ECONOMIC IMPACT OF MEASURES TO IMPROVE ENERGY EFFICIENCY FOR A THERMAL POWER STATION

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Abstract: An important part of an energy audit is finding the solutions to improve energy efficiency. After accomplishing that goal, in order to implement proposed technical measures their economic impact must be analyzed carefully. This paper presents the economical aspects of solutions proposed as a result of an energy audit.

Key words: thermal power station, energy audit, economic aspects.

1. INTRODUCTION

Some papers that discuss energy efficiency are presenting only the ways to achieve a better energy efficiency or technical solutions in order to do that [1], [2], [3], [4].

Unfortunately several of the technical solutions cannot be applied because of their cost versus benefits. Therefore, economic impact of measures must be taken into account at the beginning. Even more, if implementation of some measures is delayed for some reason, economic calculation must be carried out again, as costs can vary in time. If a number of solutions are available, the solution with the lowest payback period must be considered.

2. BRIEF PRESENTATION OF CONCLUSIONS AFTER ANALIZYNG THE ENERGY BALANCE

In paper [5], [6], [7] are presented the results of the energy audit for an unit of a thermal power plant.

How energy auditing must be carried out is presented in detail with examples

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in papers [8], [9], [10], [11].

After analyzing results the following major source of losses are highlighted:

- Heat loss due to heat rejected by condenser;
- Power loss due to condenser pressure;
- Flue gas loss;
- Piping loss.

As highlighted in [7] functioning with exhaust pressure at the outlet of the Low Pressure Turbine (LPT) close to design value which is 0.035 ata, can lead to increased generator power output, between (5–5.9)%.

Optimal condenser pressure can be ensured by proper operation of steam-air ejectors, maintaining clean heat exchange surfaces and eliminating leaks.

In order to reduce loss through flue gas and losses due to combustion and assuring a proper excess air, following measures are proposed:

- correct adjustment of air fans providing combustion air and air used for the transport of pulverized coal;
- reducing false air leakage due to improper sealing of flue gas duct;
- using high quality coal;
- minimizing flow rate of natural gas used to sustain the flame;
- heat load balancing between burners.

To reduce heat losses due to inadequate heat transfer from the flue gases from the furnace and water-steam circuit, it is necessary to periodically clean the heat exchange surfaces of the steam generator, economizer, preheater. Also regularly clean of the flue gas circuit must be performed. It should be noted that the use of quality coal will lead to lower bottom ash losses by lowering the amount of slag and ash extracted, simultaneously reducing the environmental impact. Applying these measures lead to achieving energy performance operating regimes close to optimal balance. Quantification of the proposed measures is presented in the following chapters.

Diverse losses can be reduced by measures below:

- reducing condensate flow rate losses, as at 85% load makeup water flow rate reached 32,961 $t \cdot h^{-1}$, representing 5,74 % of main steam flow rate, and condensate flow rate loss is linked to enthalpy loss;
- proper isolation of ducts;
- assuring proper operation of lubricating oil cooler, since it was working inappropriately as shown in [6];
- full condensate recovery.

Implementation of these measures will have the effect of reducing energy consumption and system operation close to parameters calculated according to the optimal balance. Energetic and economic results of measures highlighted above are analyzed in the following chapter. Given that even for the optimal balance, energy efficiency of unit 5 is lower than the efficiency of modern power plants; the possibility of implementing a combined gas-steam cycle is analyzed, that way capitalizing complementary thermodynamic performance of the steam and gas cycle.

A justification for the proposed variant is found in chapter 4.

3. ECONOMIC EFFECTS OF PROJECTED MEASURES

To compare items of actual hourly energy balance (related to particular unit loads during the tests), to optimal balance items, values are expressed using specific energy per ton of steam, in kWh·t^{-1} - Tables 1 and 2. Differences resulting from the comparisons are summarized in Tables 3 - 5. Estimates of savings achievable are summarized in Table 6.

Table 1. **Hourly optimal energy balance (expressed using specific energy)**

INPUT			**OUTPUT**		
Nom.	**kWh·t^{-1}**	**%**	**Nom.**	**kWh·t^{-1}**	**%**
Chemical heat of fuel Q_{cBi}	851.42	98.11	**USEFUL OUTPUT**		
			Output power P_g	331.23	38.17
			Energy of steam extracted for technological use P_{SRRD}	10.11	1.16
Physical heat of fuel Q_B	7.65	0.88	**TOTAL USEFUL**	**341.34**	**39.33**
			Mechanical incomplete combustion Q_{cmec}	7.65	0.88
			Chemical incomplete combustion Q_{cga}	0.0	0.0
			Heat loss through flue gas Q_{gacos}	59.57	6.86
Physical heat of air Q_L	8.79	1.01	Heat loss by bottom ash Q_{sg}	14.72	1.70
			Wall loss Q_{per}	3.79	0.44
			Mechanical loss ΔP_m	16.51	1.90
			Generator loss ΔP_m	4,91	0.57
Physical heat of makeup water P_{aad}	0.0	0.0	Heat rejected by condenser P_{cd}	412.78	47.56
			Loss in piping ΔP_{cdt}	9.21	1.06
			Loss through pressure drop for piping and valves, wall loss and leakage loss P_{div}	7.87	0.91
			Unaccounted losses ΔP_{bil}	-10.49	-1.20
			TOTAL ENERGY LOSS	**526.51**	**60.67**
TOTAL INPUT	**867.85**	**100.0**	**TOTAL OUTPUT**	**867.85**	**100.0**

Table 2. **Actual hourly energy balance (expressed using specific energy)**

	70% load		**85% load**		**94% load**	
INPUT						
Nom.	**kWh·t^{-1}**	**%**	**kWh·t^{-1}**	**%**	**kWh·t^{-1}**	**%**
Chemical heat of fuel Q_{cBi}	950.74	97.16	914.01	96.80	923.47	97.49
Physical heat of fuel Q_B	7.73	0.79	8.24	0.87	8.80	0.93
Physical heat of air Q_L	19.79	2.02	20.57	2.18	14.15	1.49
Physical heat of makeup water P_{aad}	0.33	0.03	1.36	0.14	0.89	0.09
TOTAL INPUT	**978.59**	**100.0**	**944.18**	**100.0**	**947.31**	**100.0**
OUTPUT						
USEFUL OUTPUT						
Output power P_g	314.33	32.12	305.14	32.32	312.02	32.94

Energy of steam extracted for technological use P_{SRRD}	9.61	0.98	8.64	0.92	8.72	0.92
TOTAL USEFUL	**323.94**	**33.10**	**313.79**	**33.23**	**320.74**	**33.86**
LOSSES						
Mechanical incomplete combustion Q_{cmec}	5.62	0.58	4.93	0.52	5.22	0.55
Chemical incomplete combustion Q_{cga}	0.02	0.002	0.02	0.002	0.02	0.002
Heat loss through flue gas Q_{gacos}	121.66	12.43	103.68	10.98	110.38	11.65
Heat loss by bottom ash Q_{sg}	8.57	0.87	9.20	0.97	11.20	1.18
Wall loss Q_{per}	6.25	0.64	4.09	0.43	5.61	0.59
Mechanical loss ΔP_m	4.43	0.45	3.68	0.39	3.00	0.32
Generator loss ΔP_g	3.99	0.41	3.99	0.42	3.95	0.42
Heat rejected by condenser P_{cd}	455.96	46.59	452.90	47.97	441.76	46.63
Loss in piping between steam generator and turbine P_{cdab}	5.32	0.54	2.23	0.24	1.87	0.20
Loss in piping between HPH 7 and steam generator economizer P_{cdpc}	19.84	2.03	22.00	2.33	21.31	2.25
Loss through pressure drop for piping and valves, wall loss and leakage loss P_{div}	8.81	0.90	7.87	0.83	7.77	0.82
Unaccounted losses ΔP_{bil}	14.18	1.45	15.80	1.67	14.49	1.54
TOTAL ENERGY LOSS	**654.65**	**66.90**	**630.39**	**66.77**	**626.57**	**66.14**
TOTAL OUTPUT	**978.59**	**100.0**	**944.18**	**100.0**	**947.31**	**100.0**

Physical heat of makeup water is considered null, since for optimal operation full condensate recovery is assumed. Also loss through chemical incomplete combustion is null in optimal operation mode, but items are kept in Table 1 in order to compare with values for actual hourly balance. In order to properly compare actual hourly energy balance with optimal hourly energy balance, items in Table 2 and those in Table 3-5 must describe the same type of losses.

As seen in paper [7] some losses will not appear for optimal heat balance, and as a result for actual hourly heat balance, losses in piping between steam generator and turbine P_{cdab}, between HPH 7 and steam generator economizer P_{cdpc}, through pressure drop for piping and valves, wall and leakage loss P_{div},, are presented as a sum of their values and denoted with “Sum of losses P_{div}”. For the optimal hourly heat balance the same sum of losses will represent losses through: loss in piping ΔP_{cdt} and loss through pressure drop for piping and valves, wall loss and leakage loss P_{div}.

In Tables 3 to 5 comparisons between optimal load and actual loads were carried out highlighting the absolute growth in terms of values and percentage.

Negative values denote a reduction of values associated with referred items.

As seen in Table 3, some items e.g. “Physical heat of makeup water P_{aad}” are greater by 100%. Those values must be read rather as absolute values since for optimal operations values for these items are not present.

In Table 6 only absolute values of items found in Tables 3 to 5 are used.

Table 3. **Comparison of 70% load with optimal**

	Optimal	70% load	Growth	Percentage
INPUT	**kWh·t^{-1}**	**kWh·t^{-1}**	**kWh·t^{-1}**	**%**
Chemical heat of fuel Q_{cBi}	851,42	950,74	99,32	10,45%
Physical heat of fuel Q_B	7,65	7,73	0,08	0,98%
Physical heat of air Q_L	8,79	19,79	11,01	55,61%
Physical heat of makeup water P_{aad}	0,00	0,33	0,33	100,00%
TOTAL INPUT	**867,85**	**978,59**	**110,73**	**11,32%**
OUTPUT				
Output power P_g	331,23	314,33	-16,90	-5,38%
Energy of steam extracted for technological use P_{SRRD}	10,11	9,61	-0,50	-5,16%
TOTAL USEFUL	**341,34**	**323,94**	**-17,40**	**-5,37%**
Mechanical incomplete combustion Q_{cmec}	7,65	5,62	-2,03	-36,10%
Chemical incomplete combustion Q_{cga}	0,00	0,02	0,02	100,00%
Heat loss through flue gas Q_{gacos}	59,57	121,66	62,09	51,03%
Heat loss by bottom ash *Qsg*	14,72	8,57	-6,14	-71,67%
Wall loss Q_{per}	3,79	6,25	2,46	39,43%
Mechanical loss ΔP_m	16,51	4,43	-12,09	-273,02%
Generator loss ΔP_g	4,91	3,99	-0,91	-22,84%
Heat rejected by condenser P_{cd}	412,78	455,96	43,18	9,47%
Sum of losses P_{div}	17,08	33,96	16,88	49,70%
Unaccounted losses ΔP_{bil}	-10,49	14,17	24,66	174,02%
TOTAL ENERGY LOSS	**526,51**	**654,64**	**128,12**	**19,57%**
TOTAL OUTPUT	**867,85**	**978,58**	**110,73**	**11,31%**

Table 4. **Comparison of 85% load with optimal**

	Optimal	85% load	Growth	Percentage
INPUT	**kWh·t^{-1}**	**kWh·t^{-1}**	**kWh·t^{-1}**	**%**
Chemical heat of fuel Q_{cBi}	851,42	914,01	62,59	6,85%
Physical heat of fuel Q_B	7,65	8,24	0,59	7,16%
Physical heat of air Q_L	8,79	20,57	11,79	57,30%
Physical heat of makeup water P_{aad}	0,00	1,36	1,36	100,00%
TOTAL INPUT	**867,85**	**944,18**	**76,32**	**8,08%**
OUTPUT				
Output power P_g	331,23	305,14	-26,09	-8,55%
Energy of steam extracted for technological use P_{SRRD}	10,11	8,64	-1,47	-17,01%
TOTAL USEFUL	**341,34**	**313,79**	**-27,56**	**-8,78%**
Mechanical incomplete combustion Q_{cmec}	7,65	4,93	-2,72	-55,17%
Chemical incomplete combustion Q_{cga}	0,00	0,02	0,02	100,00%
Heat loss through flue gas Q_{gacos}	59,57	103,68	44,11	42,54%
Heat loss by bottom ash Q_{sg}	14,72	9,20	-5,52	-60,00%
Wall loss Q_{per}	3,79	4,09	0,31	7,53%

Mechanical loss ΔP_m	16,51	3,68	-12,84	-349,29%
Generator loss ΔP_g	4,91	3,99	-0,92	-22,97%
Heat rejected by condenser P_{cd}	412,78	452,90	40,12	8,86%
Sum of losses P_{div}	17,08	32,10	15,02	46,79%
Unaccounted losses ΔP_{bil}	-10,49	15,80	26,29	166,39%
TOTAL ENERGY LOSS	**526,51**	**630,39**	**103,88**	**16,48%**
TOTAL OUTPUT	**867,85**	**944,18**	**76,32**	**8,08%**

Table 5. **Comparison of 94% load with optimal**

	Optimal	94% load	Growth	Percentage
INPUT	**kWh·t^{-1}**	**kWh·t^{-1}**	**kWh·t^{-1}**	**%**
Chemical heat of fuel Q_{cBi}	851,42	923,47	72,05	7,80%
Physical heat of fuel Q_B	7,65	8,80	1,15	13,07%
Physical heat of air Q_L	8,79	14,15	5,36	37,91%
Physical heat of makeup water P_{aad}	0,00	0,89	0,89	100,00%
TOTAL INPUT	**867,85**	**947,31**	**79,45**	**8,39%**
OUTPUT				
Output power P_g	331,23	312,02	-19,21	-6,16%
Energy of steam extracted for technological use P_{SRRD}	10,11	8,72	-1,39	-15,96%
TOTAL USEFUL	**341,34**	**320,74**	**-20,60**	**-6,42%**
Mechanical incomplete combustion Q_{cmec}	7,65	5,22	-2,43	-46,50%
Chemical incomplete combustion Q_{cga}	0,00	0,02	0,02	100,00%
Heat loss through flue gas Q_{gacos}	59,57	110,38	50,81	46,03%
Heat loss by bottom ash Q_{sg}	14,72	11,20	-3,51	-31,38%
Wall loss Q_{per}	3,79	5,61	1,82	32,51%
Mechanical loss ΔP_m	16,51	3,00	-13,52	-450,89%
Generator loss ΔP_g	4,91	3,95	-0,96	-24,23%
Heat rejected by condenser P_{cd}	412,78	441,76	28,98	6,56%
Sum* of losses P_{div}	17,08	30,94	13,86	44,80%
Unaccounted losses ΔP_{bil}	-10,49	14,49	24,98	172,39%
TOTAL ENERGY LOSS	**526,51**	**626,57**	**100,06**	**15,97%**
TOTAL OUTPUT	**867,85**	**947,31**	**79,45**	**8,39%**

In Table 6 evaluation of economic impact for optimal operation of unit is presented. As normally, the energy gained by applying projected measures resulting from heat balance analysis must be equal with drop of losses achieved.

As can be seen in Table 6, for this case the statement above is true, so comparison of the items is the verification method of the calculations. This is why they were presented in two consecutive rows. Values are added on from top of table to the row “TOTAL ENERGY GAINED” and from the bottom of table for “TOTAL DROP OF LOSSES”.

“TOTAL ENERGY GAINED” represents inputs and “TOTAL DROP OF LOSSES” represents outputs.

Table 6. **Evaluation of economic impact for optimal operation of unit**

Effects	**94% - optimal load**			**85% - optimal load**			**70% - optimal load**		
	kWh·t^{-1}	toe·t^{-1} ×10^{-4}	€·t^{-1}	kWh·t^{-1}	toe·t^{-1} ×10^{-4}	€·t^{-1}	kWh·t^{-1}	toe·t^{-1} ×10^{-4}	€·t^{-1}
Reducing energy consumption through:									
Chemical heat of fuel Q_{cBi}	72,05	62	2,74	62,59	54	2,38	99,32	85	3,78
Physical heat of fuel Q_B	1,15	1	0,04	0,59	1	0,02	0,08	0	0,00
Physical heat of air Q_L	5,36	5	0,20	11,79	10	0,45	11,01	9	0,42
Physical heat of makeup water P_{aad}	0,89	1	0,03	1,36	1	0,05	0,33	0	0,01
TOTAL ENERGY GAINED	**79,45**	**0,007**	**3,03**	**76,32**	**0,007**	**2,91**	**110,73**	**0,010**	**4,22**
TOTAL DROP OF LOSSES	**79,45**	**0,007**	**3,03**	**76,32**	**0,007**	**2,91**	**110,73**	**0,010**	**4,22**
Growth of energy at:									
Generator terminals P_g	-19,21	-17	-0,73	-26,09	-22	-0,99	-16,90	-15	-0,64
Steam extracted for technological use P_{srrd}	-1,39	-1	-0,05	-1,47	-1	-0,06	-0,50	0	-0,02
Drop of losses:									
Mechanical incomplete combustion Q_{cmec}	-2,43	-2	-0,09	-2,72	-2	-0,10	-2,03	-2	-0,08
Chemical incomplete combustion Q_{cga}	0,02	0	0,00	0,02	0	0,00	0,02	0	0,00
Heat loss through flue gas Q_{gacos}	50,81	44	1,94	44,11	38	1,68	62,09	53	2,36
Heat loss by bottom ash Q_{sg}	-3,51	-3	-0,13	-5,52	-5	-0,21	-6,14	-5	-0,23
Wall loss Q_{per}	1,82	2	0,07	0,31	0	0,01	2,46	2	0,09
Mechanical loss ΔP_m	-13,52	-12	-0,51	-12,84	-11	-0,49	-12,09	-10	-0,46
Generator loss ΔP_g	-0,96	-1	-0,04	-0,92	-1	-0,03	-0,91	-1	-0,03
Heat rejected by condenser P_{cd}	28,98	25	1,10	40,12	35	1,53	43,18	37	1,64
Sum of losses P_{div}	13,86	12	0,53	15,02	13	0,57	16,88	15	0,64
Unaccounted losses ΔP_{bil}	24,98	21	0,95	26,29	23	1,00	24,66	21	0,94
ESTIMATED SAVINGS	**3,03 Eu · t^{-1} (steam)**			**2,91 Eu · t^{-1} (steam)**			**4,22 Eu · t^{-1} (steam)**		

As expected, minimum value of savings is achieved for 85% of load, where efficiency is maximal.

4. ANALYSIS OF THE OPPORTUNITY OF IMPLEMENTING COMBINED GAS - STEAM CYCLE

As known maxim Carnot efficiency of a thermodynamic cycle is:

$$\eta_c^{\max} = 1 - \frac{T_i}{T_s} \tag{1}$$

where T_s stands for the is the absolute temperature of the hot reservoir, while T_i is the absolute temperature of the cold reservoir.

Thermal efficiency for a real cycle is obviously smaller. This reduction compared to the maximum value given by equation (1) is caused mainly by:

- Energy losses according to the firs law of thermodynamics;
- Exergy losses according to the second law of thermodynamics;
- Cycle reaches higher temperature than T_i and lower temperature then T_s, as an effect of real cycles (Brayton, Hirn) in which, unlike Carnot cycle, the heat transfer is isobar and not isothermal.

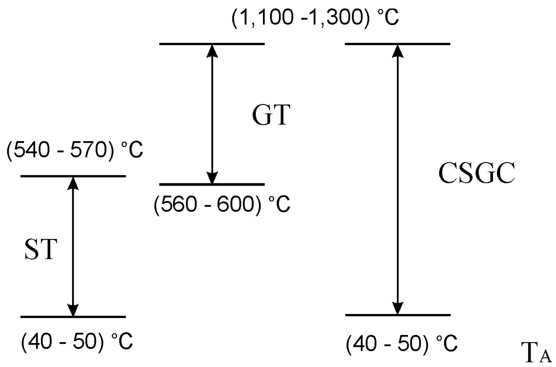

Fig. 1. Temperature range for thermodynamic work of steam turbine ST, gas turbine GT and combined gas-steam cycle CGSC

In Fig. 1 are shown common temperature ranges in which thermodynamic work for a steam turbine plant (ST), a gas turbine (GT) and a combined gas-steam cycle (CGSC) is produced.

For steam turbines thermodynamic work is produced at relatively low temperature. Though the hot reservoir temperature resulting from fuel oxidation can reach as high as (1800...2000) °C, steam temperatures are usually (540...570) °C. In contrast, the lower temperature of the cycle is very close to that of the environment.

For gas turbine cycle, work is produced starting from the temperature of the hot reservoir obtained from burning of fuel, but heat discharge at the cold reservoir is higher than the corresponding temperature of steam cycle, resulting in significant exergy losses.

From the discussion above we can draw three conclusions:

- GT works better in the high temperature range;
- ST works better in mid and low temperature range;
- Final temperature of gas cycle is close to the starting temperature of steam cycle.

As a result it is advantageous to design a two step thermodynamic cascade, which includes a gas cycle followed by a steam cycle.

Combined gas-steam cycle works between the higher cycle temperature of gas cycle and the lower cycle temperature of steam cycle. The result is a considerable increase of efficiency compared to simple Carnot cycle.

Based on temperature ranges represented in Fig. 1 maximum efficiency of corresponding Carnot cycles used for comparison, can be calculated:

$$\begin{aligned}
\eta_c^{\max}\Big|_{ST} &= 1-\frac{T_i}{T_s} = 0.393 \div 0.445 \\
\eta_c^{\max}\Big|_{GT} &= 1-\frac{T_i}{T_s} = 0.615 \div 0.617 \\
\eta_c^{\max}\Big|_{CC} &= 1-\frac{T_i}{T_s} = 0.772 \div 0.794
\end{aligned} \tag{2}$$

5. CONCLUSIONS

As shown above there are two retrofitting possibilities:

Option I: Assuring optimal operating parameters for the steam power plant by performing current repairs and maintenance. Estimated investment is 19,320,000 Euro for every unit. The desired effect is achieved through ensuring the operation at optimal balance parameters so that gross energy efficiency can reach 38.17 %, but considering in further calculus an efficiency of 34 % is a reasonable option.

Option II: From thermodynamic considerations above, operating a combined gas-steam cycle, can lead to an increase in efficiency of the Carnot cycle corresponding to combined gas-steam cycle compared to steam cycle with values from 15.7 to 17.7 %.

In order to develop the combined gas-steam cycle it is suggested to equip the unit with 2 gas turbines and a recovery boiler allowing the unit to start classically, using a steam turbine.

Gas turbines are of GE10-1 type produced by General Electric with power of 11.25 MW and gas consumption 3,616 $m^3{}_N \cdot h^{-1}$.

Analysis of equipment variants are presented in table x and calculation assumptions are:

- Lower heating values 34.851 $kJ \cdot m^{-3}{}_N$ for natural gas and 14.628 $kJ \cdot kg^{-1}$ for coal;

- Fuel price: 385 Eur for every 1,000 m^3_N natural gas gas and 56 $Eur \cdot t^{-1}$ of coal;
- Investment: 19.32 million Eur for the firs and 27.78 million Eur for second option.

The analysis does not highlight additional savings resulting from environmental taxes on emissions.

Table 7 .**Comparative analysis of economic indicators for steam turbine and combined gas-steam cycle**

INDICATOR	ST option	CGSC option	UM
Unit power output	200.0	222.5	MW
Operating time	5,767.0	5,767.0	$hours \cdot year^{-1}$
Energy output	1,153.0	1,283.0	$GWh \cdot year^{-1}$
Unit efficiency	34.0	40.0	%
Consumption	163,000.0	134,500.0	$toe \cdot year^{-1}$
Natural gas	14,270.0	34,720.0	$toe \cdot year^{-1}$
	17,150.0	41,710.0	$x10^3\ m^3_N \cdot year^{-1}$
Coal	148,700.0	99,750.0	$toe \cdot year^{-1}$
	425,500.0	285,400.0	$t \cdot year^{-1}$
Fuel costs:	30,430,000.0	32,040,000.0	$Eur \cdot year^{-1}$
- natural gas	6,601,000.0	16,060,000.0	$Eur \cdot year^{-1}$
- coal	23,830,000.0	15,980,000.0	$Eur \cdot year^{-1}$
Unit cost (fuel cost only)	26.383	24,971	$Eur \cdot MWh^{-1}$
Investment	19,320,000.0	27,780,000.0	Eur

Estimate calculations performed highlights the following:

- Unit cost is reduced by 1.412 $Eur \cdot MWh^{-1}$;
- The efficiency is increased by 6%;
- Payback of additional investment is about 5 years.

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