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Hot windbox repowering of coal-fired thermal power plants

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Abstract: The repowering of thermal power plants could be the fastest way to respond to the energy demand while decreasing the CO_2 emissions per kilowatt hour of energy generated. Hot windbox repowering of a thermal power plant was investigated in this study using Thermoflex simulations. The Soma A thermal power plant began operation in 1957 and was in service until 2010. In the current situation, the installed capacity of the power plant is 44 MW_{el}, with 2 units. The boiler was designed to operate with Soma lignite, with a lower heating value of 3550 kcal/kg. The current situation of one unit was simulated to determine the percentages of errors with respect to the design data. A fresh air dilution hot windbox repowering case was simulated and the results were compared. In the simulations, the rate of gas turbine power to the original installed power varied between 10% and 22%. According to the results, the net power was increased from 11% to 27%, and the CO_2 emissions per installed capacity were decreased by approximately 7% after repowering.

Key words: Hot windbox, repowering, CO_2 reduction, thermal power plant, combined cycle

1. Introduction

The energy demands of humans increase rapidly because of increasing population and industrialization. As a result, electricity consumption and greenhouse gas emissions due to power generation increase. In recent years, efficient use of energy, renewable energy research, and the risk of global warming due to fossil fuel combustion have been major research areas. Combined cycle power plants are the preferred power generation systems due to their efficient use of energy when compared to conventional single cycle power plants. However, old thermal power plants are still in operation with low net electric efficiencies. In Turkey, lignite is generally used for power generation in thermal power plants. The net electric efficiency of these power plants decreases with time due to aging and operational problems. Therefore, the repowering of these power plants can increase their energy efficiency and reduce their contribution to the global warming risk.

Repowering can be defined as increasing the installed capacity and the net electric efficiency and decreasing the emissions per installed capacity of an existing thermal power plant. Generally, a gas turbine is added to the cycle in thermal repowering applications. Feedwater heating, hot windbox, and parallel repowering are 3 of the most commonly implemented repowering options (Escosa and Romeo, 2009). In feedwater heating, steam turbine extraction points are repealed and heating of the feedwater is supplied from a heat recovery steam generator (HRSG) or a solar field (Popov, 2011). Aeroderivative-type gas turbines, with a capacity of 12%–30% of the existing power plant, give the optimum results for feedwater repowering applications.

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Hot windbox repowering can be applied using 3 methods. In the first one, the exhaust gas from a gas turbine is fed into the original boiler, and the O_2 content of the exhaust gas is generally enough to fire the coal particles. However, due to the high temperature of the exhaust gas, the burner section has to be upgraded with high-temperature–resistant materials (Figure 1). In the second method, the exhaust gas can be diluted by fresh air to decrease the temperature of the combustion gases and to increase the O_2 content of the gas stream (Figure 2). In the third option, an economizer is installed after the gas turbine and feedwater heating is obtained from the economizer (Figure 3).

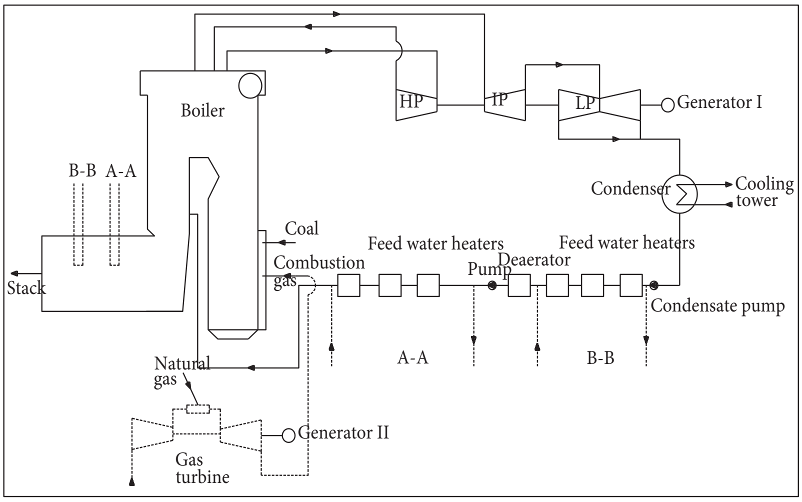

Figure 1. Direct hot windbox repowering.

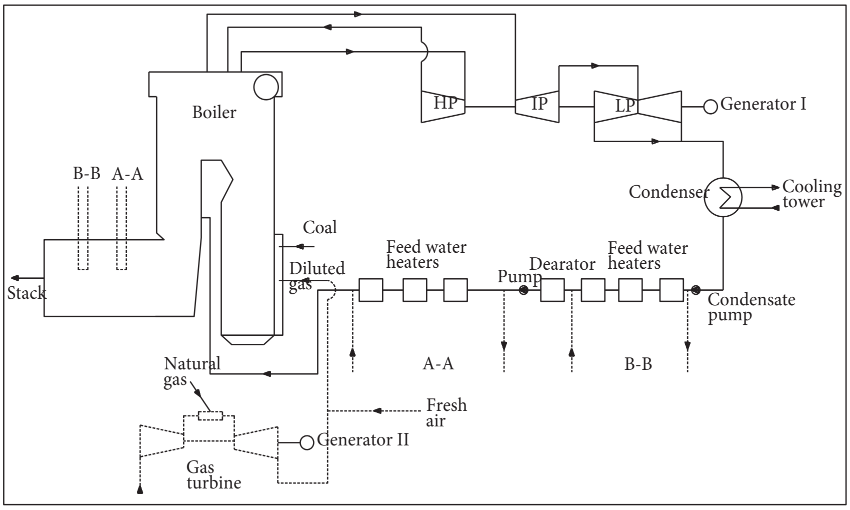

Figure 2. Fresh air dilution hot windbox repowering.

In parallel repowering, a gas turbine and a HRSG are installed and additional steam is fed into the steam turbines. A parallel repowering application with additional gas turbine stacking brings flexibility to the power plant's operation (Yılmazoğlu and Durmaz, 2011). In all of the applications, the capacity is increased with a properly selected gas turbine and HRSG combination (El Masri, 2008; Carapellucci, 2009).

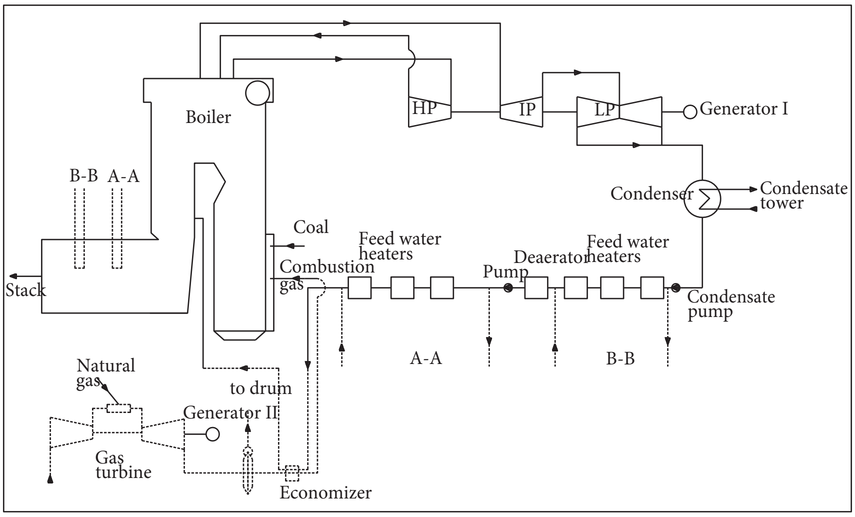

Figure 3. Precooling hot windbox application.

In thermal power plants, repowering reduces the CO_2 emissions per installed capacity (Shenk and Ehren, 2003; Walters, 2008). The most important parameter in repowering applications is the expected life of the equipment. Therefore, a detailed life expectancy analysis has to be carried out before repowering. Moreover, gas turbine and HRSG selection is crucial for the operation of a thermal power plant after repowering (D'Yakov et al., 1998; Mathieu 1998).

For the repowering analysis, gas turbine leverage and repowering efficiency are decisive parameters. Repowering efficiency can be defined as the rate of increment in the electricity generation to the increment in the heat added to the cycle, given in Eq. (1). The subscripts ar and br symbolize after repowering and before repowering, respectively. After repowering, the electricity generation is increased due to the gas turbine. Furthermore, the natural gas consumption and, as a result, the heat added to the cycle, are increased. Gas turbine leverage can be defined as the rate of increment in the electricity generation to the gas turbine installed capacity, given in Eq. (2). In a typical combine cycle power plant with an installed capacity of 400 MW_{el}, approximately 67% of the electricity generation capacity is supplied from the gas turbine. However, in the case of repowering, it is approximately 10%–25%, and this results in a smaller gas turbine selection. Moreover, this result is directly related to the first investment cost of the power plant.

$$\eta_{rep} = \frac{\Delta P_{el}}{\Delta Q_g} = \frac{P_{ar} - P_{br}}{Q_{inar} - Q_{inbr}} \tag{1}$$

$$\lambda_{GT} = \frac{\Delta P_{el}}{P_{el,GT}} = \frac{P_{ar} - P_{br}}{P_{el,GT}} \tag{2}$$

In Table 1, the date of the first operation, installed capacity, number of units, fuel type, and lower heating value (LHV)-higher heating value (HHV) of the fuel of thermal power plants in Turkey are given. Lignite is the main fuel source in electricity generation in Turkey and low-rank lignite is generally used for power generation. Most of the thermal power plants were first operated in the mid-1980s. Therefore, the net electric efficiency and availabilities of these power plants have decreased with time due to the ageing of the equipment. All of these can be repowered by gas turbines after a detailed performance analysis of the equipment.

In this study, the Soma A thermal power plant was examined and the application of hot windbox repowering of the thermal power plant was investigated using commercial Thermoflex software. The Soma

A thermal power plant was decommissioned in 2010. Currently, the installed capacity of the power plant is 44 MW_{el}, with 2 units. The current configuration, along with fresh air dilution hot windbox repowering cases with different gas turbine power rates, was simulated. In the simulations, the rate of gas turbine power to the original installed power varied from 10% to 22%. This means that the gas turbine selection range is between 2 and 4.4 MW_{el} for each 22 MW_{el} unit. Apart from the literature, real power plant data are simulated to show the benefits of a repowering application.

Table 1. General characteristics of thermal power plants in Turkey.

Name	Place	Year of first operation	Installed capacity (MW)	Number of units	Fuel type	Fuel LHV-HHV (kcal/kg)
18 Mart Çan	Çan/Çanakkale	2003	320	2	Lignite	2340–2860
Afşin Elbistan A	Afşin/Kahramanmaraş	1984	1355	4	Lignite	900–1600
Afşin Elbistan B	Afşin/Kahramanmaraş	2004	1440	4	Lignite	950–1500
Aliağa	Aliağa/İzmir	1975	180	6	Diesel	10,300–12,000
AmbarlıNG	Ambarlı/İstanbul	1988	1350	9	Natural gas	8500–9155
AmbarlıFuel oil	Avcılar/İstanbul	1967	630	5	Fuel oil	9580–10,150
Bursa NG	Osmangazi/Bursa	1998	1432	6	Natural gas	8100–10,427
Çatalağzı	Çatalağzı/Zonguldak	1989	300	2	Hard coal	3200–3500
Hamitabat	Lüleburgaz/Kırklareli	1985	1120	12	Natural gas	8060–8980
Hopa	Hopa/Artvin	1973	50	2	Fuel oil	9600–10,157
Kangal	Kangal/Sivas	1991	457	3	Lignite	1300–1430
Orhaneli	Orhaneli/Bursa	1992	210	1	Lignite	2350–3850
Seyitömer	Seyitömer/Kütahya	1973	600	4	Lignite	1500–2000
Soma A	Soma/Manisa	1957	44	2	Lignite	3050–3200
Soma B	Soma/Manisa	1981	1034	8	Lignite	2400–2640
Tunçbilek	Tunçbilek/Kütahya	1956-1966-1978	365	2-1-2	Lignite	2600–3000
Kemerköy	Gökova/Muğla	1995	630	3	Lignite	2100–2400
Yatağan	Yatağan/Muğla	1983	630	3	Lignite	2100–2400
Yeniköy	Muğla	1987	420	2	Lignite	2100–2400
Çayırhan	Ankara	1988-2000	660	2-2	Lignite	2700–2950

*Data were taken from the Elektrik Üretim A.Ş. (Electricity Generation Company).

2. Current situation and hot windbox applications

The Soma A thermal power plant was designed according to the given data in Table 2, in 1957. The power plant was operated at constant maximum load, operation condition 4. In this step of this study, the Soma A thermal power plant was simulated and the results were compared to real plant data, given in Table 3.

According to the results of the simulations, an acceptable percent error was found. The highest percent error was calculated in the net electric efficiency. The net electric efficiency is the rate of net power generated and the heat input to the cycle. In the case of net electricity generation, the percent error was 0.56%. As a result, the heat input is the dominant factor for the net electric efficiency percent error. There are many parameters that affect heat input, such as the temperature of the air, moisture content, and the temperature of coal particles.

In the second step, the offered system structure is simulated with fresh air dilution. Hot windbox repowering can be implemented in 3 different ways. In the first option, the exhaust gas of the gas turbine is fed into the burners, as shown in Figure 1. In this option, feedwater heating is supplied by 2 economizers that are installed after the boiler. In direct hot windbox application, burners and other related equipment have to be modified due to the high temperatures of the exhaust gases from the gas turbine. As a result, the first investment cost of repowering increases. Moreover, due to the low O_2 content (13%–14%) in the exhaust gases from the gas turbine, combustion problems can emerge in the steam boiler. Therefore, fresh air dilution is a necessity to lower the investment cost and prevent combustion problems. The fresh air dilution application is shown in Figure 2. In this option, fresh air is added to combustion gases to increase the O_2 content and to decrease the burner inlet temperature.

Table 2. Design data of the Soma A thermal power plant.

Operation conditions*	**1**	**2**	**3**	**4**	**5**
Turbine power (MW)	7	12	17	22	NA
Water/steam pressures (bar)					
Inlet of the economizer	62	62.6	65.7	70	72
Outlet of the dome	59.6	61.5	64	68	69.8
Outlet of the superheater	59.4	60.7	62.4	65	66.2
Temperatures (°C)					
Steam temperature at the outlet of the superheater	489.7	487.7	487	486.5	486.4
Water temperature at the inlet of the economizer	139	165	180	192	196
Water temperature at the outlet of the economizer	197	216	230	242	245
Gas temperature at the inlet of the superheater	826	872	922	980	1000
Gas temperature at the outlet of the economizer	239	261	278	296	302
Air temperature at the outlet of the air preheater	206.5	213	222.5	226.5	228
Stack temperature	129	142	152	160	162.5
Mass flow rates (t/h)					
Fuel	6.96	11.4	15.6	20.3	22
Combustion gas	60.6	93.3	121.4	150.8	161.5
Steam mass flow rate	30	51	72	96	105

*Operation conditions: 1, technical minimum; 2, constant minimum load; 3, normal load; 4, constant maximum load; 5, transient maximum load.

Table 3. Comparison of the design data with simulation results.

	Design data	Simulation results	Error (%)
Net power of 1 unit (MW)	22	21.877	–0.56
Net electric efficiency (%)	30	31.7	5.6
Stack temperature (°C)	160	157.82	–1.36
Air temperature outlet of the air preheater (°C)	226.5	226	–0.22
Combustion gas mass flow rate (t/h)	150.8	146.84	–2.63
Fuel consumption (t/h)	20.3	20.75	2.2

In the third option, a precooling system is adapted after the gas turbine, as shown in Figure 3. The temperature of the combustion gases is reduced to an acceptable range. However, the first investment cost of the precooling system is higher than that of the fresh air dilution application. Therefore, the fresh air dilution system is chosen as the base case for the simulations.

3. Results

In the simulations, the effects of different gas turbine power ratios were investigated. The gas turbine power ratio can be defined as the ratio of the selected gas turbine installed power to the currently installed power, 22 MW_{el}. The mass flow rates of the steam turbine and the condenser increased after repowering. The limit of this increment, due to the repealing of the bled steam, can be taken as 20% for design considerations. Therefore, the gas turbine selection is directly related to the rate of increase in the condenser or the steam turbine mass flow rate. The effects of different gas turbine power ratios to the repowered thermal power plant performance are shown in Figure 4. According to the results, the maximum mass flow rate was obtained with 22% of the gas turbine power, where the gas turbine installed power was 4.44 MW_{el} at site conditions. The natural gas consumption of the gas turbine was 0.338 kg/s. The net electrical efficiency and the net heat rate remained nearly constant. However, the installed capacity of the thermal power plant was 29.192 MW_{el} after repowering. The variation of the repowering efficiency and gas turbine leverage for different gas turbine power rates are shown in Figure 5.

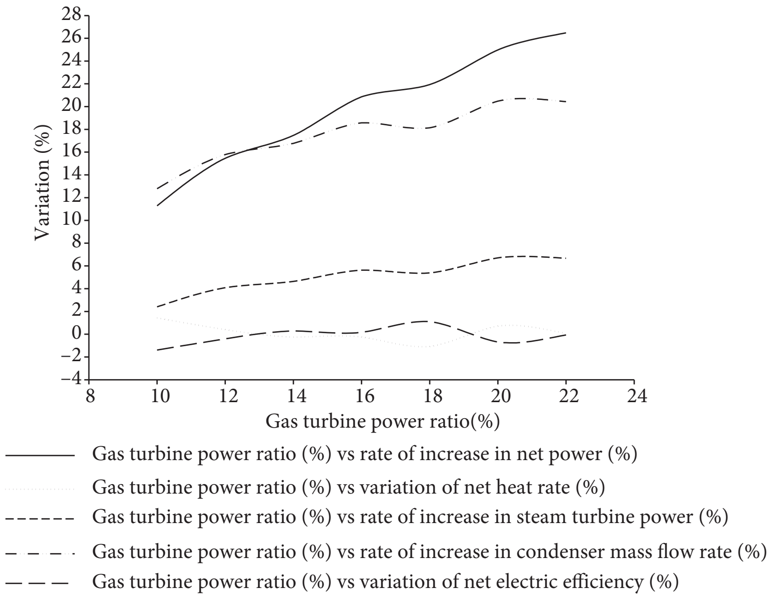

Figure 4. The effects of different gas turbine power rates on the repowered thermal power plant performance.

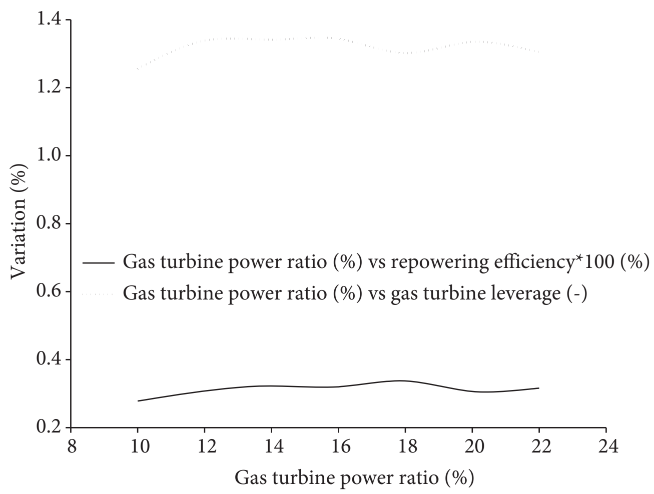

Figure 5. The variation of repowering efficiency and gas turbine leverage.

According to the results, the repowering efficiency and gas turbine leverage were 31.6% and 1.31, respectively, for a 22% gas turbine power rate. In a single gas turbine power plant, the gas turbine leverage is 1, and in a combined cycle power plant, it is generally 1.5. The results show that a power increment was achieved using less gas turbine installed power than a conventional gas/steam installed power ratio in a combined cycle. Gas turbine leverage can be approximately found with a 4.4 MW_{el} gas turbine instead of a gas turbine with an installed capacity of 44 MW_{el}.

The results of hot windbox repowering with respect to CO_2 emissions and fuel consumption are shown in Figure 6. The total CO_2 emissions of the power plant increased. However, CO_2 emissions per MW_{el} of installed capacity decreased when compared to the design data CO_2 emissions. As a result, it is possible to increase the installed capacity with decreasing CO_2 emissions by the repowering of thermal power plants. Most of the CO_2 emissions believed to contribute to global warming originate from combustion, especially combustion for the purpose of electricity generation. Therefore, countries can meet the CO_2 reduction regulations by repowering thermal power plants in the short term. In the long term, other energy conversion systems such as gasification technologies, renewable energy integrated thermal power plants, or directly renewable sources have to be developed.

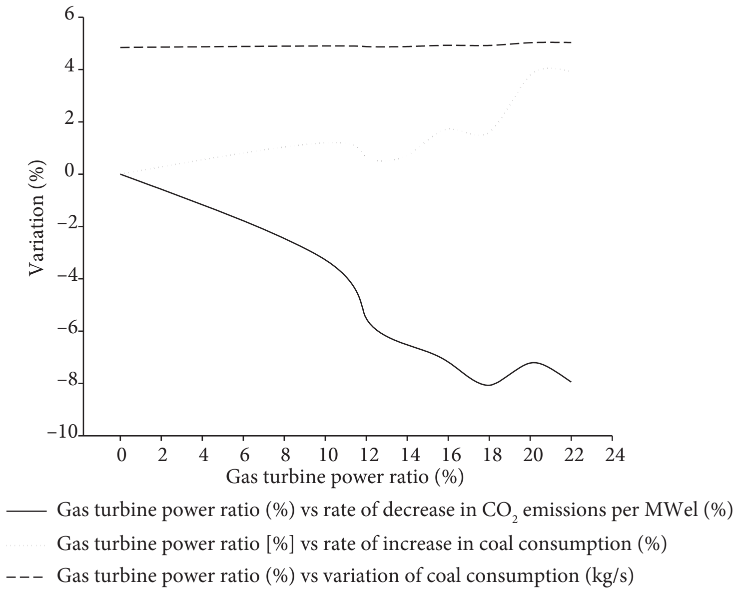

Figure 6. The variation of CO_2 emissions and fuel consumption.

The results of the economic analysis of repowering the Soma A thermal power plant by hot windbox application are shown in Figure 7. The payback time can be defined as the ratio of the initial investment cost of the project to the annual benefit of the implementation. The payback time ignores the time value of the currency. However, it is a useful tool for deciding the implementation of a project. In Figure 7, the variation of the payback time with different gas turbine power ratios is shown. In the calculations, the cost of the gas turbine, economizers, piping, and engineering expenses are taken as the initial investment cost of the repowering project. The annual operating time of the thermal power plant is taken as 6000 h. The unit electricity selling price and the unit natural gas buying price are taken as 0.119 US$/kWh and 0.281 $/m^3, respectively. The payback time decreases with an increasing gas turbine power ratio. With a 22% gas turbine power ratio, the payback time is 1.58 years.

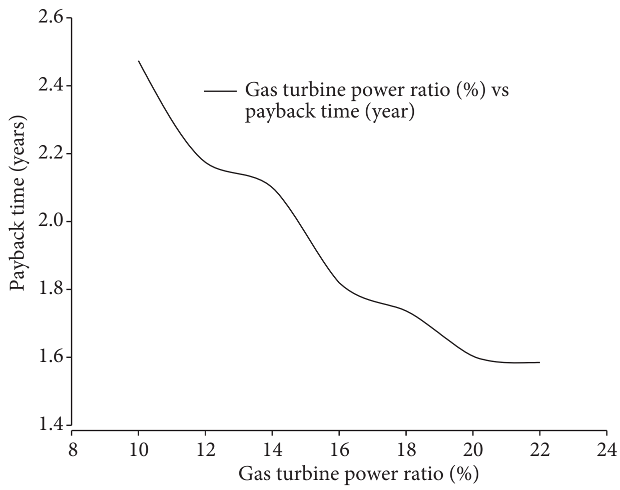

Figure 7. The variation of payback time with different gas turbine power ratios.

4. Conclusions

In this study, technoeconomic analysis of hot windbox repowering of the Soma A thermal power plant with different gas turbine power ratios is investigated. Fresh air dilution hot windbox repowering is selected due to the low initial investment cost and fewer operational problems than other alternatives. According to the results, the installed capacity of the Soma A thermal power plant increased from 22 MW_{el} to 29 MW_{el} with the selection of a 4.4 MW_{el} gas turbine. Furthermore, the CO_2 emissions per MW_{el} of electricity generated decreased by 8% with a 22% gas turbine power rate. Therefore, it is possible to decrease the CO_2 emissions while the installed capacity of the power plant is increased. Economic analysis results show that the payback time for the fresh air diluted hot windbox repowering application is 1.58 years at a 22% gas turbine power rate. In brief, fresh air diluted hot windbox repowering of the Soma A thermal power plant is necessary to avoid the deactivation of this thermal power plant. As a general result, the repowering of thermal power plants increases the installed capacity and decreases the CO_2 emissions without the need for installing new thermal power plants.

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