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Repowering strategies: Analysis of gas turbine integration with steam cycle for enhanced power plant performance

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Abstract

In this paper, various repowering methods commonly employed in practice today are discussed. A particular emphasis is put on the hot wind-box repowering method, which is examined in greater detail. This method stands out for its simpler solution and lower investment costs compared to other repowering methods. Most research and analyses on repowering, taking into account the ecological problems and the possibilities of repowering existing old steam cycle power plants, have focused on the effect of repowering on thermodynamic parameters and emission reduction. However, there are still many important questions that remain open and unexplored when it comes to analyze the selection of the right technology of the repowering and the right gas turbine for such a combined cycle power plant. For that purpose, based on the oxygen fraction in the gas turbine exhaust gases, nine different gas turbine models were tested for a 200 MW steam cycle power plant model. Calculations were carried out using the GateCycle modelling program. As a result of investigations, a GE Energy Oil & Gas MS9001E SC (GTW 2009 – with 123 MW power) gas turbine was selected as the best one for such a combination, in which case the increase of total net power output by 97.69% and the improvement of efficiency by 6.67% were registered, compared to the results before repowering, while carbon dioxide emissions were decreased by 0.29% per megawatt electrical power generated. The conducted research underscores the importance of selecting the right gas turbine for such a gas-steam system.

Keywords: Modeling of thermodynamic properties; Repowering; Gas turbine; Gas-steam system

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1. Introduction

Due to the challenging circumstances prevalent in today's world, particularly marked by a significant increase in global electricity consumption in developing countries, driven by population growth and industrialization, as well as the continued reliance on fossil fuels leading to environmental pollution, global warming, and the depletion of non-renewable resources, coupled with the substantial presence of outdated steam cycle power plants worldwide, there is a pressing need to analyse methods for enhancing the power generation efficiency using fossil fuels and reducing pollutant emissions from such power plants.

Nomenclature

$\mathrm{GT}_{power\ ratio}$ – gas turbine power ratio, %
N_{GT} – gas turbine power, MW
$N_{SCPP\ BR}$ – steam cycle power output before repowering, MW
P_{AR} – power output of combined cycle power plant after repowering, MW
P_{BR} – power output of steam cycle power plant before repowering, MW
P_{el} – combined cycle power output, MW
$P_{el\ GT}$ – gas turbine power output, MW
$Q_{in\ AR}$ – heat supplied to the cycle after repowering, MW
$Q_{in\ BR}$ – heat supplied to the cycle before repowering, MW

Greek symbols

η_{RP} – repowering efficiency, %
λ_{GT} – gas turbine leverage

According to the International Energy Agency (IEA), worldwide electricity consumption has approximately doubled since 1990, rising from 11 000 TWh to 28 000 TWh in 2022. Worldwide carbon dioxide (CO_2) emissions from human activity have increased from insignificant levels two centuries ago to annual emissions of more than 36.8 billion metric tons today (2022) with nearly 45% from coal use – mainly for power generation [1]. In Poland's energy infrastructure, coal-fired steam power plant blocks remain the dominant energy sources. And because there is significant international pressure to move away from coal-based electricity generation the share of renewable sources in the primary energy mix of the power industry is growing rapidly, especially those characterized by dynamic changes in generation capacity.

According to data published on the website of Poland's Electric Energy Distribution Network (Polskie Sieci Elektroenergetyczne), in 2022, the total share of energy generated by wind and photovoltaic farms reached an average annual level of 16.4% of national consumption. The maximum average hourly power of these sources reached 10 610 MW, while the minimum was 33.7 MW. Such significant variability in renewable energy generation underscores the need for compensating the workload with controllable sources in the energy industry. Moreover, coal-fired units have limited flexibility in load changes, whereas installations equipped with gas turbines perform much better in this regard.

Besides that, many existing thermal power plants around the world, especially in the EU, have to face their advanced age and deteriorated efficiency [2] both due to legislation [3] and rising carbon prices [4,5]. Although one of the radical and quick solutions is the rapid shutdown of coal-fired power plants, such an option is associated with huge costs [6]. In contrast to such a solution, rehabilitation and repowering of the existing units to prolong their service, increase their efficiency and reduce pollutant emissions seems more feasible [7,8]. In that case, there is a growing focus on building gas-steam systems, meaning that one of the most suitable solving methods is repowering which could improve the above presented situation and decrease the emissions and fossil fuel consumption. For example, in this context, Poland is investing in new units of this category, while also considering the repowering of existing units, which can be a slightly cheaper alternative to building new installations.

So, in general, repowering could be defined as the process of adding or replacing existing power plant equipment while retaining permitted serviceable components. This aims to enhance generation economics [9], extend equipment lifespan [10], improve environmental performance [11,12], enhance operability and maintainability [13,14], and optimize the utilization of existing sites, as mentioned above [15].

Repowering is ideal for plants in which the steam turbine, after many years of operation, still has a considerable service life expectancy, but the boilers are ready for replacement. The boilers are normally replaced or supplemented with gas turbines and heat recovery steam generators (HRSGs). Steam turbine units in older power stations generally can easily be adapted for use in a combined cycle. Repowering to a combined cycle can improve the efficiency of an existing plant to a level relatively close to that of new combined-cycle plants [16]. In this direction, the power production sector and the associated renovation activities receive a lot of attention both from governments and researchers [17,18].

2. Repowering concepts

In practice, four basic concepts of repowering steam power plant blocks into a gas-steam system are implemented: complete repowering (CR), repowering with feed water heating (FWHR – feed water heating repowering), 'hot wind-box' repowering (HWBR – hot wind-box repowering) and installation of a supplementary boiler (SBR – supplementary boiler repowering).

The first concept is sometimes used in the case of old steam units at the end of their service life. Complete repowering means replacing the boiler with a combination of one or more gas turbines (GT) and a heat recovery steam generator. Typically, repowering projects also include the modification of the steam turbine set by adapting its production capabilities to the efficiency and configuration (including multi-pressure configuration) of the recovery boiler and the modernization of instrumentation and control equipment. It is also possible to use the method of post-combustion after heat recovery steam generator (maximum supplementary firing). This method of repowering (without post-combustion) is currently being considered for 200 MW class units at the Kozienice Power Plant. The first gas turbine unit for power generation installed in Poland in the year 1999 was implemented in such a kind of repowering.

The second concept was often used in the past when superstructures of steam units were used to adapt them to cover peak loads. This solution, also known as a parallel system, involves adding a gas turbine to an existing steam unit. The coupling takes place on the side of the steam regeneration system, where the exhaust gases leaving the gas turbine are directed to heat the feed water [19,20]. This method was considered from the balance side in [19] for the superstructure of an 800 MW class lignite-fired unit at the Bełchatów Power Plant.

In the ‘hot wind-box’ system, exhaust gases from the gas turbine are directed instead of combustion air in the existing boiler. This method of coupling is also known as a system with exhaust gases discharged into the boiler or a series system. Its use requires modification of the boiler’s heating surfaces due to the introduction of hot, but still oxygen-rich exhaust gases from the gas turbine instead of the fresh air from the surroundings. This type of modification of the national 200 MW class block was the subject of consideration in [21,22].

In comparison to simple combined-cycle installations, hot wind-box repowering has some advantages and disadvantages. As an advantage, it should be noted that in this variant of solution, a different type of fuel can be burned in the steam generator, also this type of plant has a very high efficiency in part-loads. At the same time, these units have lower efficiency in nominal loads, higher investment costs and more complex installations, and are more difficult to operate and maintain, especially if the steam generator is solid fuel fired [23].

In the last of the indicated concepts, we are dealing with the addition of a gas turbine to an existing steam power plant block, where a heat recovery steam generator powered by exhaust gases from this turbine constitutes an additional source of steam for the steam part. In this system, the waste heat steam generator is a source of additional steam under peak load conditions, and it is possible to supply it to the steam turbine at more than one pressure level [24].

The methods of connecting the steam and gas parts corresponding to the discussed repowering concepts are presented in a simplified manner according to [31] in Fig. 1. More details about the above mentioned methods were presented in the following works [19,21,25].

In Table 1, there are shown general characteristics of power plants after repowering using three different methods [26–31]. It is obvious from the table that the highest capacity and efficiency are available in the complete repowering method (CR). But in hot wind-box repowering (HWBR) and feed water heating repowering (FWHR) methods, the improvement of characteristics is almost similar.

In general, higher thermodynamic characteristics can be achieved in the complete repowering method without maximum supplementary firing (without post-combustion) compared to the method with maximum supplementary firing. However, as shown in the book by Badyda and Miller [20] (Fig. 11.21 in that book), this fact does not apply to all cases. At temperatures at the gas turbine inlet not higher than about 1100°C and at temperatures at the boiler inlet not higher than about 700°C, the opposite situation is observed, i.e. maximum supplementary firing (post-combustion) leads to improvement of the thermodynamic parameters of gas-steam combined cycle.

Repowering may lead to the conversion of the fuel used, for example from coal to natural gas, or a dual-fuel system (for example gas and coal in a modified installation). Due to fuel availability limits and the current situation in the energy market, electrical energy consumption and environmental limitations, in developed countries, especially in Europe, the main emphasis is on the efficiency of the system. The mentioned fuel conversion from coal to natural gas can be helpful for the reduction of unitary CO_2 emissions. Complete repowering and repowering with feed water heating are the most frequently chosen concepts.

In developing countries, post-Soviet countries, and the Middle East, including Iran, where there are huge reserves of natural gas and at the same time there are very weak environmental restrictions, the main emphasis is on capacity – increasing the available power. Existing installations are usually modified while minimizing investment costs. The most frequently chosen concepts in these regions are hot wind-box repowering and complete repowering with supplementary firing. On the other hand, in developed countries, especially in Europe, due to fuel availability limits and the current situation in the energy market, electrical energy consumption and environmental limitations, the main emphasis is on the efficiency of the system. Complete repowering and repowering with feed water heating are the most frequently chosen concepts [25].

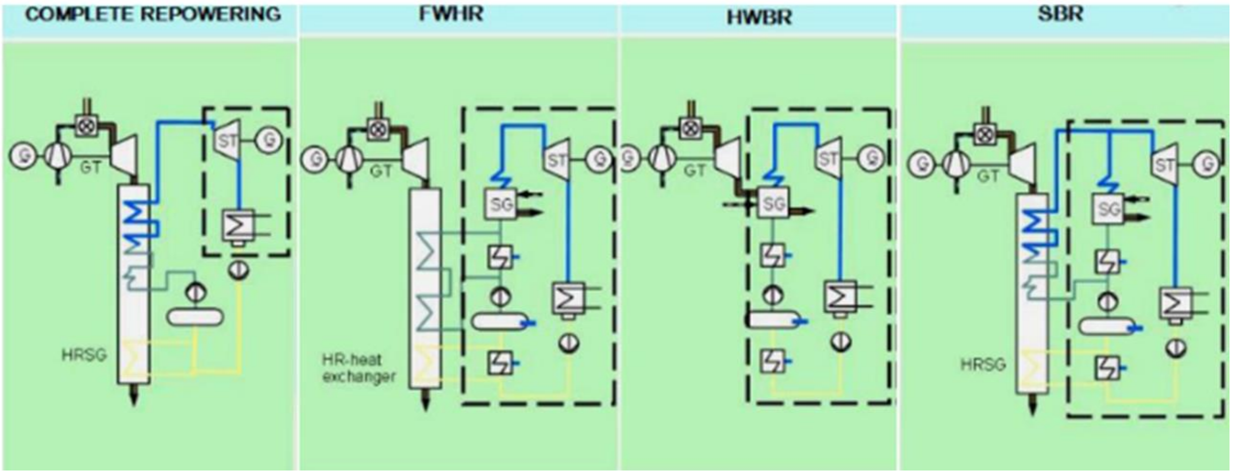

Fig. 1. Simplified diagrams of the repowering concept: G – generator, GT – gas turbine, HRSG – heat recovery steam generator, SG – steam generator, ST – steam turbine.

Table 1. Repowering options specifications [26–31].

	CR	FWHR	HWBR
Capacity increase (%)	160–200	10–30	15–30
Efficiency improvement (%)	Up to 12	2–5	3–6
NO_x decrease (%)	50–80	10–20	50–80
Limitation factor (s)	Existing condenser and steam turbine (s)	Steam turbine (s)	Existing boiler
Special advantage	Heat rate improvement up to 30–40%	Heat rate improvement 5–10%	Heat rate improvement up to 10–15%
Outage time	12–18	2	8
Gas turbine capacity	160-200% of existing steam turbine capacity	Up to 20% of existing steam turbine capacity	Up to 30% of existing steam turbine capacity

3. Analysis of thermodynamic parameters and performance on the example of the hot wind-box system

In general, the complex of analyses involved in preparing the repowering project includes a variety of technical, financial and environmental aspects, taking into account local conditions. In the initial stage of evaluating a repowering project for a generation system, the process involves determining the system's goals, encompassing factors such as assessing additional power consumption, setting targets for emission reductions, analyzing fuel availability and associated costs, evaluating transmission requirements and constraints, forecasting generation load schedules, establishing target electricity market prices and addressing other pertinent requirements and goals. Then, the existing plant is evaluated, which can be repowered to meet the above mentioned generation goals. The next step is to identify a repowering technology. If hot wind-box repowering has been selected as the main technology of a repowering project, then the right gas turbine should be selected for the existing plant. However, a critical prerequisite in selecting a gas turbine is ensuring that the oxygen content in the exhaust gases matches the required oxygen content for combustion in the existing boiler. This match should not limit the nominal load of the boiler, thus preventing the loss of its existing capacity. This alignment helps avoid additional costs associated with supplying fresh air to the boiler. It's important to note that this condition applies only if the chosen gas turbine fits within the targeted capacity limits of the steam-gas combined system intended for repowering.

In recent years, the majority of research and studies on repowering, considering ecological concerns and the repowering potential of existing old steam cycle power plants, have primarily concentrated on thermodynamic analyses and emission reduction strategies. Nevertheless, numerous significant questions remain open and unresolved, particularly regarding the selection of the most suitable repowering technologies and gas turbines for combined cycle power plants. For this purpose, the paper investigates the hot wind-box repowering method using a 200 MW steam cycle power plant as an example, with a particular emphasis on selecting the most suitable gas turbines for integration into this plant.

The commercial GateCycle software was chosen as the calculation tool, enabling the selection of system parameters using libraries containing the characteristics of gas turbines and analysis of the cooperation of the gas and steam parts in nominal conditions and in part loads (off-design). Therefore, based on the fraction of oxygen within gas turbine exhaust gases, a pool of possible gas turbine models was considered, for which the direct use of the exhaust gases leaving them in the steam boiler was assumed (without diluting the exhaust gases with additional fresh air), alternatively with their dilution with fresh air.

The subject of analyses was 9 models of gas turbines, of which the variant with dilution of exhaust gases with fresh air was adopted for five of them. This version assumes that the gas turbine exhaust gases can be diluted with fresh air to lower the exhaust gas temperature and increase the oxygen (O_2) content in the gas stream. For other gas turbine models, the oxygen content in the exhaust gases is sufficient for supplementary firing (post-combustion) in the boiler. The analysed turbines are listed below (the selected gas turbines are marked A to I in Figs. 3–5 and in Table 2):

1. Centrax Gas Turbine Trent 60 DLE SC (GTW 2009) – A,
2. Alstom GT8C2 50Hz SC (GTW 2009) – B,
3. Hitachi PG6101(FA) SC (GTW 2009) – C,
4. Ansaldo Energia V64.3A SC (GTW 2009) – D,
5. GE Energy Heavy Duty PG7121 (EA) SC (GTW 2009) – E,
6. Westinghouse 401 (97 GT World) – F,
7. Siemens V84.2-98 Vendor Data – G,
8. Mitsubishi M501DA SC (GTW 2009) – H,
9. GE Energy Oil&Gas MS9001E SC (GTW 2009) – I.

Ambient parameters for all models of gas turbines are the same, the inlet pressure and temperature are 1.0132 bar and 15°C, respectively, in a 60% relative humidity. The fuel used here is 100% methane with a 50 000 kJ/kg lower heating value (LHV).

In Table 2, the performance parameters of these gas turbines are shown, where: N_{el} – net electrical power, E_{ff} – gas turbine efficiency, CPR – compressor pressure ratio, COT – combustor outlet temperature, G_{exh} – mass flow of exhaust gases after turbine, TAT – temperature of exhaust gases after turbine, O_2 $m.fr.$ – oxygen mole fraction in exhaust gases.

The model diagram of the analyzed system illustrated in the GateCycle user interface is shown in Fig. 2.

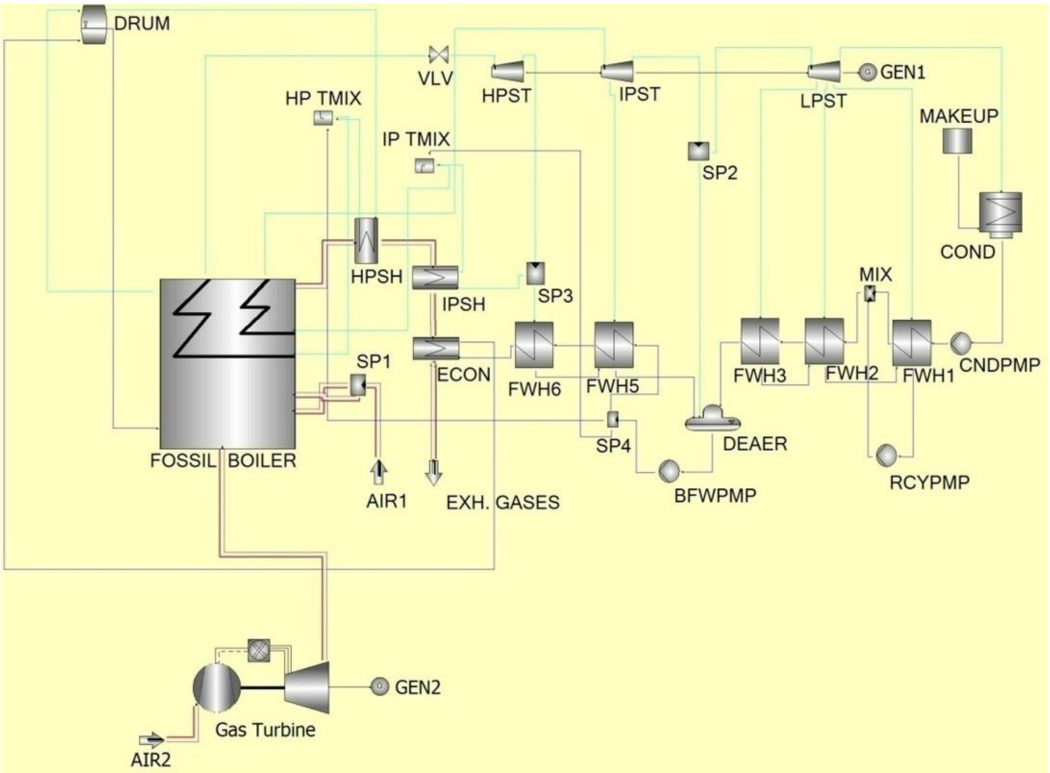

Fig. 2. The analysed model diagram of the considered 200 MW class unit after repowering with a gas turbine: HPST – high pressure steam turbine, IPST – intermediate pressure steam turbine, LPST – low pressure steam turbine, COND – condenser, CNDPMP – condensate pump, RCYPMP – recirculation pump, MIX1–3 – mixers No. 1–3, FWH1–6 – feed water heaters No. 1–6, DEAER – deaerator, BFWPMP – boiler feed water pump, SP1–4 – splitters No. 1–4, ECON – economizer, HPSH – high pressure super heater, IPSH – intermediate pressure super heater, HP TMIX – temperature control mixer in high pressure part, IP TMIX – temperature control mixer in intermediate pressure part, GEN1 – steam turbine generator, GEN2 – gas turbine generator, AIR – ambient air, EXH. GASES – exhaust gases.

Table 2. Performance parameters for gas turbines.

GT	N_{el}	E_{ff}	CPR	COT	G_{exh}	TAT	O_2 m.fr.
	MW	%	–	ºC	kg/s	ºC	%
A	50.5	38.7	35.9	1321.6	150.4	447.3	14.4
B	55.1	33.4	17.5	1211.3	195.4	511.4	14.1
C	69.9	34.1	14.9	1322.3	205.2	593.7	12.9
D	75.5	35.5	17.0	1352.7	211.6	590.1	12.9
E	82.8	32.1	12.6	1190.2	296.7	541.5	13.9
F	89.6	37.8	19.0	1366.7	227.2	582.3	12.6
G	107.7	33.6	10.9	1176.1	357.7	550.6	13.7
H	113.5	34.8	13.9	1249.5	345.6	543.6	13.3
I	122.9	33.2	12.5	1210.9	413.9	547.2	13.7

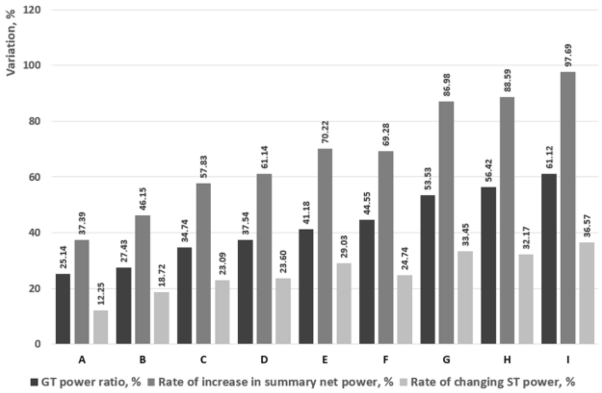

Fig. 3. Variation of GT power ratio, rate of increase of ST and CCPP power after repowering.

Figure 3 shows values of gas turbine (GT) power ratio (%), rate of increase in steam turbine (ST) power (%) and increase in summary net power of the combined cycle power plant (CCPP) (%) after repowering for nine different gas turbine models.

The gas turbine power ratio can be defined as the power value of the added gas turbine for repowering to the power value of the existed steam cycle power plant before repowering:

$$\mathrm{GT}_{\text{power ratio}} = \frac{N_{GT}}{N_{SCPP^{BR}}} \times 100\%. \qquad (1)$$

The subscripts SCPP and BR symbolize steam cycle power plant, before repowering, respectively.

The rate of increase in ST power and the rate of increase in summary net power of CCPP can be defined as the power values of ST and of the whole power plant before repowering to the corresponding values after repowering.

The charts illustrated in Fig. 3 show that, after repowering in nine different cases, the GT power ratio changed from 25.14% to 61.12% and that GE Energy Oil & Gas MS9001E SC (GTW 2009) gas turbine (123 MW) had the highest values of GT power ratio and rate of increase in ST and CCPP power. They were 61.12%, 36.57% and 97.69%, accordingly.

Repowering has the effect of increasing the heat energy provided to the steam turbine, because it increases the amount of heat energy provided to the steam boiler from the gas turbine side. This effect can be used in two ways:

1) Keeping the fuel mass flow to the steam boiler stable and modernising the steam boiler and steam turbine equipment. This means for example enlarging the heat exchange surface and changing the installation of a steam turbine electrical generator. These actions result in increasing the power of the steam turbine and increasing in turn the power of the combined cycle too.

2) Reducing the fuel provided to the steam boiler until the power of the steam turbine reaches the level it was at before repowering. This improves the fuel economy of the steam boiler and increases the efficiency of the combined cycle power plant.

The analyses are considered from the point of view of the first case. The relative improvement in efficiency as a result of repowering – repowering efficiency, defined in accordance with Eq. (2), obtained for the considered turbine models is shown in Fig. 4. Additionally, based on performance calculations, this figure illustrates the relative increase in gas turbine power – GT leverage, defined in accordance with Eq. (3).

$$\eta_{RP} = \frac{P_{AR} - P_{BR}}{Q_{inAR} - Q_{inBR}}, \tag{2}$$

$$\lambda_{GT} = \frac{\Delta P_{el}}{P_{elGT}} = \frac{P_{AR} - P_{BR}}{P_{elGT}}, \tag{3}$$

where *P* means power at the generator terminals; Q_{in} - heat supplied to the cycle; *AR* and *BR* indexes refer to the performance before and after repowering, respectively.

The highest relative efficiency improvement (0.62) as a result of repowering was obtained for the case marked with index A in Fig. 4 (Trent 60 DLE - 50.6 MW), the lowest (0.53) for the case marked with index I – MS9001E turbine (123 MW). The highest relative increase in gas turbine power – GT leverage (1.70) was obtained in the pool under consideration for the case marked with index E (Westinghouse 401 – older generation machines 82.8 MW). The above results are important, but not the only necessary result of the analyses. A broader set of results for the indicated case can be found in [1,3].

According to the results of the analyses, gas turbine models can be divided into two groups: gas turbines with indexes from A to D and gas turbine with index F were entered into the group of hot wind-box repowering with fresh air dilution, whereas the gas turbine with index E and gas turbines with indexes from G to I were entered into the group of direct (without fresh air dilution) hot wind-box repowering.

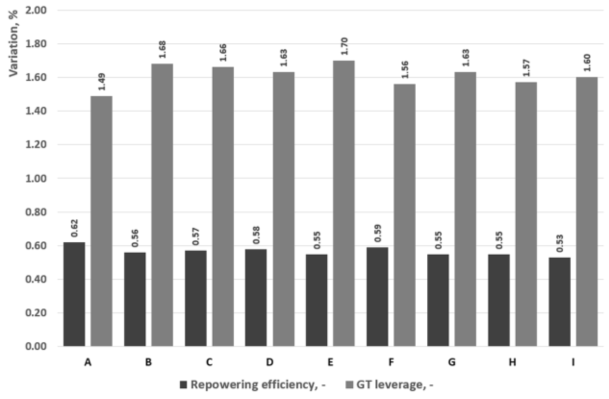

Fig. 4. Repowering efficiency and GT leverage in nine different cases.

The results of analyses, illustrated in Fig. 5 show that although the fraction of CO_2 was increased by 13.10% to 40.12% after repowering, CO_2 emissions in boiler exhaust gases per megawatt power were decreased by 0.18% to 0.29%. This finding may indicate that it is possible to increase the installed capacity while reducing pollutant emissions by hot wind-box repowering of thermal power plants.

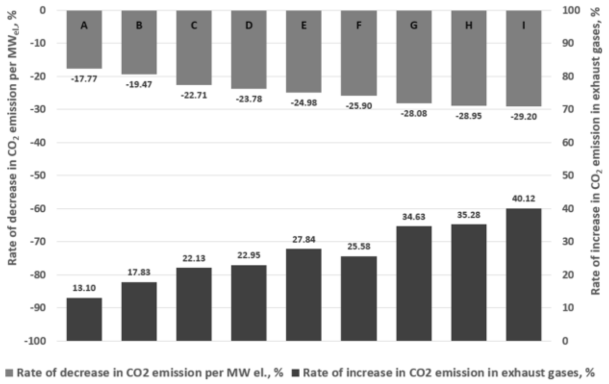

Fig. 5. Rate of increase in CO_2 emission in exhaust gases and decrease in CO_2 emission per MW electrical power.

4. Conclusions

To sum up, it is evident that the concept of repowering gains an increased significance because of the following factors:

- worldwide energy crises with the combination of environmental tight regulations;
- substantial fluctuations within the electrical grid due to the rapid expansion of renewable energy;
- the limitation of flexibility of coal-fired systems;
- the challenge of prolonging the life of existing old power plants.

Based on the past findings of both investigation and practical application, four basic concepts of repowering were defined:

- complete repowering,
- repowering with feed water heating,
- hot wind-box repowering,
- supplementary boiler repowering.

In these concepts, the following facts were registered:

- The complete repowering method without post-combustion (i.e., without maximum supplementary firing) achieves higher thermodynamic characteristics compared to the method with the maximum supplementary firing. While in some cases, the maximum supplementary firing (post-combustion) can lead to an improvement in the thermodynamic parameters of a gas-steam combined cycle.
- Significant improvements have also been observed in the thermodynamic performance of the hot wind-box repowering and feed water heating repowering concepts.
- For the hot wind-box repowering concept it is very important to select the right gas turbine based on the oxygen content in the exhaust gases to match the oxygen content required for combustion in the boiler, which allows to avoid additional costs associated with supplying fresh air to the boiler.

Depending on the objectives, evaluating a repowering concept requires consideration of a wide range of business aspects. This includes determining the additional power consumption and its value, assessing emission reductions, analysing fuel availability and costs, considering transmission requirements and limitations, examining forecasted generation load schedules, evaluating target electricity market prices, and addressing other requirements and goals.

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