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Second-Law Analysis of a Compressed Air Energy Storage (CAES) System

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ABSTRACT

Compressed Air Energy Storage (CAES) system consumes excess energy from base load steam power plant, converts it into stored pneumatic energy and then releases it during peak load period through a gas turbine.

A comprehensive analysis of exergy flows, inputs, outputs and losses in the entire (CAES and steam plant) system is carried out. The irreversible losses and the system efficiency are more realistically presented, than according to the conventional first-law analysis.

Various CAES system schemes and cycle characteristics are studied. It is shown that in some cases the overall thermal efficiency is higher in the combined CAES-Steam Plant System, than in an industrial gas turbine.

NOMENCLATURE

a_o, a_1, a_2	coefficients in the equation (5)
d_c, d_e, d_R, d_{Rec}	pressure ratio losses coefficients for intercooler (aftercooler), combustor, reservoir and recuperator, respectively
D	coefficient that determines a value of d_{Rec}
E_F, E_{FS}	fuel exergy input for CAES and the primary steam plant, respectively
E_{in}, E_{out}	exergy flow rate of air or gas on entry and exit of CAES plant element, respectively
m, n	number of turbine and compressor stages, respectively
N	mechanical capacity
N_o, N_i	electrical energy output and input for CAES, respectively
N_{nom}, N_s	nominal and actual primary steam plant electrical capacity, respectively
T_{SE}, T_{SC}, T_R	gas or air temperature before expansion, compression and in reservoir, respectively
T_{exh}	exhaust gas temperature in a CAES regeneration plant
Q	heat capacity
$x = \frac{N_s}{N_{nom}}$	partial load coefficient for a primary steam plant
β_c, β_E	compressor and turbine total pressure ratios, respectively
η, η_e	exergetic efficiency of a CAES plant and of an entire CAES-Steam Plant System, respectively
η_T	exergetic efficiency of an equivalent gas turbine
η_i, η_d, η_s	incremental, differential and average exergetic efficiency of a steam plant, respectively

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η_a	coefficient of additional losses in CAES plant
η_e'	efficiency limitations coefficient, defined by formula (13)
η_{pc}, η_{pe}	polytropic compressor and turbine efficiency, respectively
η_{REC}	recuperator efficiency
η_g, η_m	electrical generator and motor efficiency, respectively
π	exergetic losses

INTRODUCTION

Compressed Air Energy Storage (CAES) is a technique combining two features: energy storage and energy generation. Energy storage is facilitated by purchasing electricity from base-load, mainly coal or nuclear power plants during off-peak periods and converting this energy into pneumatic energy by means of compressors. The generation feature is enabled by the release of the compressed air into a combustion chamber and a turbine while producing premium peaking power.

The conventional way to assess and compare alternative energy technologies is to use monetary cost as the unit of analysis. This analysis reflects the true opportunity cost of the technology only in a perfect market. Deviation from perfect market conditions would lead to unoptimal allocation of resources. The experience of the last two decades has demonstrated that imperfections in the energy market are abundant, among the imperfections the following may be listed: price regulations, import quotas, depletion allowances, etc.

Alternatively, the second-law analysis is proposed, assessing the costs and benefits of the system in physical units. The analysis is carried out for a system planned and optimized for the Israel Electric Corporation by Nakhamkin et al. (1990).

In this study a system utilizing an aquiferous reservoir with an almost constant high pressure has been considered. For a system comprised of a constant volume reservoir such as salt cavern a transient equation describing the various mass and exergy flows would be adequate.

This paper presents an exergy analysis of an integrated CAES/Steam Power Plant, when the power of the latter is utilized for air compression into the reservoir during off-peak hours. The steam power plant incremental heat consumption and its exergy contribution is evaluated. The results of this evaluation are compared to an exergy analysis of an industrial gas turbine of the same configuration. The thermodynamic analysis points out possible ways for improving the cycle effectiveness.

Thermodynamic efficiency studying of entire system, consisting CAES and the base load steam plant, is a practically and theoretically significant problem. Such a system is rather complicated, has many interconnected elements and interaction of their irreversible losses takes place.

Some works are devoted to CAES plants thermodynamical analysis. Zaugg (1975) studied the factors, affecting CAES plant fuel efficiency and irreversible losses in a constant volume air storage reservoir. Zaugg and Stys (1980) analysed the adiabatic and diabatic CAES plants thermodynamic characteristics and composed the exergy diagram for diabatic plant. Frutschi (1985) compared thermodynamic efficiency of adiabatic and diabatic CAES system and proved that additional fuel combustion in a diabatic unit is thermodynamically profitable. Zaugg (1985), using the exergy-anergy concept, analysed a combined exergy-anergy diagram for diabatic CAES plants. Vadasz and Weiner (1986) made thermo-economic analysis and optimization of a constant pressure reservoir CAES system. Macchi and Lozza (1987) examined various efficiency coefficients for adiabatic, semi-adiabatic and diabatic CAES plants.

Our work differs from these studies in the following points:

1. Using incremental exergetic efficiency of the base steam plant, we define the exergetic efficiency of entire CAES-Steam Plant System.
2. We give the exergetic flows diagram for entire CAES-Steam Plant System.
3. We compare the exergetic efficiency of a CAES-Steam Plant System with the efficiency of an equivalent gas turbine plant.

EXERGETIC EFFICIENCY OF A CAES PLANT AND OF ENTIRE CAES-STEAM PLANT SYSTEM

Exergetic efficiency of a CAES plant (Fig. 1) may be determined as

$$\eta = \frac{N_o}{N_i + E_F}, \tag{1}$$

where

N_o is electrical energy output,
N_i is electrical energy input,
E_F is fuel exergy input,

With high accuracy E_F may be determined by lower heating value of the fuel. When other than fuel heat sources are used, E_F is an exergy of heat, supplied by them. The η coefficient characterizes thermodynamic efficiency only of CAES system, comprising compressors, air storage reservoir, combustors, recuperator (if it is used) and expanders.

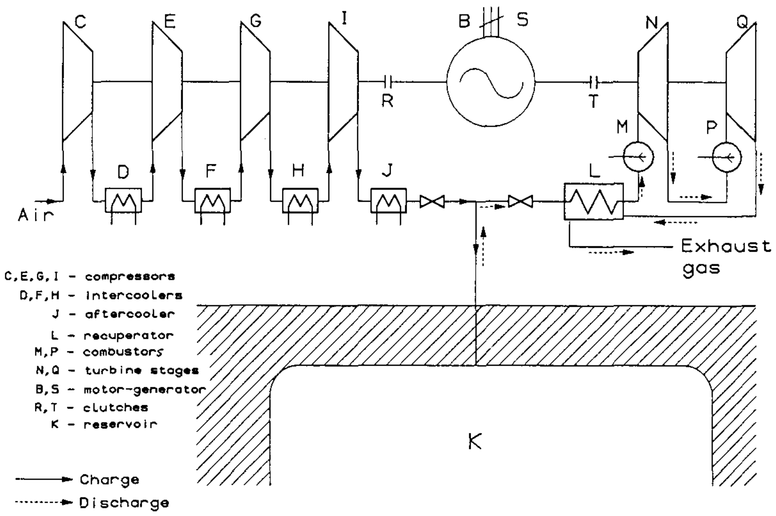

Fig. 1 CAES Plant Scheme

More valuable information gives exergetic efficiency of entire CAES-Steam Plant System. In this case it is necessary to use such considerations. We assume that initially, before switching on CAES plant compressors, the primary steam plant has a partial load $x = \frac{N_s}{N_{nom}} < 1$ (N_s is an actual plant capacity, N_{nom} is a nominal plant capacity). Energy supply to CAES plant increases steam plant load, changing it from x to Δx. In this case fuel exergy supply to the primary plant increases from $E_{FS}(x)$ to $E_{FS}(x + \Delta x) = E_{FS}(x) + \Delta E_{FS}$ and steam plant electrical load increases from $N_s = N_{nom}x$ to $N_s + \Delta N_s = (x + \Delta x)N_{nom}$. So $N_i = \Delta N_s = N_{nom}\Delta x$.

Now we may define the incremental steam plant exergetic efficiency

$$\eta_i = \frac{\Delta N_s}{\Delta E_{FS}} = N_{nom}\frac{\Delta x}{\Delta E_{FS}} \tag{2}$$

and the differential exergetic efficiency

$$\eta_d = \frac{dN_s}{dE_{FS}} = N_{nom}\frac{dx}{dE_{FS}} \tag{3}$$

It is evident that

$$\eta_i = \Delta x \Big/ \int_x^{x+\Delta x} \frac{dx}{\eta_d} \tag{4}$$

Usually we have second order equation for E_{FS}:

$$\frac{E_{FS}}{N_{nom}} = a_0 + a_1 x + a_2 x^2, \tag{5}$$

where a_o, a_1, a_2 are positive. So

$$\eta_d = \frac{1}{a_1 + 2a_2 x}; \tag{6}$$

$$\eta_i = \frac{1}{a_1 + a_2(2x + \Delta x)}; \tag{7}$$

$$\eta_s = \frac{1}{a_0/x + a_1 + a_2 x}, \tag{8}$$

where $\eta_s = \frac{N_s}{E_{FS}}$ is an average exergetic efficiency of a steam plant at the partial load. The differential efficiency η_d is always higher than the incremental one: $\eta_d > \eta_i$.

Using least squares calculations and data from Wood and Wollenberg (1984) we defined $a_0 = 0.2141$, $a_1 = 2.3025$, $a_2 = 0.0892$ for an American standard steam plant with $N_{nom} = 600$ MW.

From our analysis it follows that the incremental exergetic efficiency is always greater than the average one: $\eta_i > \eta_s$ since $a_0 > a_1$. This ensures additional energetic advantages of various energy storage technologies.

Now exergetic efficiency of entire CAES-Steam Plant System may be defined

$$\eta_e = \frac{N_0}{\Delta E_{FS} + E_F} = \frac{N_0}{N_i/\eta_i + E_F} \quad (9)$$

Formulae (1) and (9) show, that always $\eta_e < \eta$ and

$$\eta_e = \eta\eta_i \cdot \frac{1+a}{1+\eta_i a}, \quad (10)$$

where $a = \frac{E_F}{N_i}$. If $a = 0$ (adiabatic CAES plant), always $\eta_e < \eta_i$.

It is important to compare exergetic efficiency of entire CAES-Steam Plant System with exergetic efficiency of a gas turbine, that also is used for peak energy production. Exergetic efficiency of a gas turbine equivalent to CAES system is defined as:

$$\eta_T = \frac{N_0 - N_c\eta_a}{E_F}, \quad (11)$$

where a coefficient $\eta_a < 1$ takes into account, that in a CAES system are additional pressure losses and compressor of a CAES system has an electrical drive. As

$$\eta_e - \eta_T = \frac{N_c[\eta_a(\frac{N_c}{\eta_i} + E_F) - \frac{N_0}{\eta_i}]}{(\frac{N_c}{\eta_i} + E_F)E_F} = \frac{N_c}{\eta_i E_F}(\eta_i\eta_a - \eta_e), (12)$$

so the entire CAES-steam plant system has higher exergetic efficiency, than an equivalent gas turbine, if

$$\eta_e < \eta_e^{'} = \eta_a\eta_i \quad (13)$$

RESULTS AND DISCUSSION

Exergy efficiency calculations for various CAES plant schemes were made for such typical values of independent variables:

1. gas temperature before expansion in all turbine stages is the same: T_{SE}= 1200K
2. air temperature before every compression stage is the same: T_{SC} = 295K
3. air temperature in reservoir is T_R = 307K
4. polytropic compressor efficiency is $\eta_{pc} = 0.85$, polytropic turbine efficiency is $\eta_{pe} = 0.87$;
5. compressor electrical drive efficiency is $\eta_m = 0.983$, electrical generator efficiency is $\eta_g = 0.982$;
6. pressure ratio losses coefficients are: for every compressor intercooler and aftercooler $d_c = 0.01$, for every turbine stage combustor $d_e = 0.01$, for reservoir $d_R = 0.05$; for recuperator: $d_{REC} = \frac{D\eta_{REC}}{1-\eta_{REC}}$, where η_{REC} is a recuperator efficiency, $D \approx 0.03$;
7. incremental steam plant exergetic efficiency is $\eta_i = 0.417$; this value corresponds to $x = 0.352$ and $\Delta x = 0.368$ for above mentioned American standard steam plant with N_{nom} = 600 MW.
8. compressor total pressure ratio β_c range is from 10 to 100, turbine total pressure ratio β_E was calculated from a formula:

$$\beta_E = (1 - nd_c - md_e - d_R - d_{REC})\beta_c, \quad (14)$$

where

n is number of compressor stages ($n = 3 \div 5$);
m is number of turbine stages ($m = 1 \div 3$);

9. taking into consideration the possibility of a recuperator surface acid corrosion, we assumed, that exhaust gas temperature in a CAES regenerative plant is equal to T_{exh} = 473K.

In the calculations were used ideal gas formulae, this ensures satisfactory accuracy of results. Special investigation based on data from Loomis (1982), Moran and Shapiro (1988), showed that in this case an error of compressor and turbine work determination is not more than 3%. We assumed, that in compressor stages pressure ratios are equal and also that turbine stages have equal pressure ratios.

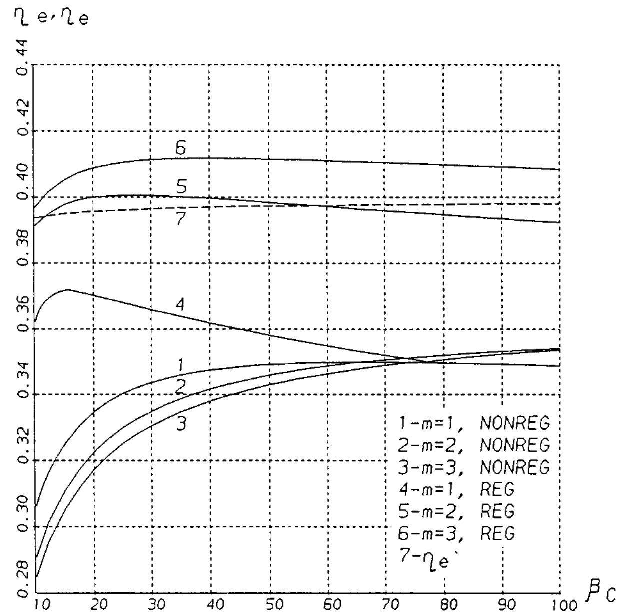

Fig. 2 The effect of compressor pressure ratio β_c on an entire CAES-Steam Plant exergetic efficiency η_e and on $\eta_e^{'}$

Some results of calculations are shown on Figs. 2 – 5. Sensitivity analysis for coefficient d_R of pressure ratio losses in reservoir was carried out. The increase of d_R from 0.05 to 0.12 changed $\eta_e, \eta, \frac{N_i}{N_o}, \frac{E_F}{N_o}$ only on 1 - 3%. Fig. 2 shows an effect of compressor ratio β_c on an entire CAES-Steam Plant exergetic efficiency η_e for various CAES plant schemes. We see, that in a non-regenerative CAES plant the reheating does not improve the efficiency at $\beta_c < 70$ and 2 turbine stages have higher efficiency than 3. Even at high $\beta_c > 70$ reheating leads only to a small efficiency rise. Optimal β_c-values corresponding to η_e maximum are higher than 70. One-stage expansion regenerative CAES plant has greater η_e, than non-regenerative plant, only at $\beta_c < 80$. Optimal β_c values for regenerative CAES plant are smaller, than for non-regenerative. Application of 2 and 3 expansion stages with reheating, as usual, improves the efficiency.

On Fig. 2 the curve $\eta_e' = f(\beta_c)$ is given. It follows from formula (13), that all nonregenerative CAES plants and one-stage expansion regenerative CAES plants at any β_c, and two-stage expansion regenerative CAES plants at $12 > \beta_c > 57$, have higher exergetic efficiency than equivalent gas turbines.

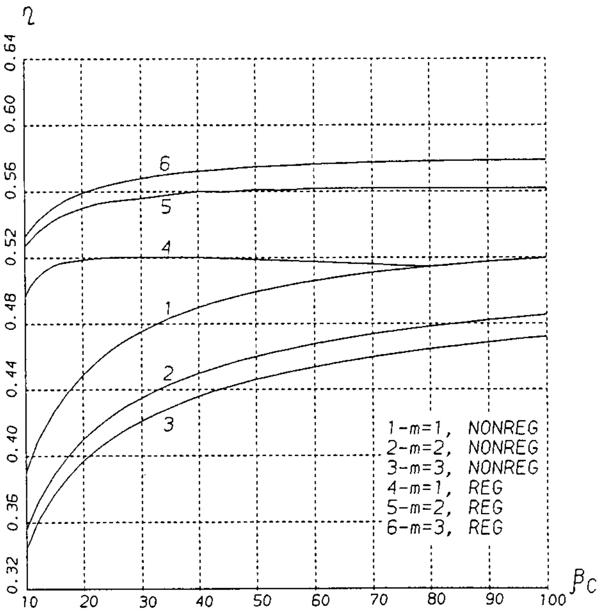

Fig. 3 The effect of compressor pressure ratio β_c on a CAES plant exergetic efficiency η ($n = 4$).

The curves for $\eta = f(\beta_c)$ on the Fig. 3 have the same peculiarities, as the curves for $\eta_e = f(\beta_c)$ on the Fig. 2.

The curves on Figs. 4 and 5 show the effect of β_c on a relative work and fuel exergy consumption $\frac{N_i}{N_o}, \frac{E_F}{N_o}$. At the same m and β_c, $\frac{N_i}{N_o}$ values for regenerative CAES plant are higher, and $\frac{E_F}{N_o}$ values are lower, than for non-regenerative plant. It means, that at the same m and β_c electric consumption is higher and fuel consumption is lower for regenerative CAES plant, than for non-regenerative plant.

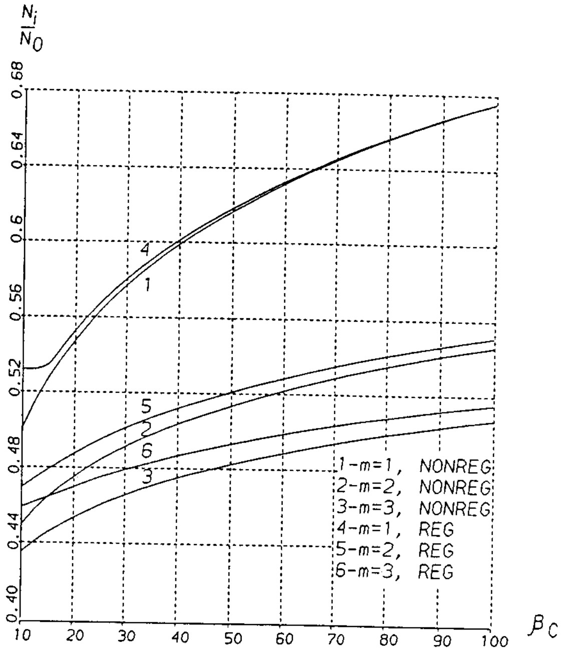

Fig. 4 The effect of compressor pressure ratio β_c on a CAES plant relative work consumption N_i/N_o ($n = 4$).

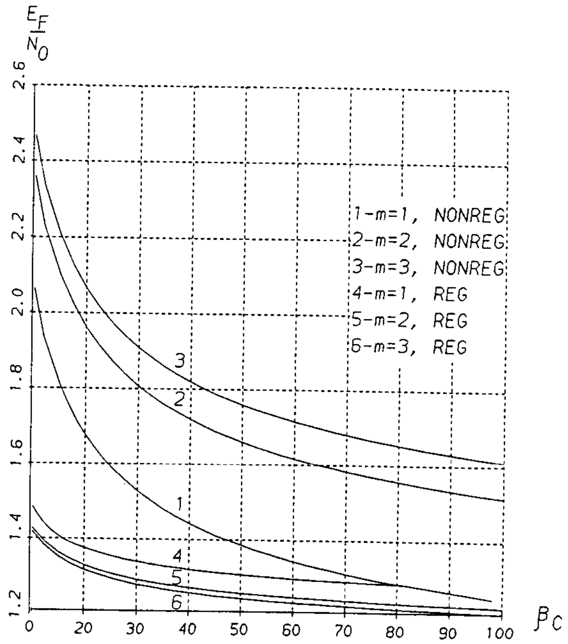

Fig. 5 The effect of compressor pressure ratio on a CAES plant relative fuel exergy consumption E_F/N_o ($n = 4$).

Full exergy flows and losses analysis was made for an entire CAES-Steam Plant System, comprising

Table 1: ENERGY AND EXERGY FLOWS IN MW FOR THE 300 MW CAES-STEAM PLANT SYSTEM

Element	N	Q	E_F	E_{in}	E_{out}	E_{out}-E_{in}	π	Exergetic efficiency	Adiabatic efficiency
Primary Steam Plant	220.68	529.21	529.21	-	-	-	308.53	0.417	-
Electric Motor	216.93	0	0	-	-	-	3.75	0.983	-
Compressor Stage No. 1	-72.84	0	0	0.03	68.49	68.46	4.98	0.932	0.898
Intercooler No. 1	0	-65.67	0	68.49	54.33	-14.16	14.16	0.793	-
Compressor Stage No. 2	-42.90	0	0	54.33	91.41	37.08	5.82	0.864	0.818
Intercooler No. 2	0	-42.90	0	91.41	83.91	-7.50	7.50	0.918	-
Compressor Stage No. 3	-47.52	0	0	83.91	121.56	37.65	9.87	0.792	0.768
Intercooler No. 3	0	-47.52	0	121.56	112.83	-8.73	8.73	0.928	-
Compressor Stage No. 4	-53.67	0	0	112.83	157.50	44.67	9.00	0.832	0.765
Aftercooler	0	-52.23	0	157.50	147.21	-10.29	10.29	0.935	-
Aquifer and Throttling Valve	0	0	0	147.21	129.42	-17.79	17.79	0.879	-
Recuperator Air Side	0	118.59	0	129.30	163.77	34.77	21.90	0.611	-
Recuperator Gas Side	0	-119.64	0	67.26	10.89	-56.37			
HP Combustor	0	122.73	122.73	163.77	230.58	66.81	55.92	0.544	-
HP Turbine	45.24	0	0	230.58	183.39	-47.19	2.76	0.961	0.886
LP Combustor	0	234.33	234.33	183.39	341.43	158.04	76.29	0.674	-
LP Turbine	260.25	0	0	341.43	67.26	-274.17	18.60	0.949	0.878
Electric Generator	300.00	0	0	-	-	-	5.49	0.982	-

1. above mentioned standard American steam plant with $N_{nom} = 600$ MW, $x = 0.352$, $\Delta x = 0.368$, $\eta_i = 0.417$;

2. CAES system with an aquifer reservoir, evaluated for The Israel Electric Corporation Ltd. [1].

In Table 1 and Fig. 6 the results of an exergy analysis are given. We see, that exergetic efficiency of an entire system is 33.2% and 66.8% of initial fuel exergy are lost. Approximately, 1/2 of these losses takes place in a primary steam plant, 1/4 of the total losses are in the combustors of gas turbines, 1/10 of the losses are expected in the heat exchangers, recuperator, compressor stages intercoolers and aftercooler and only 1/7 part of the total losses is in the machinery equipment of CAES plant : compressors, expanders, electric motor-generator. Losses, caused by throttling in an aquifer system and in a throttling valve, ensuring constant output of CAES plant, are relatively small and have, approximately, the same value, as losses in the low pressure expander. But calculations show, that this throttling increases mechanical power consumption of compressors on 16% and decreases exergetic efficiency of an entire CAES-Steam Plant System from 36.9% to 33.2%, i.e. in 1.1 times.

The same picture may be expected with the effects of machinery equipment efficiency on an entire exergetic efficiency. It means that irreversibilities in the system are tied and realistic engineering design must take into account this interception of losses. Without such investigation the full thermodynamic analysis is impossible.

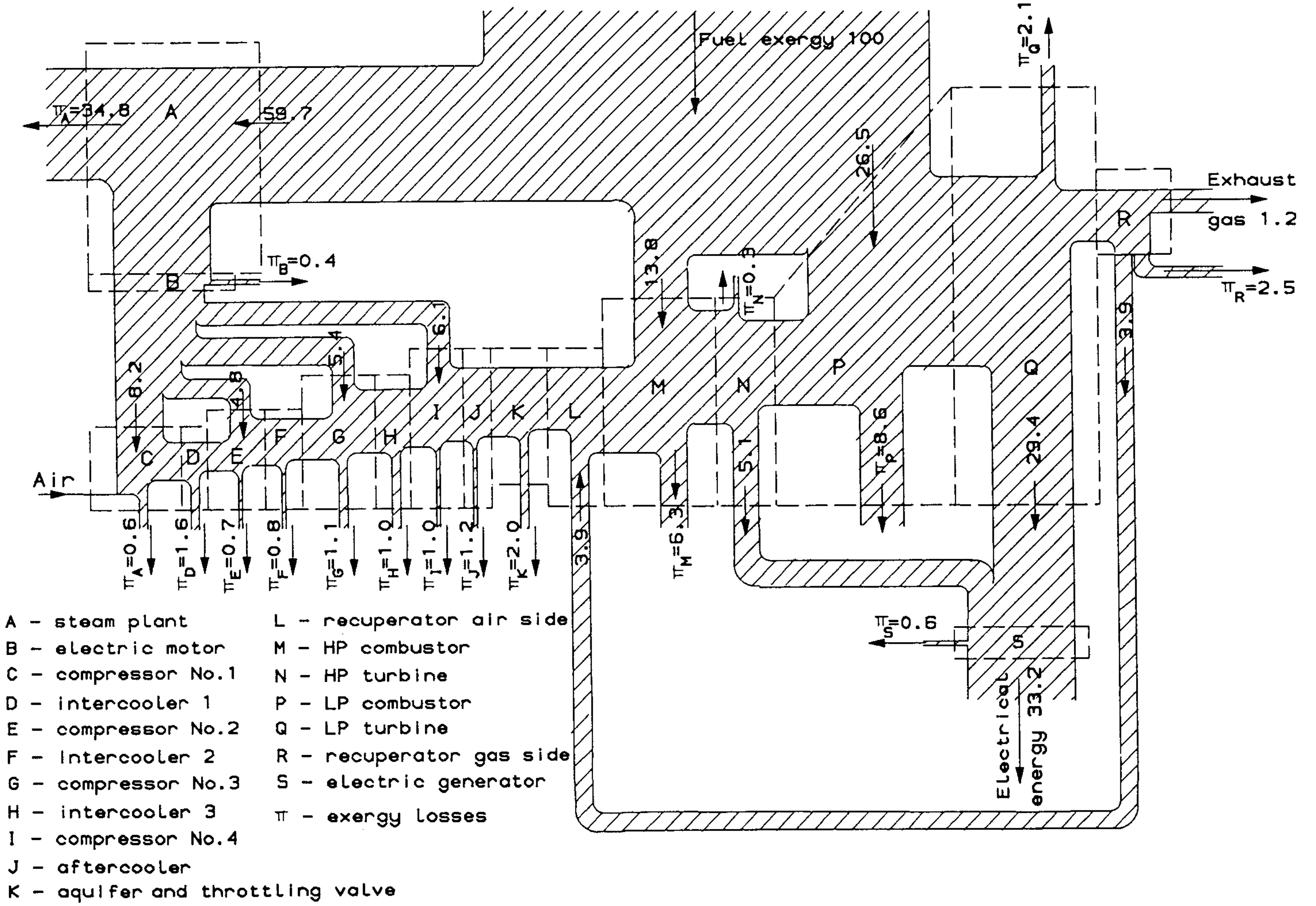

Fig. 6 Exergy flow diagram for an entire CAES-Steam Plant System.

CONCLUSIONS

Realistic efficiency determination for CAES plant must be based on the incremental exergetic efficiency of the primary steam plant and exergetic flows analysis of the entire CAES-Steam Plant System.

In some cases the exergetic efficiency of such entire system is higher than efficiency of an equivalent gas turbine plant.

The interception of irreversible losses takes place in CAES-Steam Plant System. Its investigation is necessary for realistic system design and optimization.

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