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A stochastic model for the single producer capacity expansion problem in the Italian electricity market

by

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A stochastic model for the single producer capacity expansion problem in the Italian electricity market

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Abstract. We present stochastic models for determining the optimal mix of different technologies for electricity generation, ranging from coal, nuclear and combined cycle gas turbine to hydroelectric, wind and photovoltaic, taking into account the existing plants, the cost of investment in new plants, the mantainance cost, the purchase and sales of CO_2 emission trading certificates and green certificates to satisfy regulatory requirements. We assume the point of view of price-taker producer. The stochasticity is related to the future fuel prices and to the future price of CO_2 emissions permits: we generate scenarios for the fuel prices and only one scenario fro CO_2 emission permits. The stochasticity appears in the expected costs and the probability that the total cost do not overcome a specific threshold is taken into account by considering CVaR risk measure.

1 Introduction

The incremental selection of energy generation capacity over a long term planning horizon is of great importance for energy planners. It can be considered from two different viewpoints:

1. the single power producer's (GenCo's) perspective,
2. the system operator's perspective.

For problem (1) a mathematical model is needed to determine the optimal expansion plan subject to all the relevant factors (regulations and prices) with the aim of finding an optimal trade-off between profit and risk. For case (2) a zonal representation of the production and transmission system must be used, in order to determine GenCo's expansion plans (where and when), taking into account the impact on the transmission network, aiming at minimizing the system cost of satisfying load. There are various references in the literature referring to problems (1) and (2). For problem (1) we mention the papers [1] and [4]. Paper [4] is the base of our model. We differ from it both for dealing differently with the fixed and variable costs

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and for using a stochastic programming based model. More details about our model can be found in report [11]. Reference [3] is particularly useful in evaluating the use of different risk measures. For case (2) we mention the relevant contributions by [5], [7], [10], [2], [6].

In this paper we deal with problem (1), i.e. we want to determine the optimal generation expansion plan of a single generation company (GenCo) over a long term planning horizon consisting in I years (generally, 30 or more years). In section 2 we describe the model, in Section3 the scenario generation is discussed, Section 4 discusses the numerical results and the conclusions follow.

2 The stochastic model

The main factors affecting power producers decisions can be summarized in the following:

- regulatory constraints
- uncertainty of prices (fuels, CO_2 emission permits and green certificates)
- characteristics of available technologies
- sites where plants can be located
- budget.

In the model we suppose that sites for locating new plants of each technology are already available, thus we want to determine the number of sites for each technology.

Let J^{ET} denote the set of existing thermal plants and J^{ER} denote the set of existing renewable plants, J^{NT} denote the set of candidate thermal plants and J^{NR} denote the set of candidate renewable plants. Let $J = J^{ET} \cup J^{ER} \cup J^{NT} \cup J^{NR}$. The model decision variables are the following:

- Real variables: let $E_{j,i}$ be the electricity produced by a plant of technology j in year i; the types of available tachnologies and their characteristics are illustrated in Tables 1 and 2.
- Integer variables: let $w_{j,i}$ be the number of plants of technology j whose construction has to be started in year i.

In our model the capacity expansion is not a continuous variable but takes into account the size of each candidate plant.

The main goal of the model is to determine the evolution of the optimal investment along the planning horizon of 30 years.

The total number of new plants for technology j, that can be built in the planning horizon, is bounded above by the number of available sites $\bar{Z}_j$:

Table 1: Technologies available for new plants and their characteristics

	installed capacity (MW)	construction time (years)	industrial life (years)
Coal	600	4	25
CCGT	800	2	25
Nuclear	1200	7	50
Biomass	20	1	15
Wind (non progr)	100	1	20
Geothermal	40	3	15
Mini hydro (partly progr.)	1	1	40

Table 2: Technologies available for new plants and their characteristics (cont.)

	CO2 emission rate (t/GWh)	operating hours per year (hours)	Current fuel cost (€/MWh)	Investment cost (M€/MW)
Coal	338	7884	23	1
CCGT	200	7884	45	0.47
Nuclear	–	7884	5.5	2.6
Biomass	–	6000	30	2.2
Wind (non progr)	–	2215	–	1.75
Geothermal	–	7500	–	3.5
Mini hydro (partly progr.)	–	3500	–	3

$$\sum_{i=1}^{I} w_{j,i} \leq \bar{Z}_j. \tag{1}$$

The maximum production of new plants in year i depends on the installed capacity P_j, the maximum number H_j of operating hours of plant j and on the total number $W_{j,i}$ of operative plants j available for production in year i

$$E_{j,i} \leq (1 - \nu_j) \cdot P_j \cdot H_j \cdot W_{j,i} \tag{2}$$

where ν_j represents the losses and

$$W_{j,i} = \sum_{i-(S_j+L_j-1) \leq k \leq i-S_j} w_{j,k} \tag{3}$$

that is the sum of plants j, whose construction started in year k, provided in year i construction (S_j describes the length in years for construction) is completed and industrial life L_j is not ended.

The maximum production of existing plants in year i depends on the installed capacity P_j, the maximum number H_j of operating hours of plant j and on the residual life $\hat{L}_j$.

$$E_{j,i} = \bar{E}_{j,i} = \begin{cases} (1-\nu_j) \cdot P_j \cdot H_j & \text{if} \quad i \leq \hat{L}_j \\ 0 & \text{if} \quad i > \hat{L}_j. \end{cases} \tag{4}$$

The green certificates (GC) to be bought or sold are defined as

$$G_i = \eta_i \cdot \sum_{j \in J} E_{j,i} - \sum_{j \in J^{ER} \cup J^{NR}} E_{j,i} \tag{5}$$

where the first term is the total production in year i, η_i is the ratio between renewable energy and total energy and the second term is total production using renewable in year i.

The CO_2 emission permits to be bought or sold are given by

$$Q_i = \sum_{j \in J^{ET} \cup J^{NT}} \theta_j \cdot E_{j,i} - A_i^{CO_2} \tag{6}$$

where θ_j is the CO_2 emission rate, the first term represents the total emission in year i (existing and new thermal plants) and the last term represents the CO_2 emission allowance.

The budget constraint is given by

$$\sum_{i=1}^{I} \frac{1}{(1+r)^{i-1}} \cdot \left(\sum_{j \in J^{NT} \cup J^{NR}} I_j^a \cdot W_{j,i} \right) \leq B \tag{7}$$

where r is the discount rate, the quantity in parenthesis represents the annual investment cost, I_j^a represents the annual investment cost for technology j and B the available budget.

The GENCO's initial market share is given and an hypothesis is made on the evolution of the GENCO's market share along the planning horizon: $\overline{M}_i$ represents the GenCo's market share in year i. In this way we take into account the fact that the producer cannot reduce his own bid prices below a certain level (the marginal production cost) and therefore its production will be bounded above by the market share

$$\sum_{j \in J} E_{j,i} \leq \overline{M}_i. \tag{8}$$

The expected profit term F in the objective function takes the following form:

$$\begin{aligned} F = \sum_{i=1}^{I} \frac{1}{(1+r)^{i-1}} \Bigg(& \pi_i^E \cdot \sum_{j \in J} E_{j,i} - \pi_i^{GC} \cdot G_i - \pi_i^{CO_2} \cdot Q_i + \\ & - \sum_{j \in J^{ER}} (f_j + v_j \cdot E_{j,i}) - \sum_{j \in J^{NR}} \left[(I_j^a + f_j) \cdot W_{j,i} + v_j \cdot E_{j,i} \right] + \\ & - \sum_{s \in S} p_s \cdot \left\{ \sum_{j \in J^{ET}} (f_j + v_{j,s} \cdot E_{j,i}) + \sum_{j \in J^{NT}} \left[(I_j^a + f_j) \cdot W_{j,i} + v_{j,s} \cdot E_{j,i} \right] \right\} \Bigg) \end{aligned} \tag{9}$$

where $\pi_i^E, \pi_i^{GC}, \pi_i^{CO_2}$ are respectively the prices for electricity (exogenous to the model), green certificates and CO_2, f_j are fixed costs, v_j are variable costs for renewable, $v_{j,s}$ are variable costs for thermal plants depending on fuels prices and p_s is the probability of scenario s.

For the risk term we consider the conditional value at risk ($CVaR$) of profits.

The CVaR is given (see [8] and [9]) by

$$CVaR = VaR - \frac{1}{\alpha} \cdot \sum_{s \in S} (p_s \cdot d_s) \tag{10}$$

with d_s subject to the following constraints:

$$d_s \geq VaR - F_s, \qquad d_s \geq 0. \tag{11}$$

beeing F_s defined by

$$\begin{aligned} F_s = \sum_{i=1}^{I} \frac{1}{(1+r)^{i-1}} \Bigg(& \pi_i^E \cdot \sum_{j \in J} E_{j,i} - \pi_i^{GC} \cdot G_i - \pi_i^{CO_2} \cdot Q_i + \\ & - \sum_{j \in J^{ER}} (f_j + v_j \cdot E_{j,i}) - \sum_{j \in J^{NR}} \left[(I_j^a + f_j) \cdot W_{j,i} + v_j \cdot E_{j,i} \right] + \\ & - \sum_{j \in J^{ET}} (f_j + v_{j,s} \cdot E_{j,i}) + \sum_{j \in J^{NT}} \left[(I_j^a + f_j) \cdot W_{j,i} + v_{j,s} \cdot E_{j,i} \right] \Bigg) \end{aligned} \tag{12}$$

Our objective function becomes $F + \lambda \cdot CVaR$, to be maximized, and λ represents the risk-aversion parameter. $\lambda = 0$ represents maximization of expected profit, while increasing values of λ gives importance to the fact that we want to limit the probability to get a value for profit less than a certain threshold.

3 Scenarios generation

In this paper we consider scenarios for fuel prices (coal, gas, nuclear fuel). Scenarios are built on the ratios "estimated price over current price" of fuels for thermal plants combining in all possible ways the quantities in Tables 3, 4 and 5, giving a total of 512 scenarios

Table 3: COAL (23 €/MWh)

ratio	0.85	0.90	1.00	1.30	1.80	2.30	2.70	3.00
prob	0.010	0.050	0.560	0.220	0.109	0.035	0.014	0.002

The supply of gas may in some period be more critical than coal, while the supply of nuclear fuel is always available. These considerations are reflected in price scenarios, leading to more stable prices for nuclear fuel with respect to coal and more volatile price for gas with respect to coal.

Table 4: GAS (45 €/MWh)

ratio	0.90	0.98	1.00	1.20	1.60	2.20	2.60	3.00
prob	0.005	0.030	0.500	0.300	0.116	0.030	0.014	0.005

Table 5: NUCLEAR FUEL (5.5 €/MWh)

ratio	0.80	0.90	1.00	1.40	1.80	2.00	2.50	3.00
prob	0.020	0.090	0.752	0.120	0.010	0.005	0.002	0.001

We suppose that the price $\pi_i^{CO_2}$ for CO_2 emissions increases of a certain percentage per year which is related to CO_2 allowances, see Figure 2. For green certificates, π_i^{GC} currently represents the green certificate price; it is already foreseen that this incentive will be substituted by feed-in tariff (or feed-in premium) for renewable sold energy in the Italian market (Decree 3 March 2011).

As far as annual market share for energy production, $\overline{M}_i$ of the GENCO, see Figure 1.

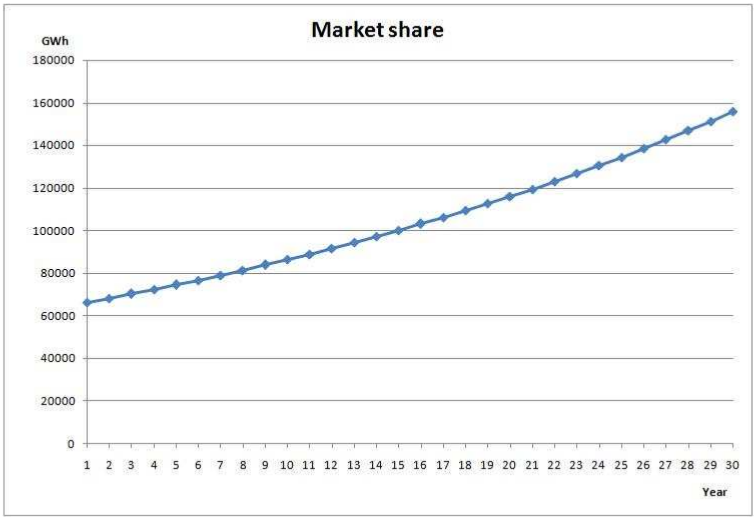

Figure 1: Scenario for market share.

4 Computational results

We consider two stochastic models using 512 different scenarios; both models maximize a linear combination of function given by (9) with the risk measure given by (10), suitably weighted by the risk-aversion parameter λ, subject to

1. constraints (1) to (7) plus constraints (11)
2. constraints (1) to (8) plus constraints (11).

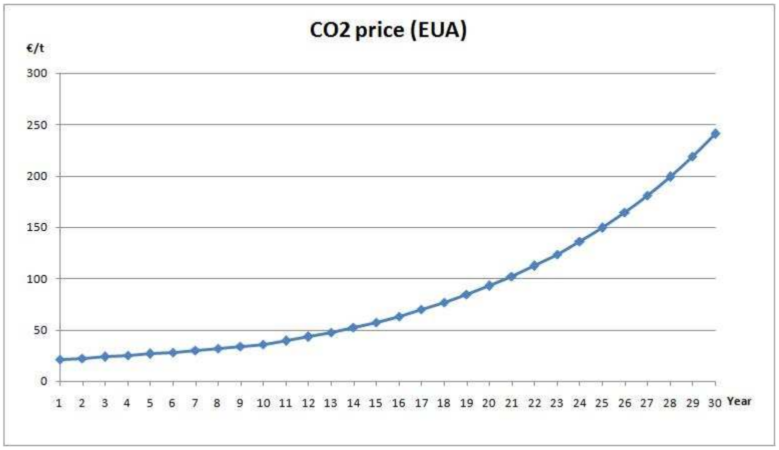

Figure 2: Scenario for CO_2 price (EUA)

4.1 Case 1. (without market share constraint)

To make a comparison among the two models, we have produced Table 6, where we report the different risk-aversion coefficients, the expected profit and the value of CVaR for medium-large GENCO. The installed electric power for this GENCO is about 9 GW and the current annual energy production is 67,000 GWh. We suppose no constraints on the possibility to increase electric power.

Table 6: Results of stochastic model - Case 1

risk-aversion	Profit	$CVaR$	VaR	Risk premium
0.01	$1.08 \cdot 10^8$	$-1.62 \cdot 10^8$	$1.53 \cdot 10^7$	6.63
0.13	$8.92 \cdot 10^7$	$4.16 \cdot 10^6$	$2.51 \cdot 10^7$	15.92
1.35	$7.37 \cdot 10^7$	$4.90 \cdot 10^7$	$5.53 \cdot 10^7$	28.72

For different risk-aversion coefficients, it appears the role of CVaR: more risk-aversion corresponds to larger CVaR, larger VaR (it means that our threshold is increasing) and larger risk premium. See Figures 3, 4, 5 of profit distributions for different risk-aversion values.

Figures 6, 7, 8 illustrate the optimal technologies mix for different values of risk-aversion parameter. For risk-aversion equal to 0.01 we get CCGT plants for 98.71%, the rest is in renewable due to their small budget requirement. For risk-aversion equal to 0.13 we have 25% in CCGT plants, 71.66% in coal and the rest in renewable due to their small budget requirement. The choice of coal is motivated by the fact that this technology is less influenced by the price of fuels. For risk-aversion equal to 1.35 we have 50.06% in nuclear plants, 41.93% in coal and the 8.01% rest in renewable.

Total annual energy production given by the optimal decision variables are shown in Figures 9, 10, 11.

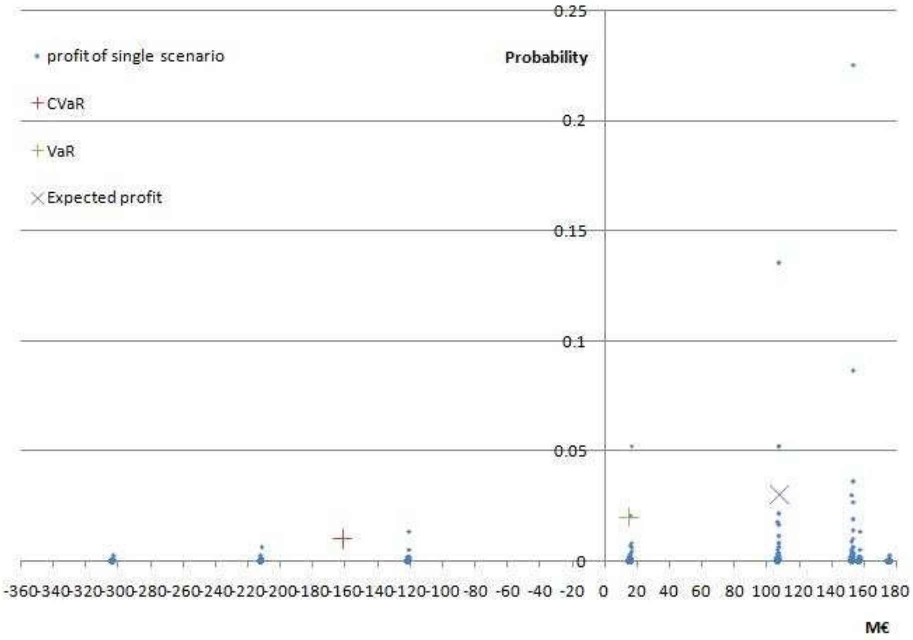

Figure 3: Case 1, risk-aversion parameter = 0.01: profit distribution.

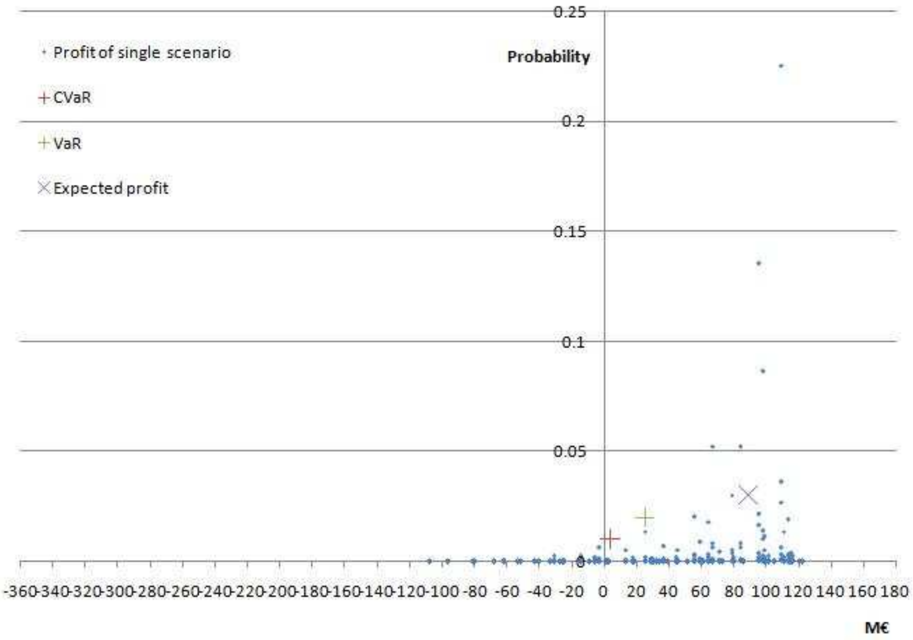

Figure 4: Case 1, risk-aversion parameter = 0.13: profit distribution.

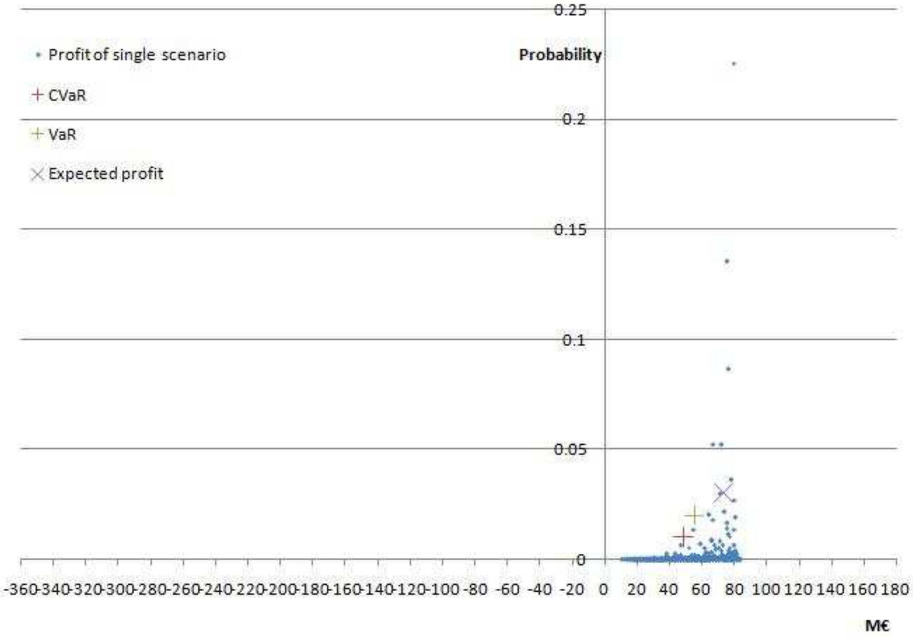

Figure 5: Case 1, risk-aversion parameter = 1.35: profit distribution.

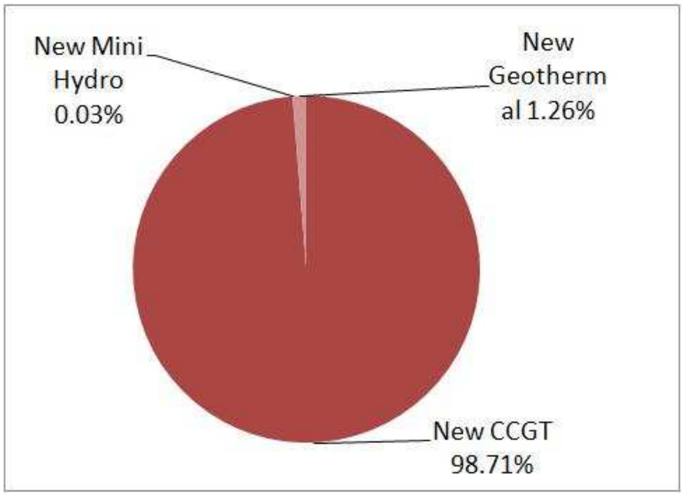

Figure 6: Case 1, risk-aversion parameter = 0.01: optimal new technolgies mix.

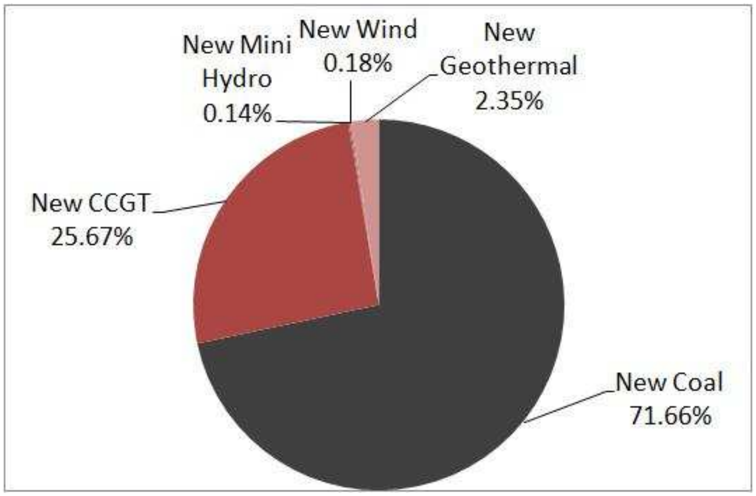

Figure 7: Case 1, risk-aversion parameter = 0.13: optimal new technolgies mix.

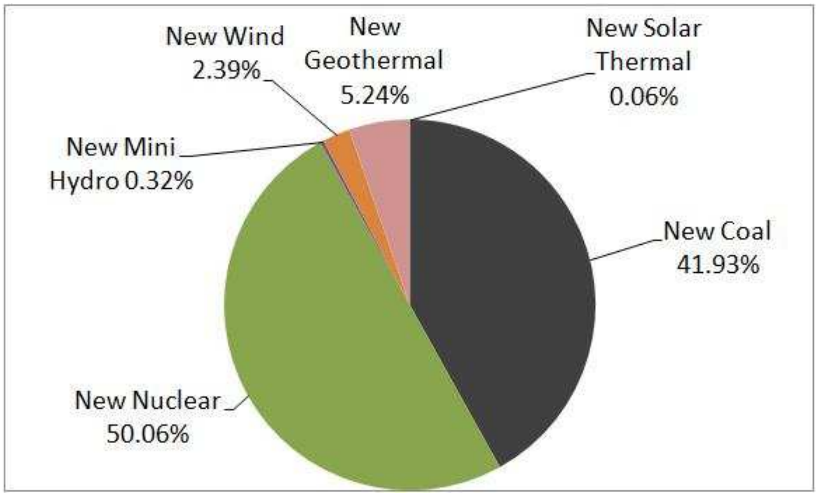

Figure 8: Case 1, risk-aversion parameter = 1.35: optimal new technolgies mix.

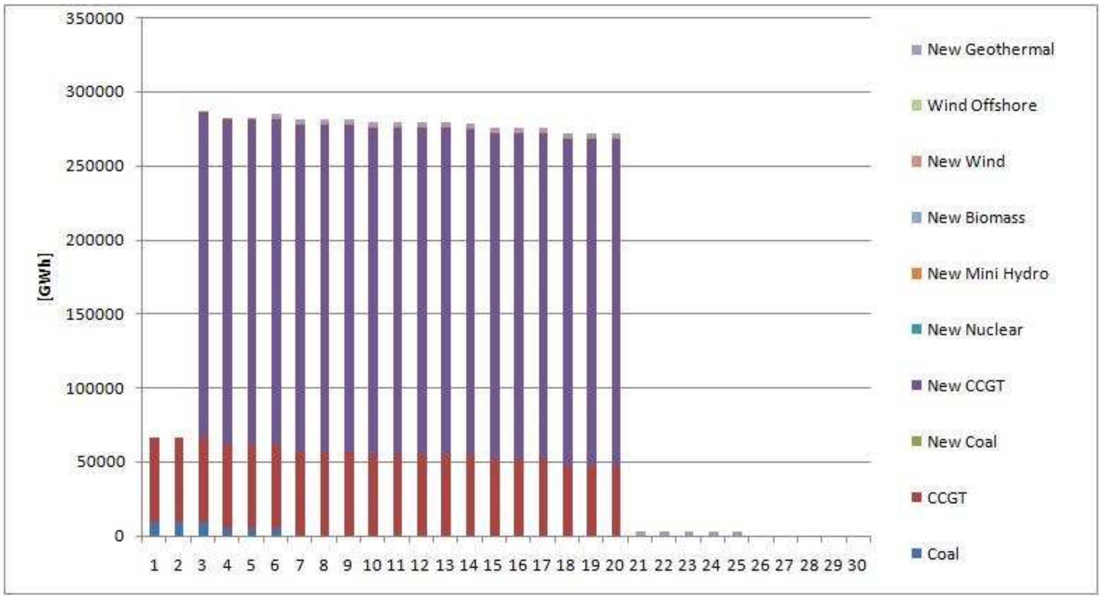

Figure 9: Case 1, risk-aversion parameter = 0.01: optimal new technolgies mix.

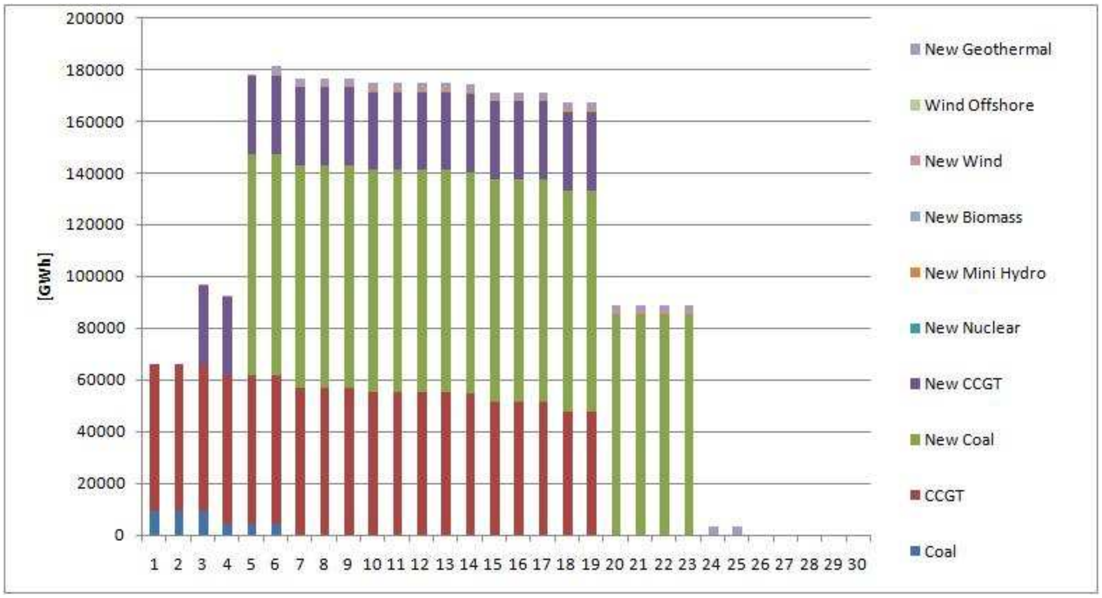

Figure 10: Case 1, risk-aversion parameter = 0.01: optimal new technolgies mix.

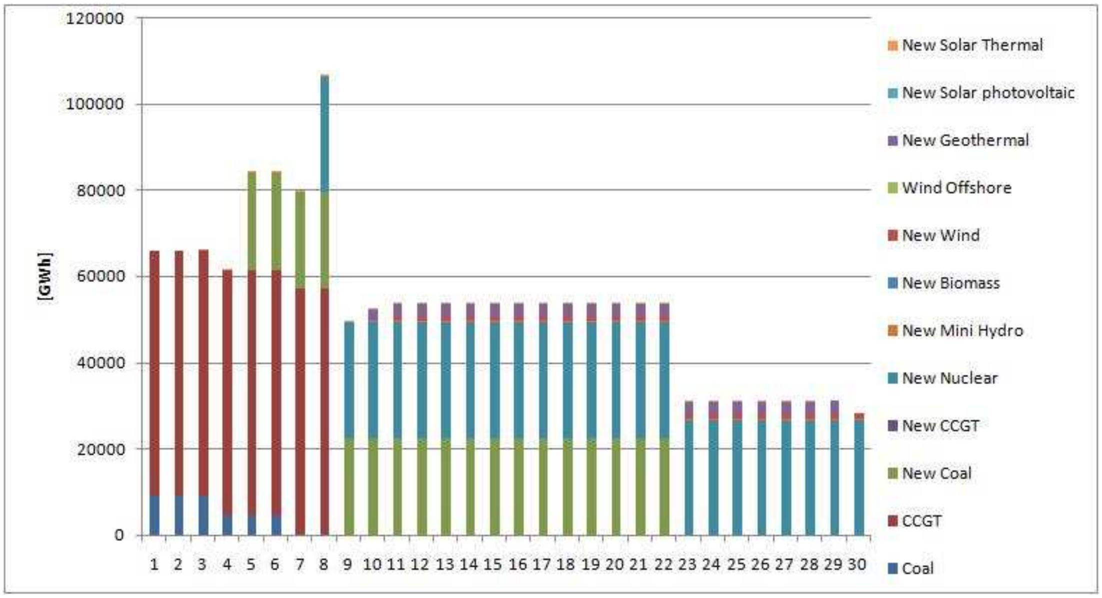

Figure 11: Case 1, risk-aversion parameter = 0.01: optimal new technolgies mix.

4.2 Case 2. (with market share constraint)

To make a comparison among the two models, we have produced Table 7, where we report the different risk-aversion coefficients, the expected profit and the value of CVaR for medium-large GENCO. We suppose that this production may increase by a 3% per year, see Figure 1. We also suppose this evolution is fixed for each of our generated scenarios.

Table 7: Results of stochastic model - Case 2

risk-aversion	Profit	$CVaR$	VaR	Risk premium
0.01	$8.63 \cdot 10^7$	$1.71 \cdot 10^7$	$6.13 \cdot 10^7$	20.98
0.13	$8.51 \cdot 10^7$	$3.21 \cdot 10^7$	$5.94 \cdot 10^7$	23.72
1.35	$7.38 \cdot 10^7$	$5.02 \cdot 10^7$	$5.69 \cdot 10^7$	30.47

For different risk-aversion coefficients, the behavior is similar to Case 1., i.e more risk-aversion corresponds to larger CVaR, larger VaR (it means that our threshold is increasing) and larger risk premium, see Table 7.

Figures 12, 13, 14 show the profit distributions for different risk-aversion values.

Figures 15, 16, 17 illustrate the optimal technologymix for different values of risk-aversion parameter. For risk-aversion equal to 0.01 we have CCGT plants for 31.66%, nuclear plants for 23.13%, wind powr plants for 23.78%, biomass plants for 13.78%, geothermal plants for 7.26%. For risk-aversion equal to 0.13 we have 34.81% in coal, 23.08% in nuclear, 20.42% in wind, 14.05% in biomass and the rest 7.24% in geothermal. For risk-aversion equal to 1.35

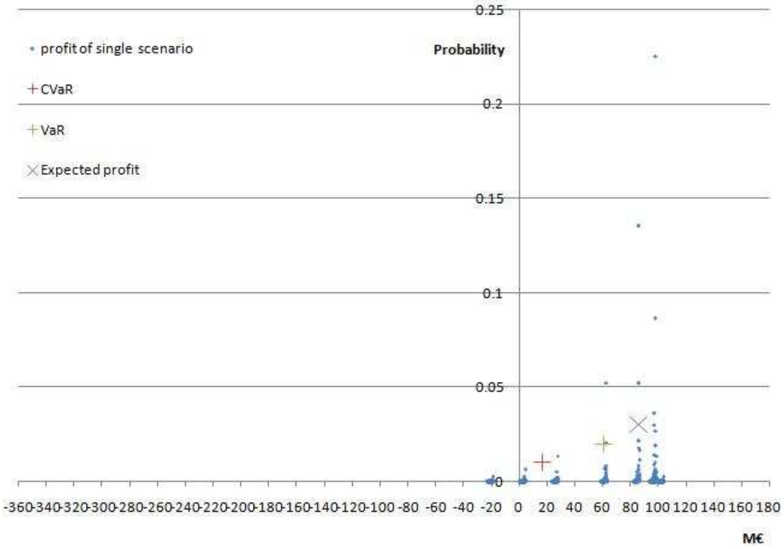

Figure 12: Case 2, risk-aversion parameter = 0.01: profit distribution.

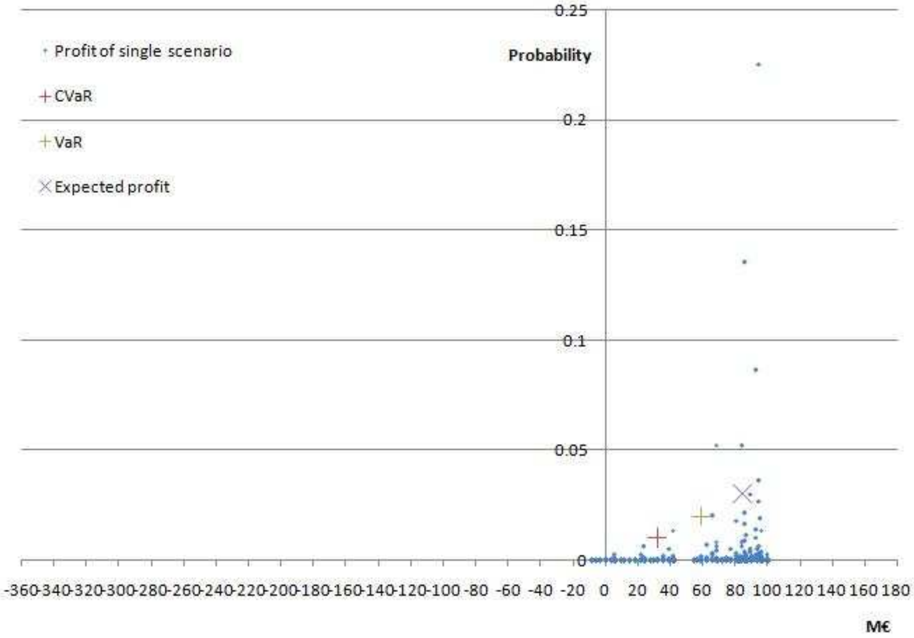

Figure 13: Case 2, risk-aversion parameter = 0.13: profit distribution.

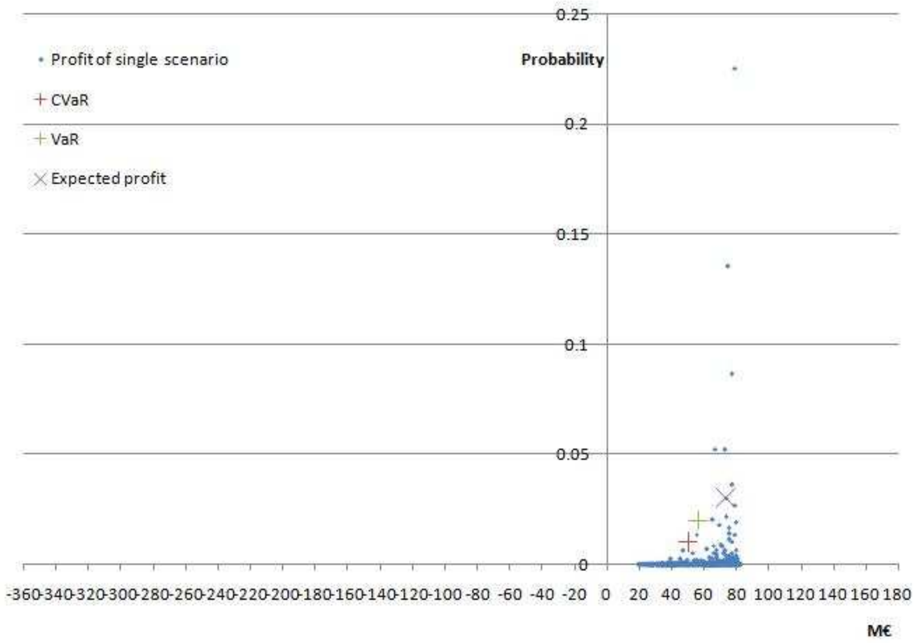

Figure 14: Case 2, risk-aversion parameter = 1.35: profit distribution.

we have 54.68% in nuclear plants, 27.49% in coal and the 11.33% in biomass and 5.72% in geothermal.

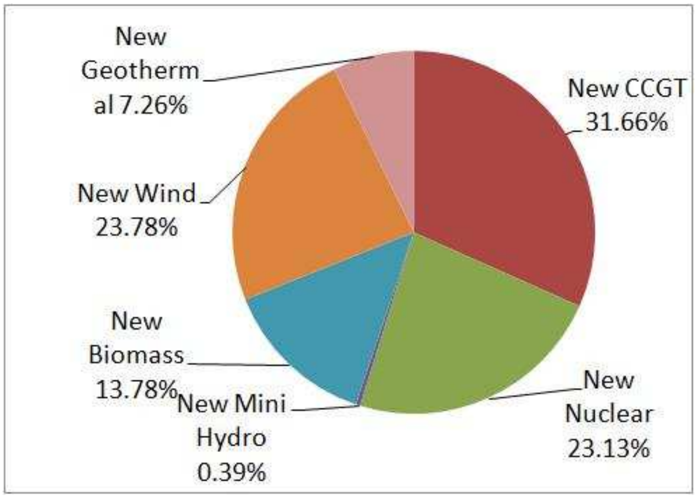

Figure 15: Case 2, risk-aversion parameter = 0.01: optimal new technolgies mix.

Total annual energy production given by the optimal decision variables are shown in Figures 18, 19, 20.

Comparing Tables 6 and 7 corresponding respectively to results with and without constraint (8), we observe that, for the same risk-aversion, we get a CVaR larger in Case 2 with

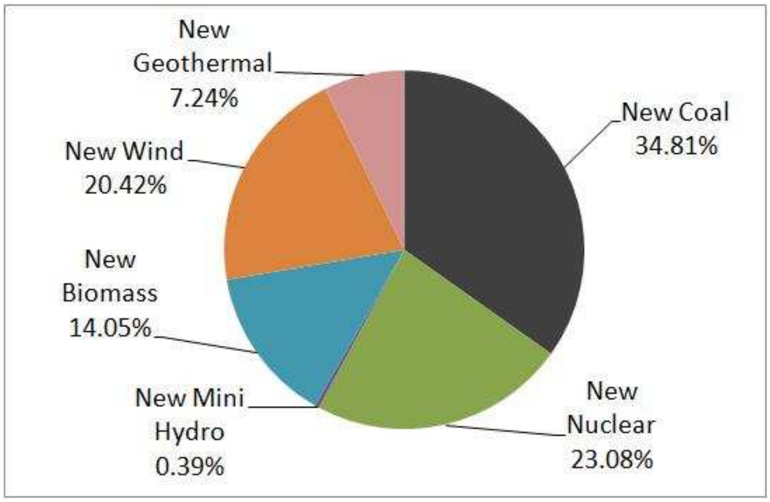

Figure 16: Case 2, risk-aversion parameter = 0.13: optimal new technolgies mix.

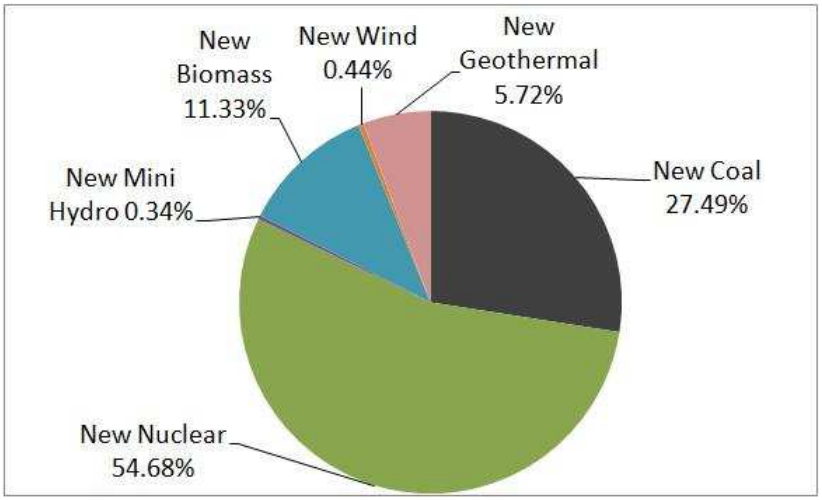

Figure 17: Case 2, risk-aversion parameter = 1.35: optimal new technolgies mix.

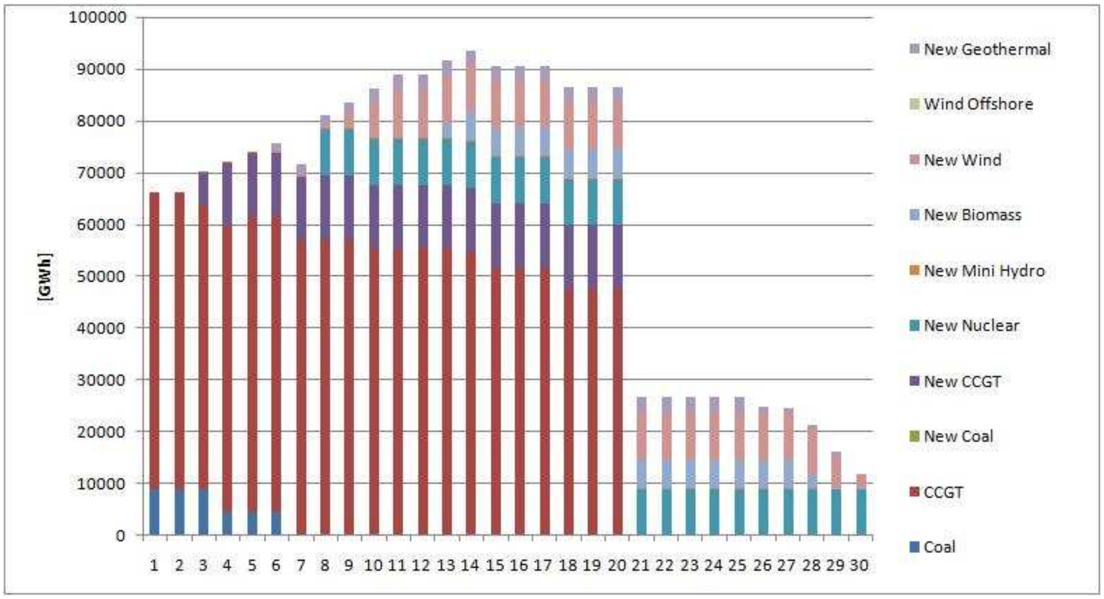

Figure 18: Case 2, risk-aversion parameter = 0.01: optimal new technolgies mix.

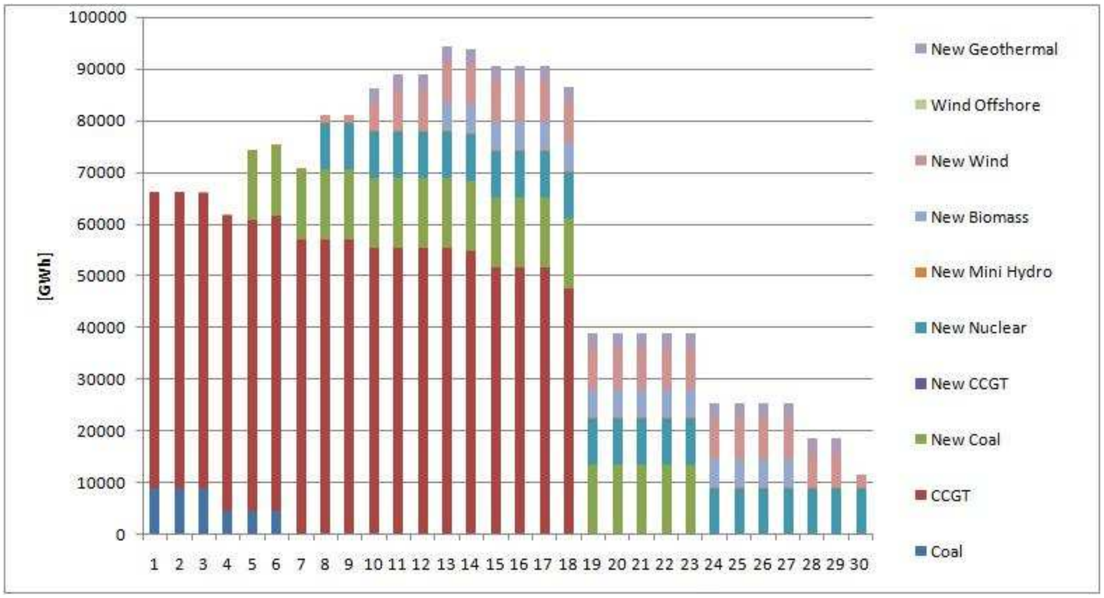

Figure 19: Case 2, risk-aversion parameter = 0.13: optimal new technolgies mix.

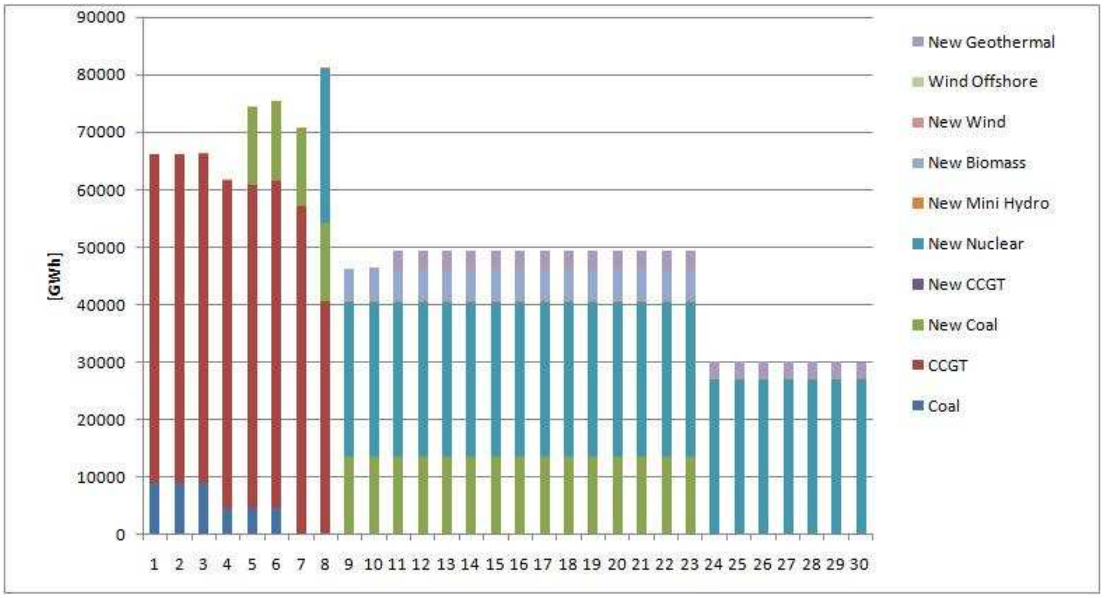

Figure 20: Case 2, risk-aversion parameter = 1.35: optimal new technolgies mix.

respect to Case 1. This means that we are moving towards choices of investment that are more diversified.

5 Conclusion

We adopt a simple scenarios generation combining in all possible ways the 8 scenarios for coal, gas and nuclear fuel for a total of $8^3 = 512$ scenarios. The results from the stochastic multiperiod model show that, taking into account risk, the total expected profit decreases. There is a substantial difference of behavior between the total energy production when we consider or not the limitation on the market quota. The case with market quota is more reqalistic. Moreover, once the new plants come in operation, there is a period of stable energy production that declines towards the end of the planning period. This may be due to the so-called end of effect, related to the fact that you may have new plants that still have some residual life beyond the end of the planning horizon.

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