On the production of hydrogen via alkaline electrolysis during off-peak periods

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Key words

Hydrogen production, alkaline electrolysis, spot markets, off-peak periods

(Production d'hydrogène, électrolyse alcaline, marché spot, heures creuses)

Abstract

This article studies the opportunity for producing hydrogen via alkaline electrolysis from consumption of electricity during off-peak periods. Two aspects are dealt with: electricity spot markets and nuclear electricity production against the French backdrop.
From market points of view, when there is a significant fluctuation in electricity prices, using an electrolysis installation during off-peak periods enables rather considerable savings in production costs. Savings vary enormously from one market to the next; some highly fluctuating markets offer very low off-peak prices and enable viable hydrogen production, even if, at first sight, average electricity prices are high. For other more stable markets, the use of an electrolysis installation during off-peak periods does not appear to be a relevant proposition.
From the point of view of French electricity production, the availability of current nuclear power plants and the estimation of available energy for mass production of hydrogen show that the installations studied would not be viable. For a "peak period" use, it would certainly be of greater interest to have electrolysers with a lower investment proportion, even if this means slightly higher operating costs. Research into large-capacity electrolysers should, therefore, both develop low production cost electrolysers, for use in base load mode where dedicated production means are concerned, and highly flexible electrolysers, with low investment costs, which could easily be viable with low rates of use.

Introduction

Hydrogen is shaping up more and more as one of tomorrow's main energy vectors. Although today the most viable production technology is steam natural gas reforming, in this communication we shall be studying alkaline electrolysis whose cost depends on that of electricity and not that of natural gas which has increased significantly over the past months. So as to reduce the production cost of hydrogen via alkaline electrolysis, in the first part we envisage purchasing electricity at low cost on liberalized spot markets by taking advantage of off-peak period rates. In the second part, we study the quantity of energy available during off-peak periods in France, focusing on nuclear plants.

1 Cost of hydrogen production in a liberalized market

1.1 Electrolysers used

The problem with mass producing hydrogen via alkaline electrolysis has already been dealt with by Miller [1] and Ewans [2]. Since the aim of this study is to envisage the emergence of a hydrogen market, we consider large-scale electrolysers such as NorskHydro (Table 1, and see Sigurvinsson [3], Ivy [4]), both to meet demand and guarantee the lowest production costs. In addition, so as to highlight possible economies of scale, four installations of different sizes are studied, with 8, 32, 64 or 96 electrolysers (Table 2).

1.2 Spot markets studied

We compare four structurally different spot markets (Rothwell [5]):

- **Powernext** in France [6]: independent stock exchange proposing a day-ahead spot market (requests taken into account from one day to the next);

- **Nord Pool** in Scandinavian countries [8]: first multinational market and Europe's leading one proposing, among other things, a day-ahead Elspot market;
- **AESO** (Alberta Electric System Operator) in Canada [7]: only a real-time market exchange;
- **PJM** (Pennsylvania, New Jersey, Maryland) in the US [9]: day-ahead and real time markets; just the day-ahead is studied here.

For each market, the evolution in the average electricity price between 2001 and 2005 is represented Figure 1.

1.3 Cost of hydrogen production with optimization of electricity consumption

1.3.1 Presentation of calculations with an example: the Powernext market in 2005

For a specific year and a given market, the Levelized Total Cost of hydrogen production (LTC) is calculated according to the size of the installation and the discount rate, by only purchasing on the spot market electricity whose price is below a fixed threshold. The levelized total cost of production takes into account investment, operation and purchase of electricity, presupposing a duration for the construction of the installation of one year and a life span of 30 years (Sigurvinsson [1]). It is calculated on the basis of the following equation (1):

$$LTC = \frac{C_i + \sum_{n=1}^{30} \frac{1}{(1+t)^n}(C_0 + C_{elec})}{\sum_{n=1}^{30} \frac{1}{(1+t)^n} \mathrm{Pr}od} \quad (1)$$

Where:
LTC = Levelized Total Cost of hydrogen production.
Ci = investment cost.
Co = annual operating cost.
Celec = total annual cost of purchased electricity
Prod = annual production of hydrogen
t = discount rate

This supposes the following hypotheses:

- The power required to operate the installation is available, without market prices being modified.
- Electrolysers may be stopped and restarted instantaneously without extra cost or transient effect.
- Only the purchase price of electricity on the market is taken into account (access to the network, to the organized market, or any other taxes are not taken into consideration).

Figure 2 shows the levelized total cost of hydrogen as a function of the maximum fixed purchase price of electricity, as well as the corresponding annual production of hydrogen. The figures are taken from the French Powernext market in 2005, for the installation with 96 electrolysers (installation D), with a 6% discount rate.

This figure shows that there is an optimum hydrogen production cost of €2.56/kgH_2, for an approximate electricity purchase price of €48/MWhr. This use corresponds to a 64.3% time use, particularly at night and during the week-end. If we choose a lower threshold, we do not purchase sufficient electricity, hydrogen production is too low, investment, which is a fixed expense, is not sufficiently amortized and hydrogen production cost is high. With a higher threshold, the electricity purchased is too expensive and production less viable.

It is therefore preferable not to use the installation all the time, in which case there is a reduction of about 15% in the hydrogen production cost in comparison with an almost continuous use (95% time use).

It is possible to calculate the LTC for the different installations illustrated, and for different discount rates (Figure 3 and 4). Although the largest installation is the most viable, smaller ones should be studied if there is a gradual take-off of the hydrogen market. It is also very important to study several discount rates, depending on whether investments are private or State-backed.

The maximum purchase price is very slightly different depending on the size of the installation or the discount rate chosen. Economies of scale (going from installation A to installation D) are limited, since increasing the size means installing more electrolysers, in which case savings just come from other equipments, representing only a lesser share of the cost.

1.3.2 Comparison of the different markets and different years

It is possible to carry out the same calculations for the four spot markets studied, with figures for the years 2001 to 2005. For the analysis of results, installation D, with a 6% discount rate, is taken as a benchmark.
For each market, the evolution of the hydrogen production cost and that of the average price of electricity are similar (Figures 4 and 5). The nature of the curves is, however, remarkable: the average AESO price is higher than Nord Pool's, and yet its hydrogen production cost from 2002 to 2005 is lower.
The AESO Canadian market, the only one to have been studied by Miller [1], would be most advantaged by optimum market use (Figure 6): in 2005, use of electrolysers in off-peak periods and not in practically continuous mode (95% of the time) would bring about a reduction of almost 25% in production costs. The French and North-American markets would also take advantage of this optimization to a lesser extent and depending on the years. With regards to the Scandinavian market, only years 2002 and 2003 could have taken advantage of an optimization; as for the other years, optimum percentage of use is higher than 95% which is the maximum we set ourselves. It is consequently more viable to use the installation to a maximum.

We note that, even if the average market price fluctuates a lot over the years (Figure 4), optimum use is more or less steady (Figure 7).

1.3.3 Impact of the characteristics of the different markets on optimum installation use

In order to help understand the differences in the results observed between the different markets, the evolution of prices on these markets is illustrated (Figure 8) for one week in winter and one week in summer.

Variations in the price of electricity on the Nord Pool market are very low, around €5/MWhr or less, between the daytime and night time peaks, whereas variations on the North-American and French markets are around €50 to €70/MWhr between daytime and night time peaks during the week. Variations in prices are also very significant on the Canadian market, but are much less predictable.

The Nord Pool market is very stable and has a low price average. This is certainly due to the large volume of hydroelectricity, which is a very adaptable and viable source. Particularly in Norway, hydraulic energy makes it possible to supply basic and peak electricity at low cost if hydrological conditions are favourable. Consequently, price variations on this market are significant from one season to another, depending on hydrological conditions, but very low on a day or week scale, and there is not much advantage in using off-peak periods.

As for other markets, even if the average annual price is higher, off-peak prices are very low and it is worthwhile taking advantage of them. Thus, fluctuation in spot markets is very important for obtaining a low production cost, and this makes it possible to take advantage of very low prices during off-peak periods, even if the market has a fairly high average price.

1.3.4 Duration of the periods of use

The different market fluctuations are reflected in the characteristics of the periods when installations are used (Table 3).
Thus, for Nord Pool, time use is 98.8%. Here, it is more a case of stopping the installation for the few high-price peaks rather than taking advantage of off-peak. On the other hand, for AESO, the periods of a few hours (less than 48) represent the majority of use. PJM uses off-peak hours during the daytime and at week-ends, together with a small amount of price reductions over the week. For Powernext, use is both over periods of a few hours during daytime off-peak and periods of one to two weeks.

1.3.5 Correlation between electricity demand and market price

The study of correlations between market price and demand for electricity over a territory (calculated with Excel), for different markets and different years (Figure 9) shows that the correlation between price and demand for electricity is very strong for the three day-ahead markets on a daytime scale, and even a week and sometimes a month scale, but for AESO's real-time market, the correlation is very low.

The low annual correlation reflects a strong variation in demand for electricity between summer and winter, which is not necessarily found in spot prices, and in variations in hydrological conditions, particularly for the Scandinavian market.

Demand for electricity over a territory may be accurately forecast over a few days. Differences between forecasts and actual demand are due to climatic uncertainties.
If spot prices are sufficiently correlated to demand for electricity over one or several days, an electrolysis installation operator can forecast approximately what the use of his installation will be, thus facilitating operation.

Fluctuation in spot prices is therefore conducive to obtaining low hydrogen production costs, but when such volatility is difficult to predict, it makes the operation of an electrolysis installation more complicated and risky.

2 Means for producing electricity with a view to implementing electrolysis in France

In the previous section, we estimated the cost of producing hydrogen via electrolysis on the assumption that the energy we needed was available on the market. This hypothesis is now examined against the French backdrop, looking at the means of production and domestic consumption for 2004.

In the case of mass production of hydrogen via alkaline electrolysis, the nuclear plants would have to be operated in base load mode, consuming the energy produced but not consumed by the country's energy demand for purposes of electrolysis. Thus, the load follow would no longer be carried out by modulating power produced by the plants but by modulating power consumed by the electrolysers.

France has 58 PWRs (Pressurized Water Reactors), producing a total output of 63,130 MW. For 2004, net nuclear electricity production was 426,800 GWhr (Elecnuc [10]) and according to EDF, available energy was 19.2 TWhr. The distribution of this energy depends on plant production modulations. In order to estimate the number of electrolyser installations, it is necessary to know the power available at any given moment, i.e. know how this distribution is carried out. To estimate it, we construct a hypothetical load curve of French nuclear plants for base load operation, with shutdowns for refuelling and maintenance work planned in such a way that total nuclear electricity output follows mean domestic consumption and does not exceed 63,130 MW (Figure 10). Total nuclear-produced electricity is in this case 446,000 GWhr (426,800 + 19,200) and corresponds to the space below the load curve.

In accordance with this simulation, electrolysis installations may benefit from energy for approximately 34% of the time, with maximum power of 16,643 MW. This energy may be absorbed by the operation of 75 installations of 223.5 MW (type-D installation with 96 electrolysers each).

Figure 11 illustrates the total production and total levelized cost of hydrogen (with the previous hypotheses: 1 year of construction for the electrolyser, 30 years life span, 6% discount rate), as a function of the number of installations built, with available energy being distributed fairly between installations.

Three prices of electricity are considered:

- €30/MWhr: top-end estimation of the total cost of producing electricity for a PWR,
- €0/MWhr: bottom-end cost marker,
- Powernext prices corresponding to each half-hour of use.

The cost goes from 1.5-3.1 €/kg when there is only one installation, to 5.9-7.5 €/kg when the available energy is distributed across the 75 installations. In fact, the more electrolysis installations there are, the smaller the divisions of available power when this is insufficient to supply all electrolysers to a maximum. In other words, whereas the time use percentage per installation remains the same when their number is increased, the rate of use in energy is reduced and the levelized total cost of production increases.

Operating nuclear plants in base load mode makes it possible to recover energy for approximately one third of the time, which is fairly low to obtain a competitive hydrogen production cost. But above all, the rate of energy use drops significantly when the number of installations is increased, and, where almost all available energy is consumed for electrolysis, the cost of hydrogen production is very high, at over €5/kg.

By just using current electricity production means, it seems difficult to make off-peak mass production of hydrogen a viable proposition against the French backdrop, since this would require significant power consumption, but over a very short space of time. Operating nuclear plants in load base mode might, however, be beneficial.

Conclusion

Two aspects of the cost of hydrogen production via electrolysis during off-peak periods have been illustrated here corresponding to different scales: electricity spot markets and French nuclear production.
From market points of view, when there is significant fluctuation in the prices of electricity (according to very expensive peak production means and spot market characteristics), optimizing the use of an electrolysis installation enables not inconsiderable savings in production costs to be made. By optimizing production periods, the savings made vary enormously from one market to the next. Some highly fluctuating markets offer very low prices during off-peak periods and enable viable hydrogen production, even if, at first sight, average electricity prices are high. For other more stable markets, this optimization offers much less interest. These differences stem from the modes of electricity production, their production cost and adaptability, as well as market structures. But calculations carried out are only relevant on a small-scale, since they suppose that neither production nor prices are modified by purchasing electricity for the purposes of electrolysis.

From the point of view of electricity production, the availability of current French nuclear plants and the estimation made of available energy for mass production of hydrogen show that the installations studied would not be viable. This is due to the fact that the electrolysis installations studied have relatively high investment costs. When the percentage of use is between 30 and 50%, this cost represents a highly significant share of the total production cost. For a off-peak period use as is envisaged here, it would certainly be more advantageous to have electrolysers whose investment proportion was lower, even if this meant having slightly higher operating costs. Research into large-capacity electrolysers should, therefore, be focused on both electrolysers with high efficiency and correspondingly low production costs for use in base load mode where dedicated production means are concerned, and highly flexible electrolysers, with low investment costs, which could easily be viable with low rates of time use.

If the scenario of a gradual development of the hydrogen market proves to be accurate, consumption of off-peak electricity, where prices are sufficiently low, will be of interest in those countries which

offer a highly fluctuating electricity spot market. There, such installations could be implemented very quickly.

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Figures:

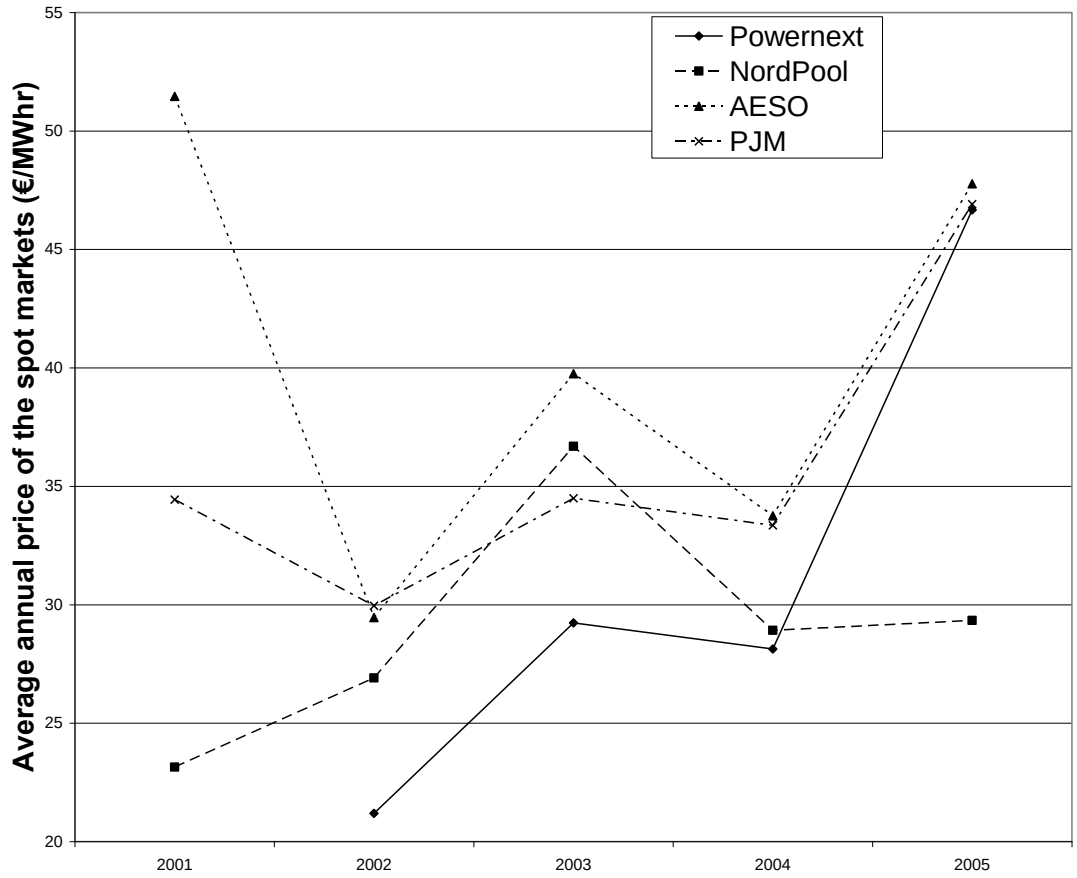

Figure 1. Average annual price for electricity of the different spot markets from 2001 to 2005

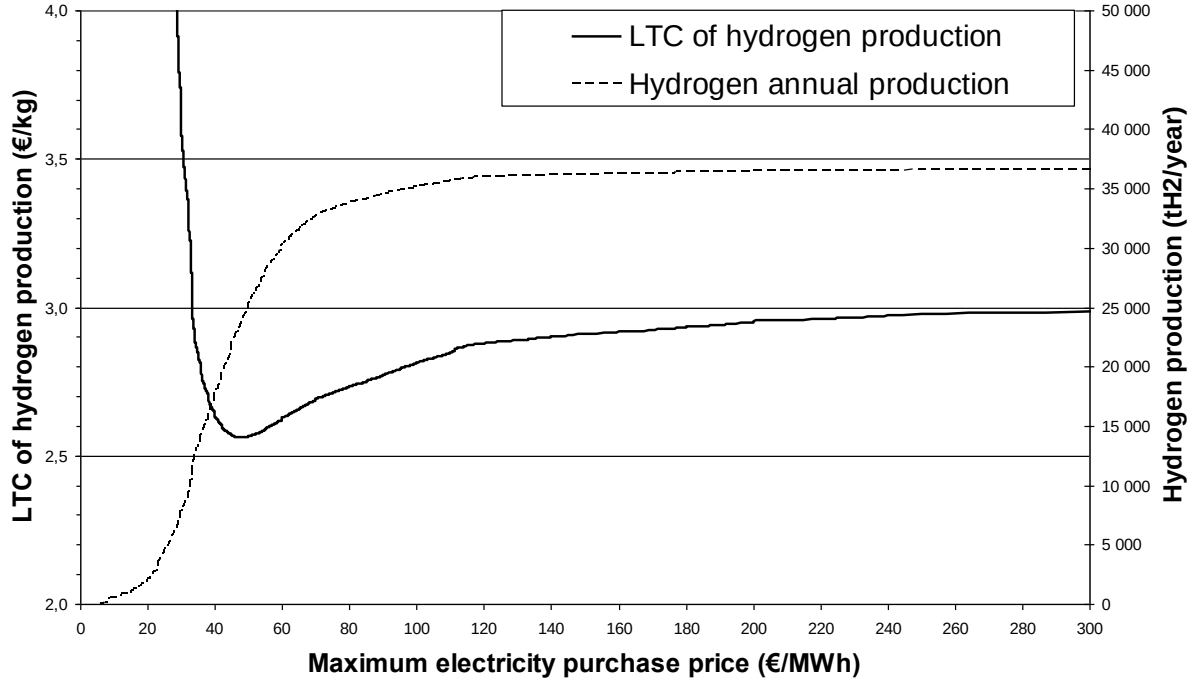

Figure 2. LTC of kgs of hydrogen and annual production for Powernext Day-ahead 2005 (Installation D, 6% discount rate)

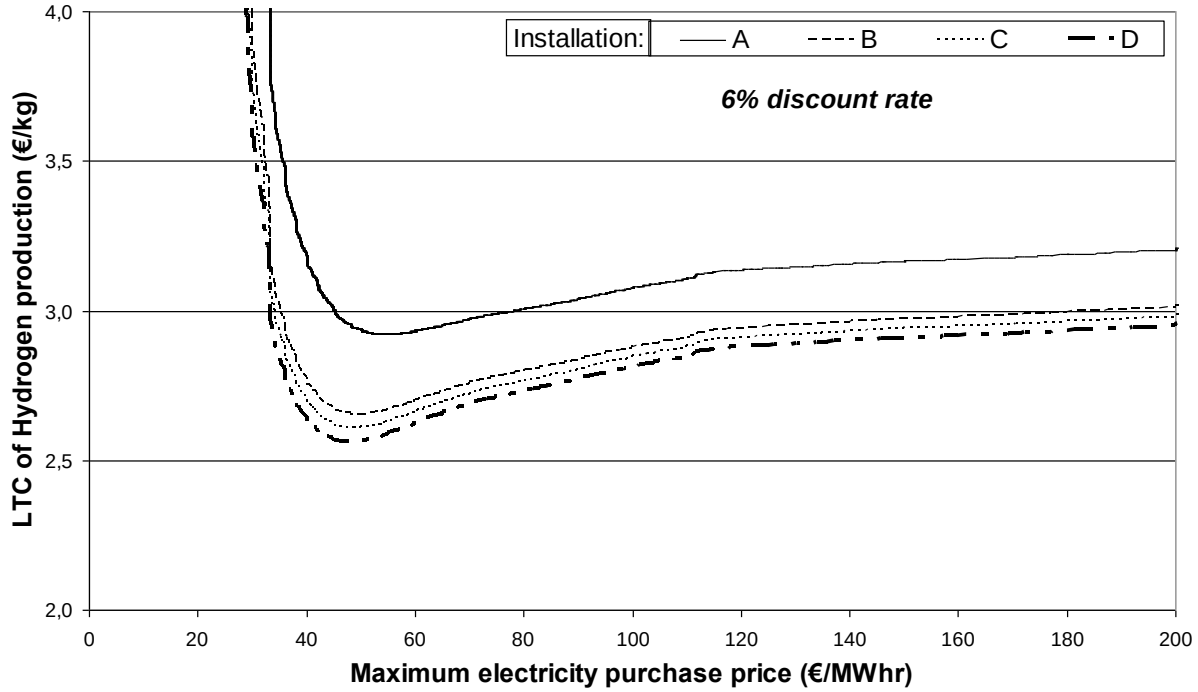

Figure 3. LTC as a function of the maximum electricity purchase price for the different installations

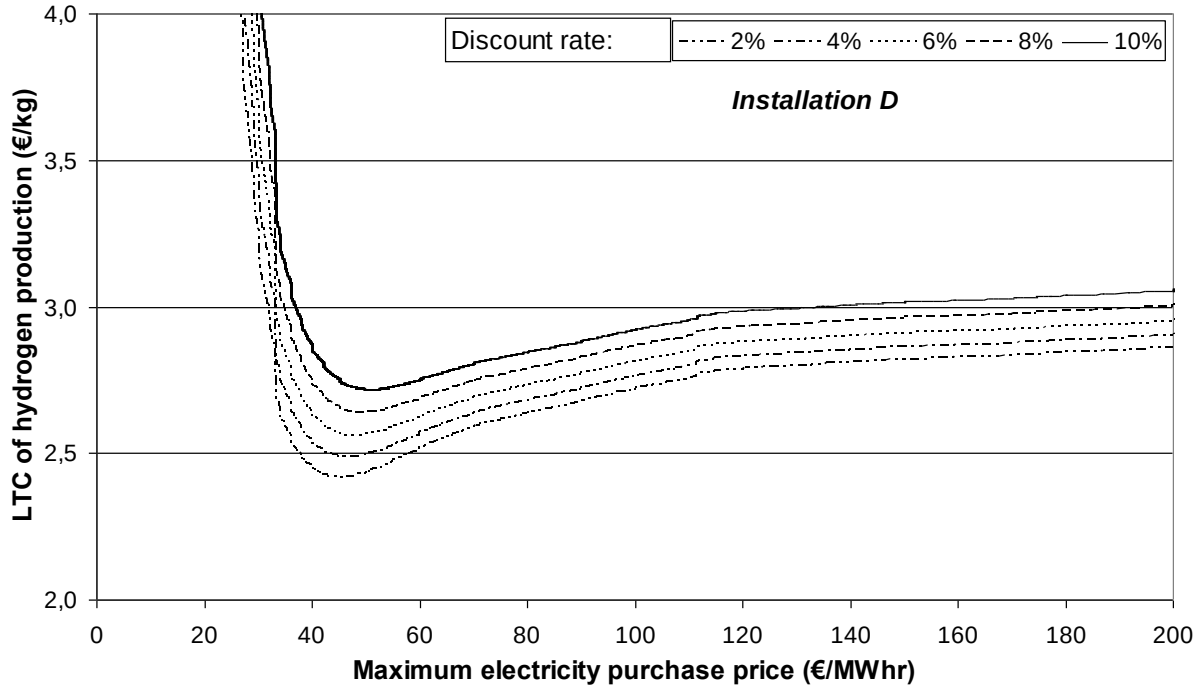

Figure 4. LTC as a function of the maximum electricity purchase price for the different discount rates

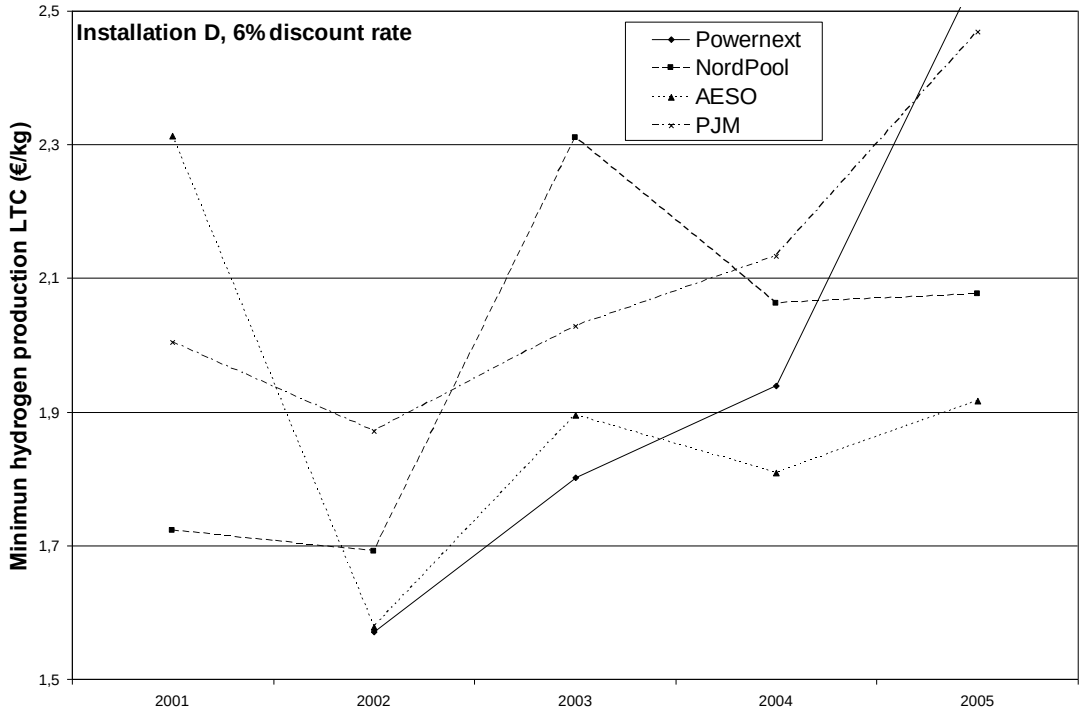

Figure 5. Minimum hydrogen production LTC in accordance with markets from 2001 to 2005

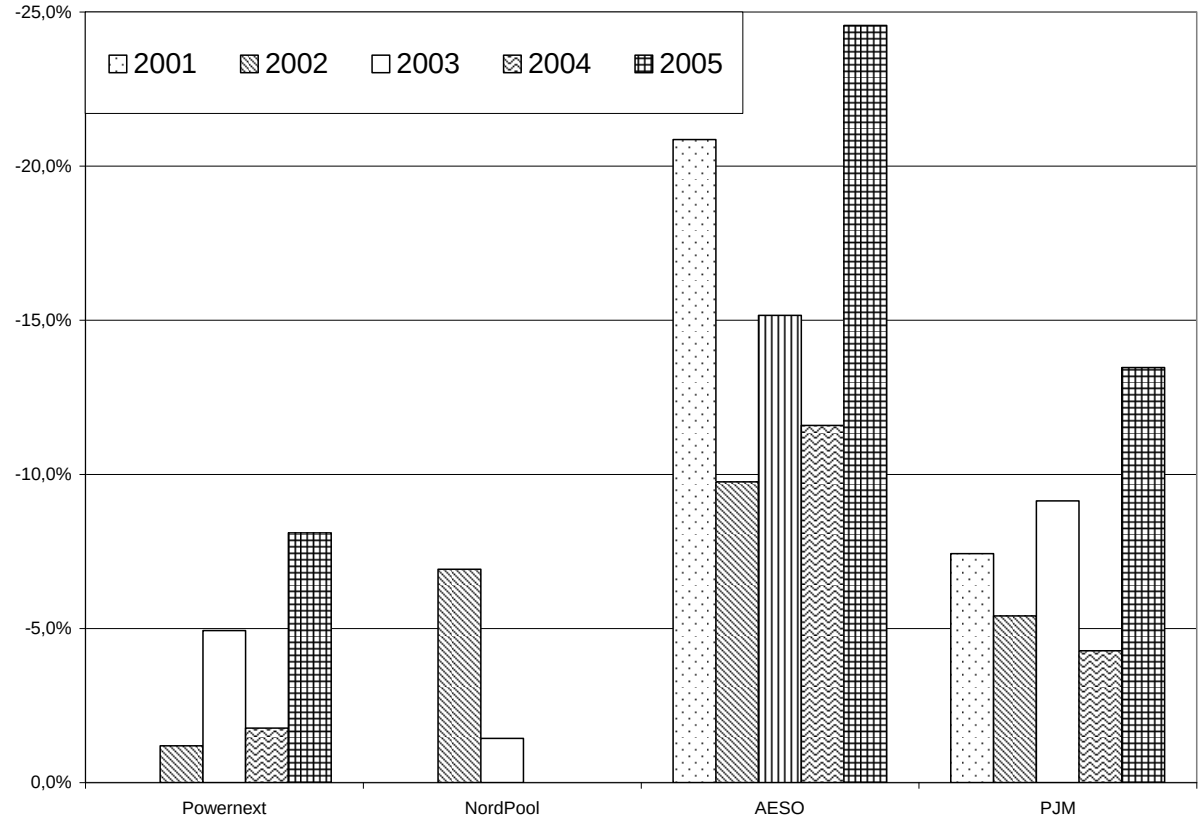

Figure 6. Reduction of LTC in relation to almost continuous use in accordance with markets from 2001 to 2005

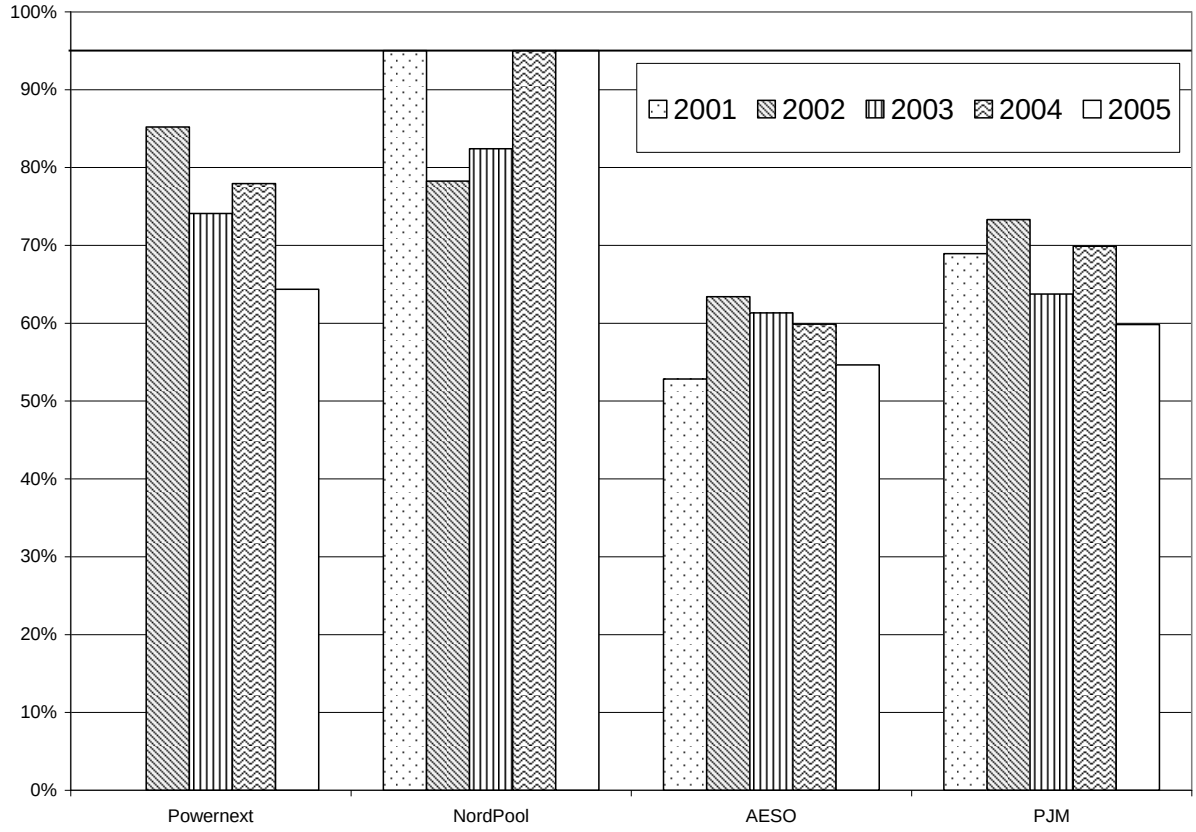

Figure 7. Optimum rates of time use in accordance with markets from 2001 to 2005

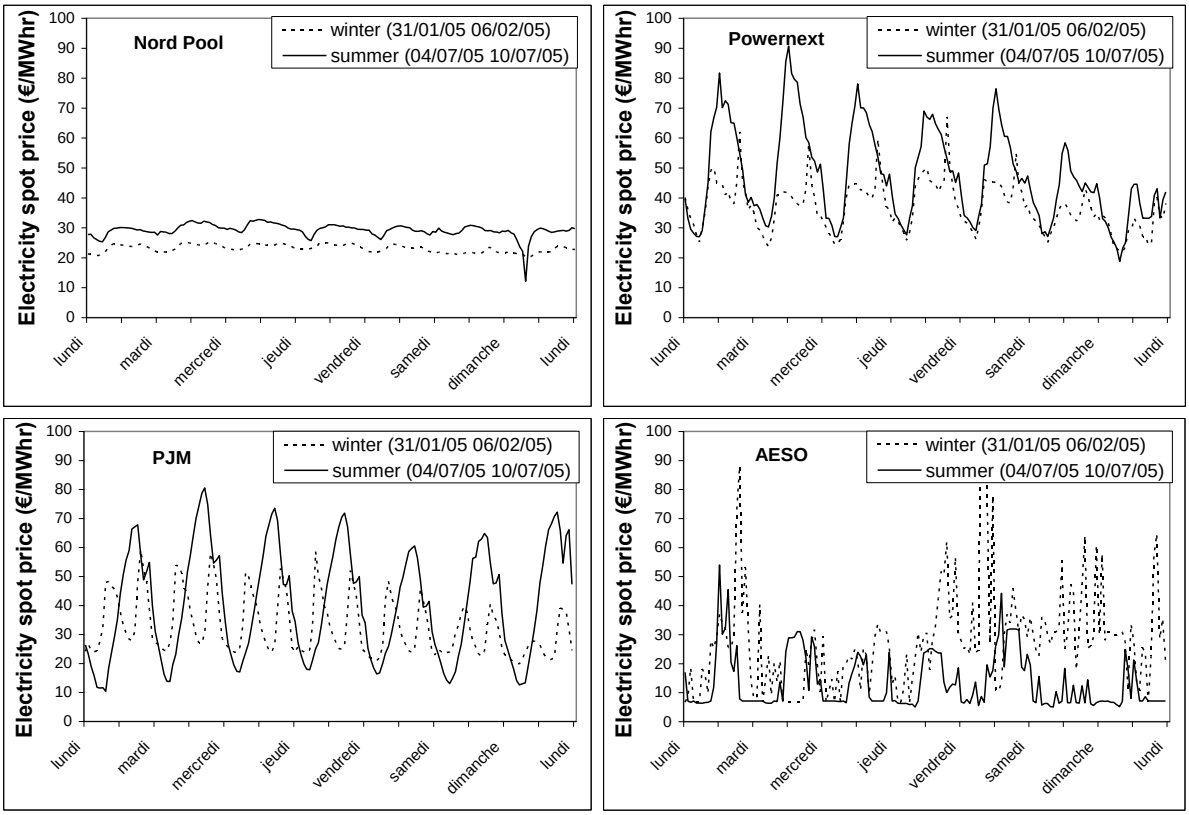

Figure 8. Spot prices in €/MWhr for the weeks from 31/01/05 to 06/02/05 and from 04/07/05 to 10/07/05, for the different markets

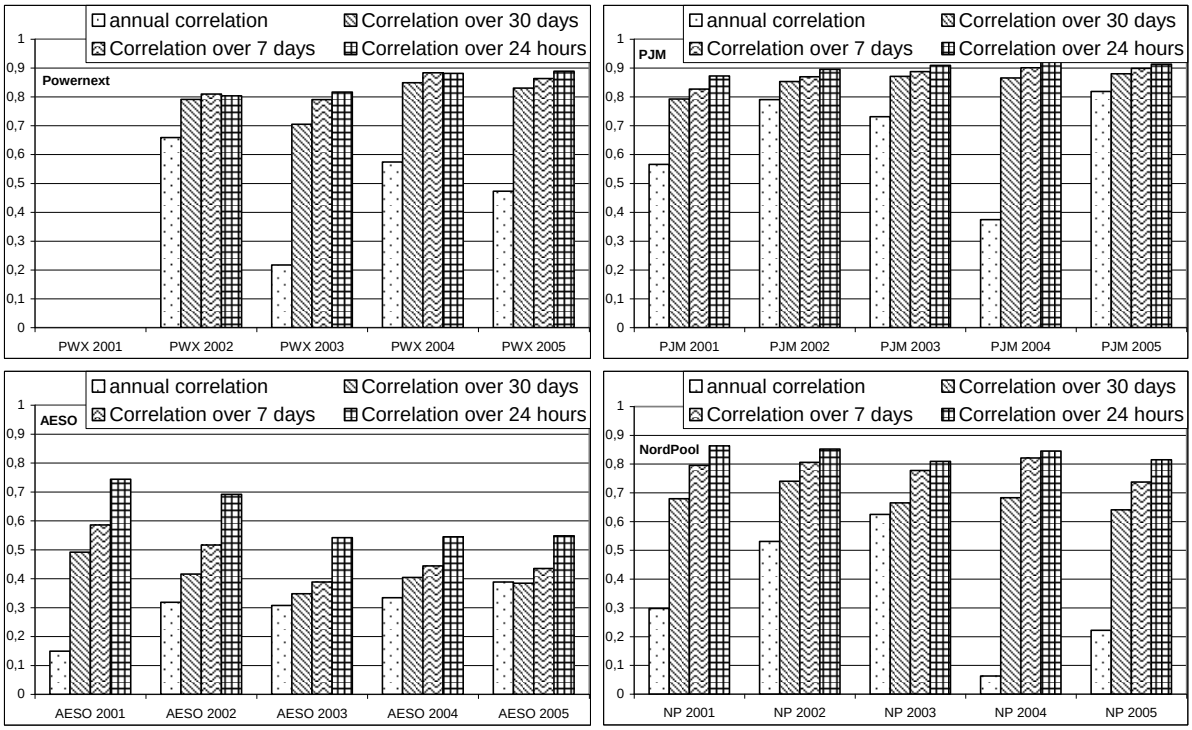

Figure 9. Comparison of correlations between spot prices and demand for electricity for the different markets

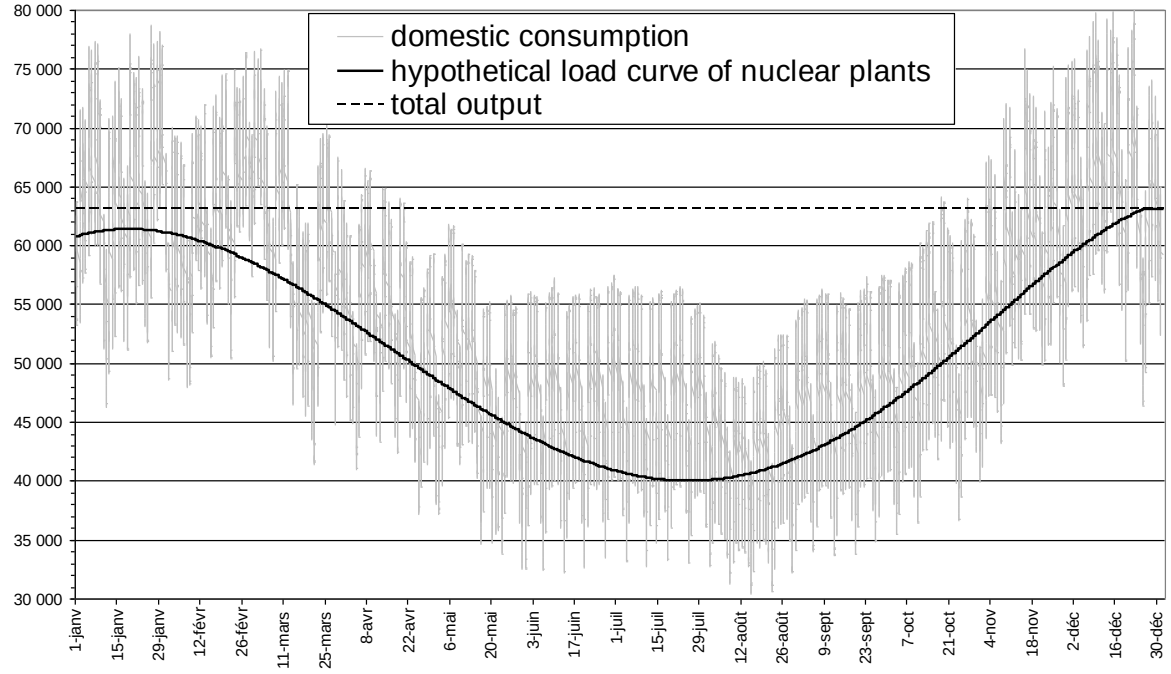

Figure 10. Nuclear plant load curve in base load mode

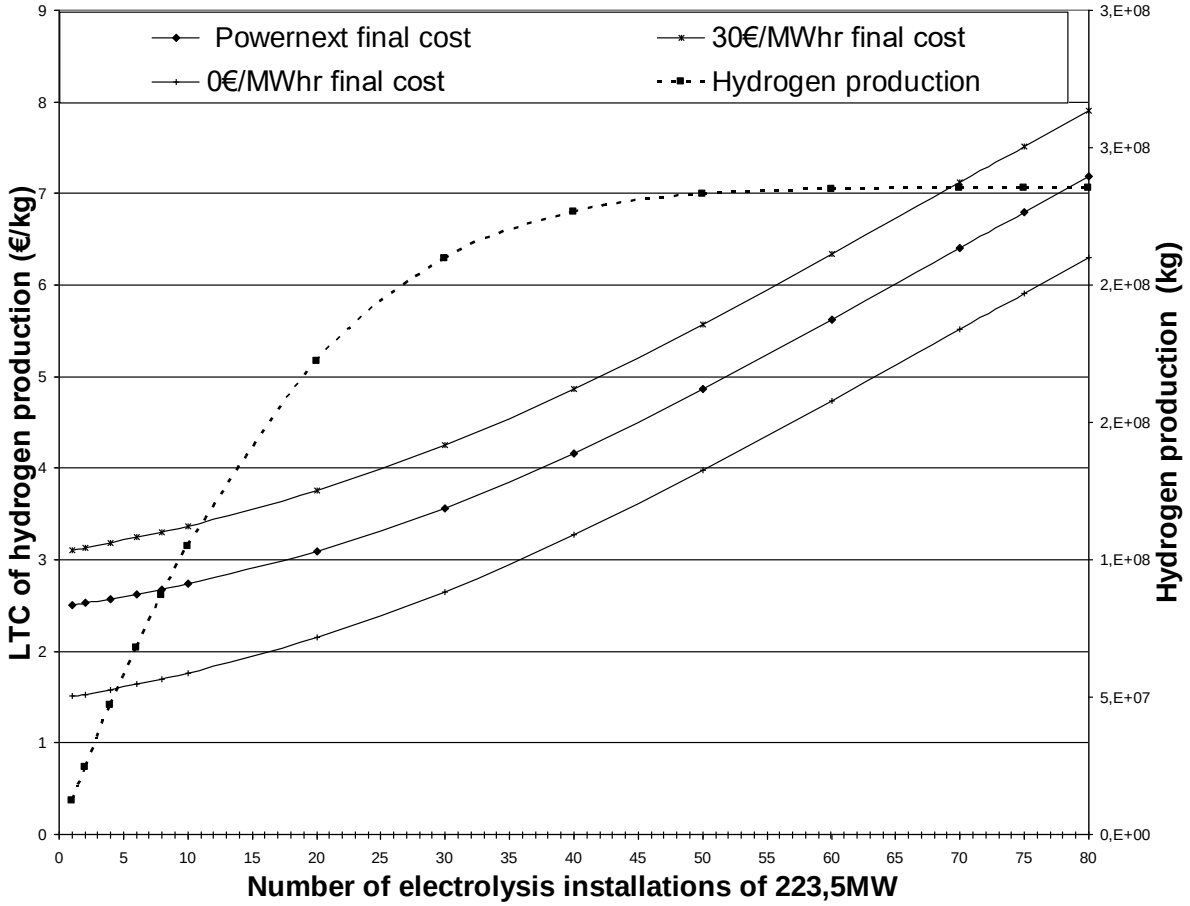

Figure 11. Production cost and hydrogen production depending on the number of electrolysis installations of 223.5MW

Tables:

Maximum current:	5150 Amp DC
Hydrogen production:	300 - 485 Nm^3H_2/hr
Electricity consumption:	4.30 ± 0.1 kWhr/Nm^3H_2
Operation:	20% - 100%

Table 1. Technical specifications of the No. 5040 Atmospheric electrolyser (manufacturer NorskHydro)

Installations:	A	B	C	D
Technical data:				
Number of electrolysers	8	32	64	96
Total electricity consumption [GWhr/y]	153	611	1222	1833
Total power for production [MW]	18,6	74,5	149	223,5
Maximum capacity [tH_2/year]	2860	11441	22882	34323
Maximum operation [hrs/year]	8200	8200	8200	8200
Economic data:				
Total investment cost [M€]	11.714	42.366	83.555	116.297
Variable operating cost [M€/year]	0.788	3.151	6.302	9.317
Fixed operating cost [M€/year]	0.678	0.702	0.735	0.762
Total operating cost [M€/year]	1.466	3.853	7.037	10.079

Table 2. Technical and economic data concerning installations

	Powernext	**PJM**	**AESO**	**Nord Pool**
Number of periods	369	421	720	42
Minimum duration	1 hr	1 hr	1 hr	3 hrs
Maximum duration	396 hrs	215 hrs	94 hrs	3837 hrs
Share of durations <=8hrs	16%	22%	33%	0.5%
Share of durations <=48hrs	62%	74%	89%	6%

Table 3. Characteristics of periods of use of the different markets in 2005