to reinforce the network adding an 80 MW transmission capacity to the existing powerline for a cost of 10 million euros. Besides, we assume that the situation of figure 9 is on average representative of the 8760 hours of a year (to the exception of the distribution function of the wind generator). Before calculating the frontier of efficiency between the reactive TSO and the proactive TSO, we need to determine how wind power with a support scheme should be valued in the network planning.

The value of renewable electricity with support schemes in the network planning

Wind energy is characterized by its marginal cost being close to zero (RAE, 2004). But the nullity of their marginal cost reflects neither the behavior of wind producer nor the economic value that the support schemes for renewable gives to wind energy. Indeed, to promote this CO₂-free energy despite its still high cost compared to conventional energy, wind power producer currently receives some supports based on the amount of produced electricity (RAE, 2004).²¹ These support schemes aim at maximising the amount of electricity produced by renewable sources.

Congestion can lead in some areas to limit the amount of electricity from wind farm. As a result, it limits the penetration of renewable energy sources in the power system. Of course, such congestion can be relieved but with a cost to upgrade the network. As a consequence, from a social point of view, there is an arbitrage to realise between the amount of electricity produced by wind farm and the cost of the network to relieve congestion linked to this kind of generators. As the support schemes stand for the economic value of wind power²², the arbitrage has to be realized between the loss of wind power (from congestion) valued at the level of the support scheme and the cost of upgrading the network (to relieve congestion). We represent this arbitrage by the equations 6 & 7. Consequently, wind power must be valued in the network planning with a negative sign and at the level of the support scheme in absolute value.^{23, 24}

$$\min_{K, P_e} C(K) * K - S \times P_e \quad (6)$$

Such that

$$\begin{cases} 0 \leq P_e \\ P_e \leq \overline{P_e} \\ f(P_e) \leq K \end{cases} \quad (7)$$

With :

²¹ The scheme implemented to support wind energy can take different forms: the price mechanisms called "Feed-in Tariff", the quantities mechanisms called "tradable green certificates" and the calls for tender.

²² With this assumption, we do not wonder here how to set the support schemes to the social value of renewable energies. Further elements can be found on this topic in Finon and Perez (2007) and EWEA (2005).

²³ We consider here a support scheme such as a call for tender or a feed-in-tariff but the same rationale can be applied with green certificate. It is then needed to add the price of electricity to the price of green certificates to obtain the social value of wind energy in this case.

²⁴ The same rationale can be applied to any other types of supported renewable energy sources.

- S the level of the support scheme in €/MWh;
- P_e is the current production level of the wind power producer following restriction of the TSO;
- \overline{P}_e is the maximal production of the wind farm considering the current availability of the primary energy wind. \overline{P}_e is an exogenous stochastic variable standing for the electrical energy extractible from wind;
- f stands for the function that link the production of wind farm and the flow of the line that can be congested;
- K is the capacity of the line that can be congested by electricity from the wind farm;
- $C(K)$ is the cost for this line for a capacity K .

This result is also relevant compared to the compensation that a supported wind producer should receive to be incentivised to relieve congestion.²⁵ Indeed, if wind producer is imposed a limit on their production to relieve network congestion without any adequate financial compensation, then wind producer is deprived from a part of its revenue. The wind generator is then not incentivised to decrease its production. To incentivise the wind generator to decrease its production in case of congestion, the TSO must consider that this type of power plants has a cost “for not producing” (when adjusting them downward) that is negative and whose absolute value is determined by the level of the support scheme. Indeed, when the primary energy of these non-dispatchable generators is available but they are not allowed to produce because of congestion, these generators have an opportunity cost for not producing. This cost for not producing is negative and equal in absolute value to the level of the support scheme. To show this, we consider the maximization of the profit function (represented by equation 8) of a non-dispatchable generator with a support scheme and whose production can be limited by the TSO because of congestion (represented by equation 9). This profit function is based on the non-dispatchable power (\overline{P}_e) that he could generate instantly at maximum and on the power P_e that the TSO imposes him because of congestion.

$$\max_{P_e} S \times P_e + p_A (P_e - \overline{P}_e) \quad (8)$$

Such that

$$\begin{cases} 0 \leq P_e & \perp \lambda_1 \\ P_e \leq \overline{P}_e & \perp \lambda_2 \end{cases} \quad (9)$$

With :

- S , P_e and \overline{P}_e have the same definition as previously;
- p_A is the price that the wind power would bid in a balancing market for adjusting its power downward;
- $P_e - \overline{P}_e$ gives the downward adjustment;
- λ_1 and λ_2 are the shadow prices of the constraints (9).

²⁵ In practice, such a compensation should not be implemented. Indeed the absence of compensation for production limitations due to congestion gives good locational signals to wind power producers. They are then incentivized to locate in areas with enough accommodation capacities.

We search for the condition so that a supported non-dispatchable producer accepts downward adjustment needed to relieve congestion. So we want that $0 \leq P_e < \overline{P_e}$, that is to say in terms of shadow prices that $\lambda_1 \geq 0$ and $\lambda_2 = 0$. With these conditions, from the differentiation of the Lagrangian²⁶, we obtain the following result $-S \geq p_A$, which means that the downward adjustment price should be negative and equal or greater than the level of the support scheme in absolute value for the wind power be incentivized to adjust downward.

Calculation of frontier of efficiency between the reactive TSO and the proactive TSO for the connection of a windfarm

Considering the above assumption for the connection of a windfarm and the economic value of wind power in the network planning (see above), we can now determine the frontier of efficiency between the reactive TSO and the proactive TSO.

First we represent the probability limit of connection of a windfarm beyond which the TSO must be proactive for a given cost of anticipation α (equal to 10% of the network investment cost). The probability limit can then be defined as a function of the difference d between the time to build a new power plant and the time to reinforce the network. This function is drawn on figure 10.²⁷

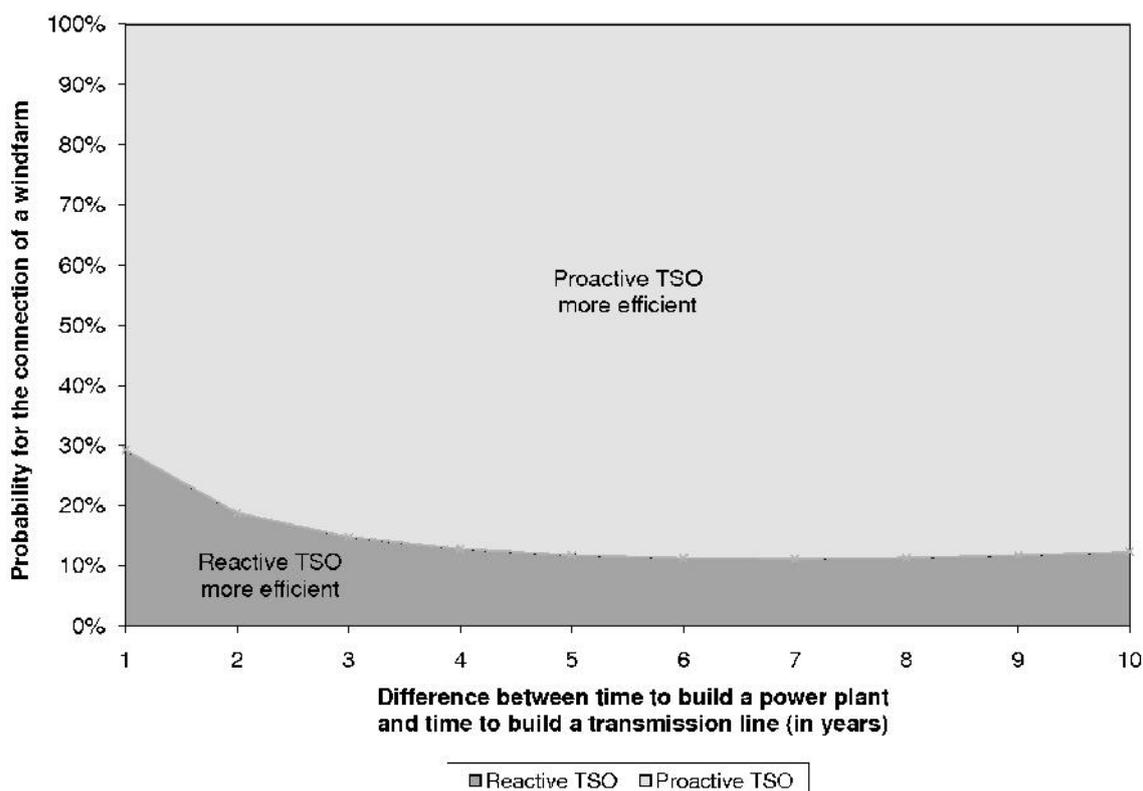


Figure 10. Probability limit of connection beyond which the TSO must be proactive depending on the difference in dynamics between the network investments and a windfarm

²⁶ In this case, the Lagrangian of the problem of profit maximisation for the wind generation is $L(P_e) = S \times P_e + p_A (P_e - \overline{P_e}) + \lambda_1 P_e$. Differentiating this function with respect to the variable P_e , we have the following relation $S + p_A + \lambda_1 = 0$. As $\lambda_1 \geq 0$. Hence we have $-S \geq p_A$.

²⁷ As previously, above the curve associating the probability limit with the difference in dynamics of investments, proactivity is the optimal behaviour for a TSO. Below this curve, reactivity is the optimal behaviour for a TSO.

We can draw lessons a little bit different from the previous ones. Indeed, figure 10 differs slightly from the one previously drawn in the case of a CCGT. With a wind farm connection in a load pocket, the congestion cost decreases with time because the load located at the same node as the windfarm increases with time and then absorbs an increasing share of the local generation. Therefore, the evolution of the probability limit with the difference in dynamics of generation and network investments is not monotonous. There is a small increase beyond seven years of difference in the time to build a windfarm and the time to build a powerline. This can be confirmed when one make the cost of anticipation vary (figure 11).²⁸ And this effect is all the more important that the cost of anticipation is great. For differences in dynamics that justify an anticipation of the network investments (beyond three years of differences), the strategy to anticipate remains on average the one that must be chosen.

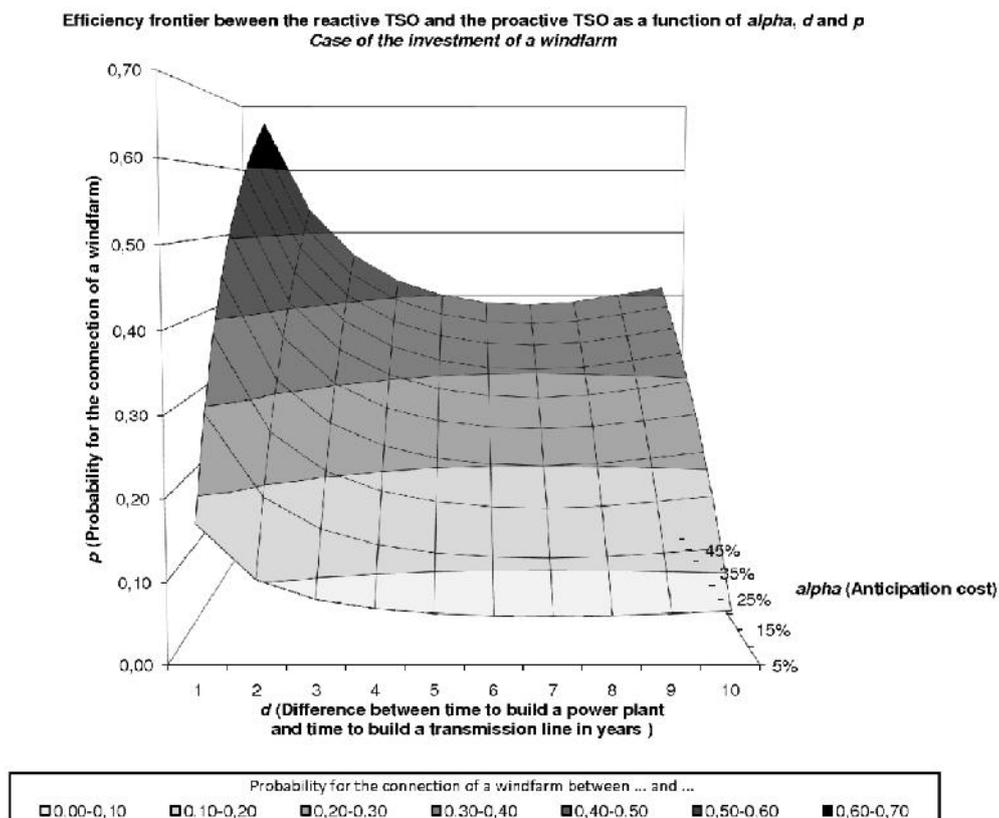


Figure 11. Combination of parameters α , d and p that sets the limit of efficiency of the proactive TSO for the connection of a windfarm

For this example representative of realistic situations, it remains efficient on average to anticipate the connection of windfarms. Indeed, the difference in time to build a windfarm and the time to reinforce the network can reach five years. Then, taking again a cost of anticipation equal to 50% (of the cost of reinforcing the network), the probability limit beyond which the TSO must be proactive is 40%. That is to say that, in our example, for three connections of windfarms over five, the strategy of anticipation is more efficient than the reactive strategy.

²⁸ Above this surface, it is more efficient for a TSO to be proactive. Below this surface, it is more efficient for a TSO to be reactive.

V. Conclusion

By favoring the construction of new power plants, the anticipation of transmission investment has a central role in coordinating the generation and transmission investments. Regarding this statement, the paper has brought two contributions.

First this paper has shown that the liberalization of the power system has complicated transmission planning while making its anticipation even more essential, for two reasons. First, the Combined Cycle Gas Turbines and the wind farms which stand for the biggest amount of generation investments in Europe and in the USA can be built in less time than the transmission lines that should transmit the power from these power stations through the core of the network. Second, the duration of the administrative procedures required before the construction of a powerline stands for almost three quarter of the time to realize a powerline.

The second contribution of this paper is the model. Our model allows evaluating the efficiency of the strategy of anticipating the connection of power plants to the network for the TSO in terms of the minimization of the network cost where anticipation is costly because of the administrative procedures. This model has permitted to see on an analytic study with conservative assumption and on simple but realistic examples that it can be quite efficient for a TSO to anticipate the connection of power plants. In spite of the uncertainties associated to the connection of new power plants, the TSO can identify the areas where new generators would find resources to locate, the subsequent network constraints that may then occur and the reinforcements that may relieve them. The anticipation of these network investments avoids that costly congestion appears while power plants are already built but powerlines are still in its administrative phase. Taking into account the interest of investors for generation technology with short lead construction time, the proactive behavior of the TSO can facilitate the connection of these types of power plant and increase the market entries.

In addition to the compensation of the difference in dynamics between transmission and generation investments, anticipating the connection of new generators to develop the network has other virtues. This approach by the TSO, if it is public, can stimulate the dialog with other stakeholders in the electricity system and identify in advance a shared view of the system evolution (Bråten, 2004). In particular, it allows to provide the market participants with new opportunities in terms of location and primary energy. It allows also to report any problems with security of supply. Some generation units may be geographically concentrated, while the transmission network cannot or will not be able to evacuate their whole production to consumption centers in a timely manner. Furthermore, Besides, the sooner the residents are involved in the transmission investment process, the easier the powerline would be built (Hughes, 2000; MacLaren Loring, 2007).

Our paper now opens the way to new questions: toward academic world, we pave the way to new works on this issue taking into account the limits of our study. Works need to be done to take into account the inclusion of locational signals, incentive regulation for anticipation, the problem of investment incentive for generator without anticipation of grid development, or the effect of milestones payment of the connection tariffs to create increasing location commitment from generator. Toward the relationship between regulator and TSO, our work shows that efficient regulation should include anticipation as a core issue in the regulated TSO activities. Lastly, toward TSO directly, we think that even in the case of incomplete regulation on this issue, TSO should perform anticipation of network investments by their own means as it solves the operational problem of congestion management in advance.

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