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ECONOMIC PROSPECTS FOR THE APPLICATION OF NEW ELECTRIC ENERGY STORAGE DEVICES

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Summary

The technical and economic properties of new storage devices for electric energy such as batteries, hydrogen storage systems, flywheels, steam storage plants and compressed air storage facilities are compared with conventional peak power plants such as gas turbines and hydroelectric storage systems. The analysis shows that batteries, steam storage plants and compressed air storage facilities may be economically competitive with conventional peak power devices. Batteries are especially appropriate for dispersed energy storage systems.

Utilization of storage devices instead of gas turbines results in substitution of oil or natural gas by coal or nuclear fuel.

Introduction

Load levelling and peak shaving will become more and more important because of the increasing contribution of nuclear base load plants to total electric energy production. Several new storage devices such as batteries, flywheels and hydrogen storage systems are under discussion and/or investigation for this purpose. This paper presents and discusses the results of a study [1] comparing technical and estimated economic properties of these new storage systems with those of conventional peak power plants.

Most of the properties of conventional peak power plants are satisfactory today. In the future, however, the disadvantages of conventional systems will create restrictions for their application. Gas turbines have to be fueled with highly refined oil or with natural gas, the resources of which are getting short. For hydroelectric storage facilities the availability of acceptable sites and the long construction time will create serious problems. The new systems will hopefully not have these disadvantages. The following properties are of importance: utilization of abundant primary fuel, availability of construction materials, high efficiency, short construction time, siting flexibility, high safety and low pollution, good economy.

The decisive criterion for the economy is the price per unit of electric energy to be paid by the consumer. This price includes production costs and distribution costs. The distribution costs are different for central and dispersed storage systems. Since some storage devices are suitable for central, and others for dispersed storage, the costs of the electric network have to be estimated for each case. The economic comparison between different peak power plants has therefore been performed by taking into account the depreciation costs of the electrical network tailored for each storage system within a model area.

Properties of the systems

The technical and economic properties of the following systems are considered: electrochemical storage devices (batteries and hydrogen storage devices); flywheels; steam storage/turbine facilities; compressed air storage plants; gas turbines and pumped hydro for comparison. It is probable that all these systems can be fully developed before 1990. Other systems, which will be under investigation for a longer period of time, such as superconducting magnets and thermochemical cycles for hydrogen production, are not considered within this study.

Batteries

A battery storage system consists of the battery, a transformer, an a.c./ d.c. converter and power conditioning devices. Figure 1 shows the connection diagram of a battery storage system.

The technical properties and the costs of the supplementary electric equipment to operate a battery are well known. The properties of conven-

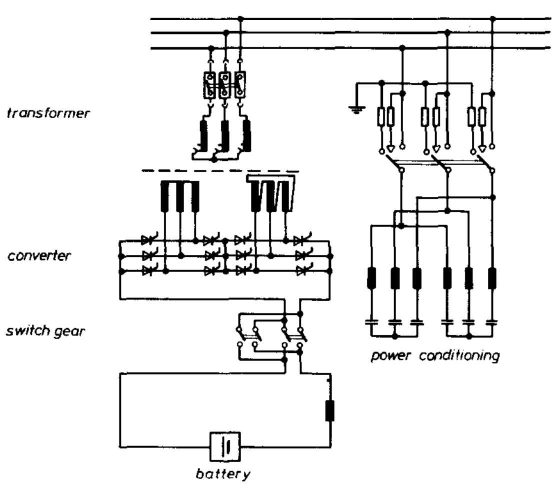


Fig. 1. Connection diagram of a battery storage system.

tional lead–acid and nickel/cadmium batteries are also known, but the lifetime of these batteries is too low and the costs are too high. The main effort with respect to storage batteries is directed towards the improvement of lifetime and reduction of costs.

Several types of batteries which possibly will be appropriate for load levelling applications, are under investigation. Table 1 lists some properties of such batteries. It shows that the cycle life is low or not known in some cases. In other cases a long life has been attained only with laboratory cells for partial charge/discharge conditions. In all cases a high cycle life has still to be demonstrated for practical batteries. It is expected that the cycle life of new batteries will exceed that of today's batteries. It is assumed, that fully developed batteries will achieve a life of at least 10 years corresponding to 3000 - 4000 cycles (Table 5).

Charge–discharge efficiencies η are not included in Table 1. All types of batteries allow η values of 0.6 - 0.8 or higher, depending on current density.

The investment costs are estimated for mass production. They are split up into a power and an energy related portion* [1]. In most cases the investment costs of Table 1 are at the upper limit of estimations of other recent publications [20 - 23].

Electrochemical hydrogen storage

Figure 2 shows a schematic diagram of a water electrolysis/hydrogen storage system. The system consists of several subsystems, some of them having properties which are relatively well known. The water electrolyzer, however, is a subsystem the properties of which are dependent on the results of current investigations. The principal goal of these investigations is to develop electrolyzers which can produce hydrogen more cheaply than conventional electrolyzers. This may be achieved by increasing the ratio of current density to investment costs and by increasing the efficiency. Different systems are under investigation. The expected properties of these systems are shown in Table 2.

Hydrogen is stored most economically in a spherical or cylindrical steel vessel, the price of which including auxiliary equipment amounts to 15 - 70 DM/kWh$_{el}$ at pressures of 30 - 70 bar. The energy refers to the electric energy attained from a hydrogen fueled generator with an efficiency of 30 - 40%. Metal hydride storage systems cost 100 - 150 DM/kWh$_{el}$ [39]. They are therefore not considered for this application. Liquid hydrogen storage must be ruled out because of the low efficiency caused by the liquefaction and vaporization process [33 - 35].

Generation of electric energy from hydrogen can be performed with fuel cells or gas turbines. Fuel cells are reversed electrolysis cells. Some types

*The investment costs of the other peak power generation plants are split up also (Table 1). In the case of hydroelectric power plants, for instance, the water reservoir represents the energy related portion and the turbines the power related portion of the plant. The partition of the investment costs enables the calculation of power generation costs (eqn. (1)) of peak power plants assembled for different discharge times.

TABLE 1

Data for battery systems[a]

Type	Pb/PbO_2 (advanced)[b]		Na/S		LiAl/FeS_x		Redox systems (Cr^{6+}/Cr^{3+} or Ti^{3+}/Fe^{2+})	
Operating temperature	20 - 40 °C		300 - 350 °C		400 - 450 °C		20 - 50 °C	
Literature references	[2 - 5]		[6 - 11]		[12]		[13, 14]	
Investment costs (estimated)[c]	DM/kW	DM/kWh	DM/kW	DM/kWh	DM/kW	DM/kWh	DM/kW	DM/kWh
battery	140 - 190	160 - 230	105 - 190	90	⩾Na/S (battery, assembly, converter)		215 - 550	30
assembly	–	20 - 25	–	30 - 55			–	20 - 25
converter, transformer cos ϕ-compensation	85 - 110	–	85 - 110	–			85 - 110	–
buildings	–	15 - 25	–	15 - 25			–	25 - 40
	225 - 300	195 - 280	190 - 300	135 - 170			300 - 655	75 - 95
Charge–discharge cycles attained in laboratory	~1500		10,000[d]		700		–	
Availability of reactants (years)[e]	Pb 26[f]		Na: 6000 S: > 10,000		Li: 400[g] Al: 160 Fe: 400			Cr: 550

[a]Expectation for other batteries (*e.g.* Zn/Cl_2 [15] or Na/$SbCl_3$ [16]) are similar to those of this Table. Investment costs are split up into energy related and power related costs.

[b]SLI batteries: 100 - 500 cycles. Stationary batteries: >1000 cycles, ⩾500 DM/kWh [23].

[c]1977 costs for mass production, in some cases due to our own estimates.

[d]At partial recharge.

[e]Resources divided by present annual consumption [17 - 19].

[f]Lead can be recovered and recycled.

[g]More than 95% of resources in U.S.A. and Canada.

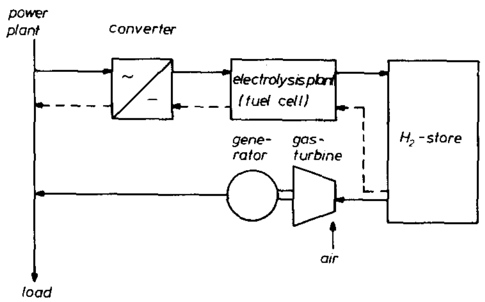


Fig. 2. Schematic of H_2O electrolysis/H_2-storage plant. ———, Electric energy is produced by gas turbine; -----, electric energy is generated by fuel cells. Fuel cells operate alternately as generator and as electrolysis plant.

TABLE 2

Data for hydrogen storage systems

Characterization of electrolyzer	Atmospheric pressure (conventional)	High pressure (30 bar)	Solid electrolyte	
Hydrogen generation:				
Type of electrolyte	aqueous KOH	aqueous KOH	solid polymer electrolyte (Nafion)	zirconia
Operating temperature	70 - 90 °C	100 - 150 °C	80 - 150 °C	800 - 1000 °C
References	[18, 24, 25]	[18, 26 - 28]	[18, 29]	[18, 30 - 32]
Price[a], DM/kW_{input}	530 - 600[b]	360[c]	240 - 290[c]	260 - 320[c]
Lifetime achieved (years)	30 - 40	10	4	1
Efficiency	0.7[b]	0.8 - 0.85[c]	0.8 - 0.85[c]	0.9[c]
Availability of materials (years)[d]	Ni: 120	Ni: 120	Pt: 130	Zr,Y,La:>50 Ni: 120

Electric energy generation:

Characterization of generator	Low temp. fuel cell (electrolyte KOH or acid)	Solid electrolyte fuel cell (electrolyte Nafion or zirconia)	Gas turbine
References	[18, 37, 38]	[29, 30, 32]	[39, 40]
Price DM/kW	700 - 1200[c]	700 - 1100[c]	390 - 420[b]
Efficiency	0.45 - 0.6[c]	0.45 - 0.6[c]	0.25 - 0.35[c]
Lifetime achieved (years)	2 - 4	4	20

[a]1977 prices including auxiliary equipment.
[b]Achieved.
[c]Expected for mass production.
[d]Resources divided by present annual consumption [36].

of cells such as solid polymer or zirconia electrolyte cells can be utilized as electrolysis cells and fuel cells alternately. This is shown by the broken line in Fig. 2. The investment costs may be reduced in this way. The properties of hydrogen fueled generators are included in Table 2.

Flywheels

A rotating flywheel stores energy as kinetic energy. Charging is effected by an electric motor which works as generator during the discharging process. It produces alternating current with a decreasing frequency. A constant frequency is achieved by a.c./d.c. conversion and by subsequent generation of 50 cps alternating current. Two converters are needed therefore. Further more auxiliary devices such as power conditioning equipment and buildings have to be installed. Table 3 presents some data for a flywheel storage plant.

The material of the flywheel is assumed to be steel. Other materials such as fibre strengthened materials are more expensive [41, 42].

Steam storage

Steam storage/turbine facilities have already been used for approximately 50 years [43]. They consist of steel vessels containing steam, a steam turbine and a generator. The steam reservoir is provided with steam by a base load plant during times of low energy demand. During peak power demand the stored steam is used to power a separate turbine. Proposals for a system with three turbines which are operated at different pressures and which are connected alternately with steam reservoirs of appropriate pressure have been published by Gilli and Beckmann [43, 44]. It is claimed that energy related investment costs of 70 - 100 DM/kWh* and power related investment costs of 215 - 285 DM/kW can be obtained. New pressure vessels have to be developed in order to achieve these costs. The efficiency of steam storage plants is about 70%.

TABLE 3

Economic data for a 1 MWh/1 MW flywheel storage plant [1, 46]

Specific prices	DM/kW	DM/kWh
Flywheel (material steel, 40 t, 4.5 m ϕ, 3600 rev/min)	–	500 - 800
Motor/generator	150	–
2 Converters, power conditioning and aux. electric devices	170 - 220	–
Buildings	50	–
Total	370 - 420	500 - 800

*Corrected to 1977 costs, recent estimation led to 70 - 110 DM/kWh and 440 - 500 DM/kW [47].

Compressed air storage

A gas turbine power plant with an air reservoir has been built recently and will be put into operation within some months [45]. A schematic of a compressed air storage plant is shown in Fig. 3. The air reservoir may be a salt cavern made by water dissolution, a natural cavern or a confined aquifer. During periods of low power demand it is filled with compressed air. For peaking the energy of stored air and fuel is converted into electricity using a gas turbine. Table 4 lists some properties of this kind of peak power station.

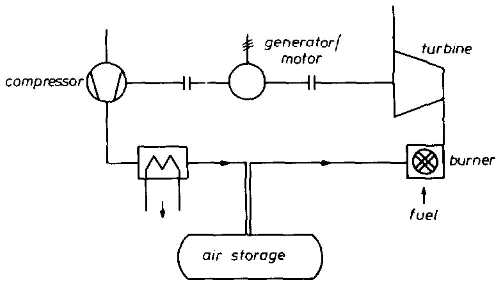


Fig. 3. Compressed air storage–gas turbine power plant.

TABLE 4

Data for a typical compressed air power plant [1]

Electric energy consumed/electric energy produced	0.77 - 0.85
Fossil energy consumed/electric energy produced	1.64
Specific price: energy related price	25 DM/kWh
power related price	240 DM/kW

Economy of storage plants

Table 5 gives a survey of the data necessary for the calculation of the energy production costs including gas turbines, pumped hydro storage plants and the systems of Tables 1 to 4.

Peak power generation costs

Energy costs are the most relevant parameter which characterizes the power plant economy. Neglecting the distribution costs in the first instance they can be calculated from the data for the different systems. The following formula will be utilized for calculating the cost of energy [46]:

$$c = \frac{I_E a_E}{ne} + \frac{I_p a_p}{npt} + \frac{f}{\eta} \tag{1}$$

The symbols have the following meaning:

c cost of electric energy (DM/kWh),

TABLE 5

Data for peak power plants for the calculation of energy costs

	Power related price (DM/kW)	Energy related price (DM/kWh)	Efficiency	Lifetime (years)
1 Pumped hydro storage plant	550	25	0.75	30
2 Gas turbine	400	–	0.26 - 0.3	20
3 Compressed air power plant	240	25	0.7	20
4 Battery (Na/S)	190 - 300	135 - 170	0.7	10
5 Battery (Redox)	300 - 655	75 - 95	0.7	10
6 Hydrogen storage (solid electrolyte H_2O-electrolysis-gas turbine)	1090 - 1415	15	0.2	10
7 Hydrogen storage (solid electrolyte cells used for the electrolysis and as fuel cells alternately)	790 - 1115	15	0.45	10
8 Hydrogen storage (high pressure-H_2O-electrolysis-gas turbine)	1390 - 1915	15	0.2	10
9 Steam storage	215 - 285	70 - 100	0.7	20
10 Flywheel	370 - 420	500 - 800	0.7	20

I_E, I_p energy and power dependent investment costs in DM/kWh and DM/kW respectively,
a_E, a_p annualization factors,
n number of discharges per year,
e degree of discharge (= 1 if fully discharged),
p load factor (= 1 at maximum power),
f fuel costs, DM/kWh (electric energy: 0.02 DM/kWh$_{el}$, oil: 25 DM/Gcal),
η efficiency (energy output/energy input),
t discharge time, (h).

Figure 4 presents a plot of the power generation costs *versus* the daily operation time. Some assumptions for the calculation are mentioned in Fig. 4. The comparison is not significantly affected by other assumptions.

The curves of Fig. 4 show that at operation times of 1 - 3 hours daily the peak power generation costs of most systems do not differ very much from each other. Daily operation times of 1 - 3 hours are typical for peak shaving. Using hydrogen storage devices or flywheels, however, leads to higher energy costs than in the other cases. With daily discharge times of 10 hours the power generation costs of hydrogen storage plants (curve 7 in Fig. 4) become comparable with those of other peak power devices.

It can be concluded therefore that the cost of peak power produced from compressed air storage plants, batteries and steam devices will most probably become comparable with those of pumped hydro and gas turbines. Hydrogen storage devices may become competitive only for discharge times $\geqslant$ 10 hours per day.

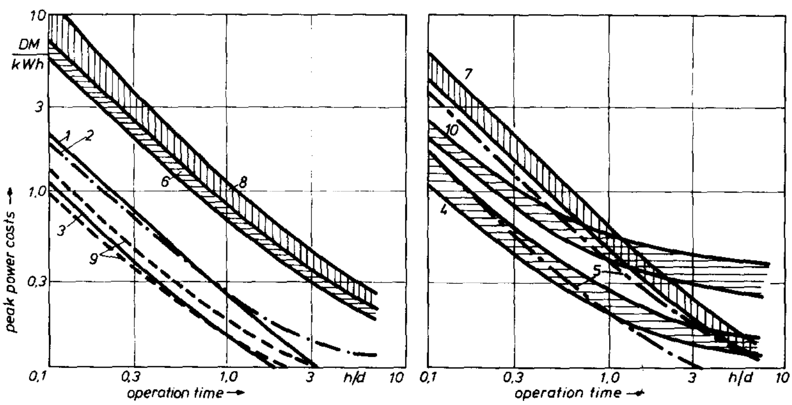


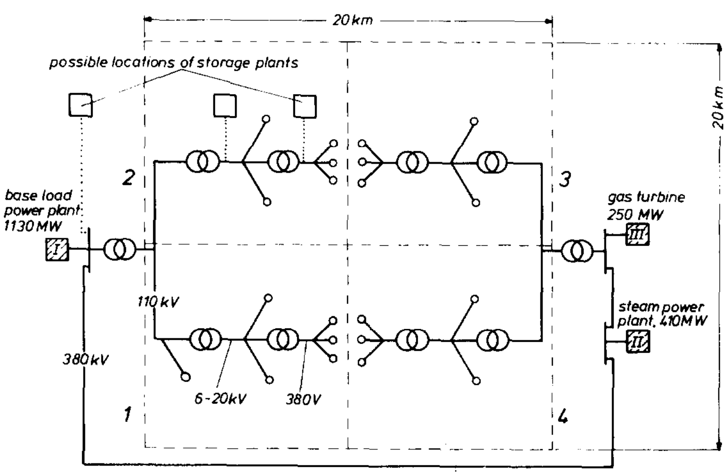
Fig. 4. Peak power generation costs. Assumption: n = 365 per year, $e = p$ = 1. 1, pumped hydro; 2, gas turbine; 3, compressed air storage; 4, battery (Na/S); 5, battery (Redox); 6, hydrogen storage (solid electrolyte–H_2O electrolysis–gas turbine); 7, hydrogen storage (solid electrolyte cells used for the electrolysis and as fuel cells alternately); 8, hydrogen storage (high pressure H_2O-electrolysis–gas turbine); 9, steam storage; 10, flywheel.

Electric network with storage devices

The actual criterion for the economy of an energy storage system is the price per unit of energy for the consumer. This price includes the distribution costs which have hitherto not been taken into account. The structure and the price of an electric network are strongly dependent on the type of consumer and on the density of population. To simplify matters a special network is considered which represents a model for a large area with a high density of population typical for Europe in 1990.

The model area is illustrated in Fig. 5. It consists of 4 areas. The first area includes an industrial consumer who is connected to the 110 kV line. Each area contains 10 kV and 380 V consumers. The peak power density for the 380 V-consumers decreases from 40 MVA/km^2 at the centre of the area to 1 MVA/km^2 at the edge. The total energy demand for the total area is assumed to be 9500 GWh per year. In the standard case 77% of the total energy is generated by a nuclear base load plant, 20% by a steam power station and 3% by a gas turbine. Alternatively the energy demand is provided by substituting the gas turbine and partly substituting the steam power station within storage devices. The question is whether the mean energy costs are decreased or increased by this substitution. It is sufficient in this case to design the line between storage device and base load plant for mean power only. In this way transmission and distribution costs can be saved.

Figure 6 shows a plot of the mean energy costs *versus* the percentage of total energy delivered to the customer from storage devices. The mean energy costs include capital, maintenance and fuel costs. They amount to 0.088 DM/kWh in the standard case where no energy storage devices are used.



power plant	operation time h/a	energy produced GWh/a	%
I	6470	7315	77
II	4630	1900	20
III	1140	285	3
		9500	100

Fig. 5. 400 km^2 model area.

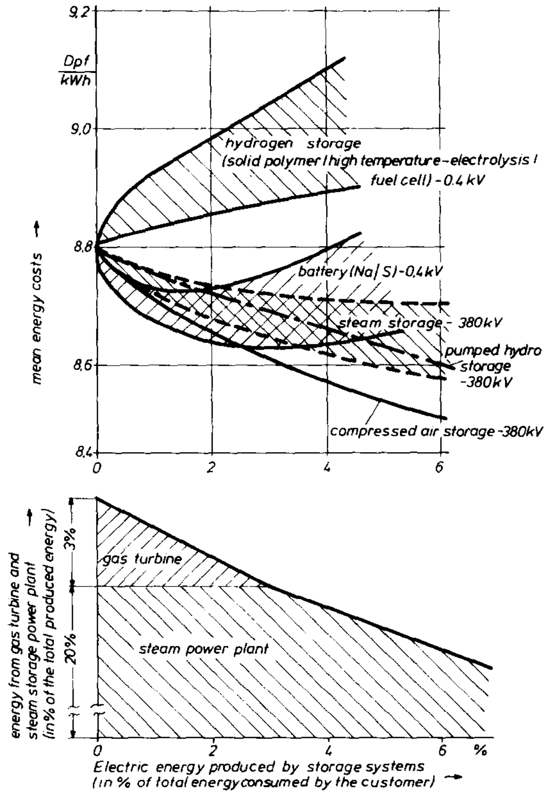


Fig. 6. Mean costs of electric energy.

Substituting the gas turbine and partly substituting the steam power plant results in a change of the mean energy costs the magnitude of which depends on the type and location of the power plant.

Figure 6 shows that the mean energy costs are lower than in the standard case for pumped hydro storage, steam storage, air storage and batteries. They are higher for hydrogen storage. The result is in accordance with the conclusion drawn from Fig. 4. This means that considering the mean energy costs instead of the peak energy generation costs has qualitatively no effect on the assessment of the economy of the different systems.

It should be mentioned, however, that storage devices can be arranged at different locations within the electric network. Possible locations are illustrated by squares in the second area of Fig. 5. If many small storage devices are installed in the 380 V network, high network installation cost savings are possible since almost the whole network can be designed for mean power instead of designing for peak power. The savings are smaller if the storage devices are arranged near the base load plant. In the first case the power peaks are more pronounced, which means that more energy must be stored than in the second case. Therefore a part of the network cost savings are counterbalanced by higher storage plant investments. Detailed calculations show that the total energy costs for batteries seem to be slightly lower if they are installed close to the consumer. On the other hand, maintenance is complicated in this way. Therefore it seems to be a good compromise to install batteries within the 6 - 20 kV line, for instance at the 110 kV/6 - 20 kV transformer. Most of the other storage systems are not appropriate for dispersed energy storage because of the higher specific investment costs connected with smaller units.

Network extension considerations

In most practical cases an electric network will be extended rather than designed for an unpopulated area. The following consideration compares two possibilities of network extension. It is assumed for this purpose that the power density is 4.3 MVA/km^2 at the beginning of a 20 year period with 7% power increase per year.

In the first case the extension is performed by addition of base load plants, gas turbines and the necessary network components. In the second case batteries are added instead of gas turbines. The result of this consideration is summarized in Table 6. The Table shows that case 2 seems to be slightly more favourable than case 1, partly due to the possibility of realizing the extension in smaller steps.

Conclusions

(1) Gas turbines and hydroelectric storage stations will be used for peak power generation as long as the constraints (oil or natural gas shortage, site restrictions) are of minor importance.

(2) Compressed air, steam storage and advanced batteries will economically become competitors to gas turbines and pumped hydro.

(3) Battery storage systems have the particular advantage of being assembled from modules. For this reason small units up to 20 MWh capacity can be produced almost as cheaply as larger units. Many of these batteries may be installed within a network. A network with dispersed battery storage devices may be designed only for mean power (base load) distribution and

TABLE 6

Investment costs for two cases of network extension

Peak power extension with	Total investment costs 20 years (%)	Total present values (%)
1 gas turbines + base load plant - see text	100	100
2 batteries (Na/S)	98 - 99	96.5 - 97.7

not for peak power distribution as in the case of central peak power generation. Capital costs of network components may be saved which leads to a further reduction in energy costs.

(4) Flywheels and hydrogen storage facilities will not become competitive for peak power generation. More favourable prospects with respect to the economy of hydrogen storage plants are expected if hydrogen is used for more than ten hours per day. A reasonable aim is to produce hydrogen electrolytically for chemical industry applications in competition with hydrogen generation by steam reforming. Economic production of hydrogen by electrolysis appears possible if oil and natural gas prices will further increase and if the investment costs envisaged for electrolysis plants (Table 2) can be achieved. In this case part of the hydrogen produced could be stored and utilized for peak power generation.

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