PROCESS WASTE ENERGY AS AN ELECTRICAL ENERGY SOURCE

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Abstract

A new direction of activity, which has been developed very heavily over the last years, and which is in compliance with the sustainable development policy, is i.a. increasing the participation of renewable and alternative sources of energy, improving the energy efficiency, and climate changes prevention. On the other hand, the use of process waste energy which can be a source of electricity, is relatively low. Most of the solutions regarding the application of waste energy relate to drying and heating processes the application in drying processes or for heating purposes. New low-temperature energy generation techniques in ORC systems or in the Kalina cycle, created the conditions for a different, more environmentally friendly, manner of applying process waste heat. The article presents the method of using waste enthalpy of high-temperature thermal processes within WHR (Waste Heat Recovery) systems, which rely on combining the technological process with generating "clean" electricity, without the gas emission. The production of electricity combined with the production process, similar to cogeneration in the commercial power industry, is a technology of the future, which, apart from its economic benefits, also has great ecological importance.

Keywords: *Waste Heat Recovery, Combined Heat and Power, cement industry, Organic Rankine Cycle, rotary kiln, carbon dioxide emissions*

1. INTRODUCTION

The worldwide increase in the consumption of electricity and non-renewable fossil fuels, which is the result of the progressive economic and civilization development, results in the deterioration of the natural environment and the rapid depletion of fuel resources. The Sustainable Europe for a Better World strategy identifies climate change as an important barrier to sustainable development. It obliges EU countries to limit gas emissions from fuel combustion processes and to search for alternative sources of electricity. Therefore, one of the most important problems to be solved in the European Union in line with the Lisbon Treaty and the idea of sustainable development is increasing the share of renewable fuels in industrial processes, improving energy efficiency, development of new and methods of energy production and limiting the harmful impact on the environment - counteracting climate changes. Striving to lower energy consumption (production costs) and reduce the consumption of fossil fuels not only results from the progressive increase in energy prices, but also from the need to improve working conditions and reduce the harmful impact of industry on the environment and adjust it to the emission standards of EU countries. Combustion of fossil fuels, and especially coal, is characterized by a significant emission of carbon dioxide, the main greenhouse gas. Actions so far, in line with the 3x20 climate and energy package, consisting in reducing CO_2 emissions by 2020, did not fully meet their goal. Therefore, there are current problems related to the reduction of greenhouse gas emissions (GHGs - Greenhouses Gases) and the search for new techniques for generating electricity [1]. One of the conditions for reducing greenhouse gas emissions is limiting the consumption of fossil fuels, especially coal, and increasing the share of production of clean energy from renewable sources. Efforts in the industry to date to reduce CO_2 emissions and electricity generation focused mainly on the use of renewable energy sources and improving the efficiency of production processes. However, there was little interest in using process waste heat to produce electricity. The 3x20 climate package and increasingly stringent standards of permissible gaseous and dust emissions have resulted in the fact that practically most of the production processes operate at the level of energy efficiency and harmful gas and dust emission standards in accordance with the BREF (BAT Reference Document). A further reduction of energy consumption is often practically unprofitable or, at the present technical level, impossible to achieve. The only chance to further reduce the harmful effects on the environment and

improve the energy efficiency of the production process is to use processes waste heat to generate electricity or heat. The superstructure of the technological process with the WHR (Waste Heat Recovery) system can be compared to the CHP (Combined Heat and Power) cogeneration system in a power plant or heating plant, consisting in the combination of heat and electricity generation. Such activity is in line with the trends prevailing in the European Union, perceiving development of distributed cogeneration as an opportunity to increase local energy security with a simultaneous reduction of CO_2 emissions (Directive 2004/8 / EC (CHP) concerns the promotion of distributed cogeneration).

2. NEW TECHNIQUES FOR GENERATING ELECTRICITY

New methods of generating electricity in WHR installations, which operation is based on the use of process waste enthalpy, are based on the following electricity generation techniques:

- classical steam cycle CR (Clausius-Rankine's cycle),
- organic Rankine's cycle (ORC),
- Kalina's cycle.

Already in the 1980s, attempts of using waste heat to produce electricity in the Clausius-Rankine process were made all over the world.Due to the high cost of this system and its relatively low efficiency, this solution did not find much interest. Today, C-R technology (e.g. from Kawasaki) is widely used in Asian countries, while in Europe ORC installations or recently the Kalina's cycle have been used mainly. Fig.1 shows the process scheme of the ORC and Kalina's systems. The basic difference between the C-R system and the ORC and Kalina's systems is mainly the change of the working liquid. Water, which is a working liquid in the classic Rankine cycle, was replaced in the ORC system with an organic liquid (e.g. pentane), which has a much lower boiling point and a lower vaporization enthalpy compared to water. The ORC cycle is a two-circuit system. One circuit creates the so-called indirect medium - heating, e.g. thermo-oil or water. The second main cycle, on the other hand, creates a working medium - an organic liquid. The two-circuit system is used for the safety of ORC systems. Process waste heat - e.g. exhaust gas enthalpy, heats the intermediate factor in the recovery boiler, most often it is thermo-oil (silicone oil). The hot thermo-oil is then used in the evaporator to generate steam from the organic liquid that drives the turbine coupled to the generator. A similar solution to the ORC system, also based on the Rankine cycle is the Kalina cycle. The main difference of the Kalina cycle in relation to the ORC cycle concerns changing the working medium. In the Kalina cycle, in place of the organic liquid, a two-component mixture (water with ammonia), the so-called binary system, is applied. The boiling point of the mixture (NH_3 / H_2O) depends on the proportion of water and ammonia in it. Typically, the proportion is 70% ammonia and 30% water.

As a result of heat supply (exhaust gas enthalpy) to the recovery boiler, the working medium is evaporated in the Kalina cycle - a mixture (water and ammonia). Then, in the separator, steam with a high ammonia content is released from the vapor phase formed, which drives the turbine. On the other hand, the water phase from the separator flows through the exchanger and then mixes with the ammonia vapor expanded in the turbine. The resulting mixture of steam and water is led through a recuperator to the condenser. The resulting condensate is pumped through the regenerator by means of a circulating pump and then the exchanger-heater to the evaporator.

Kalina's cycle is an increasingly used technique of using waste heat to produce electricity. It is used similarly to the ORC cycle for low and medium temperatures of waste heat (400 - 700 K).

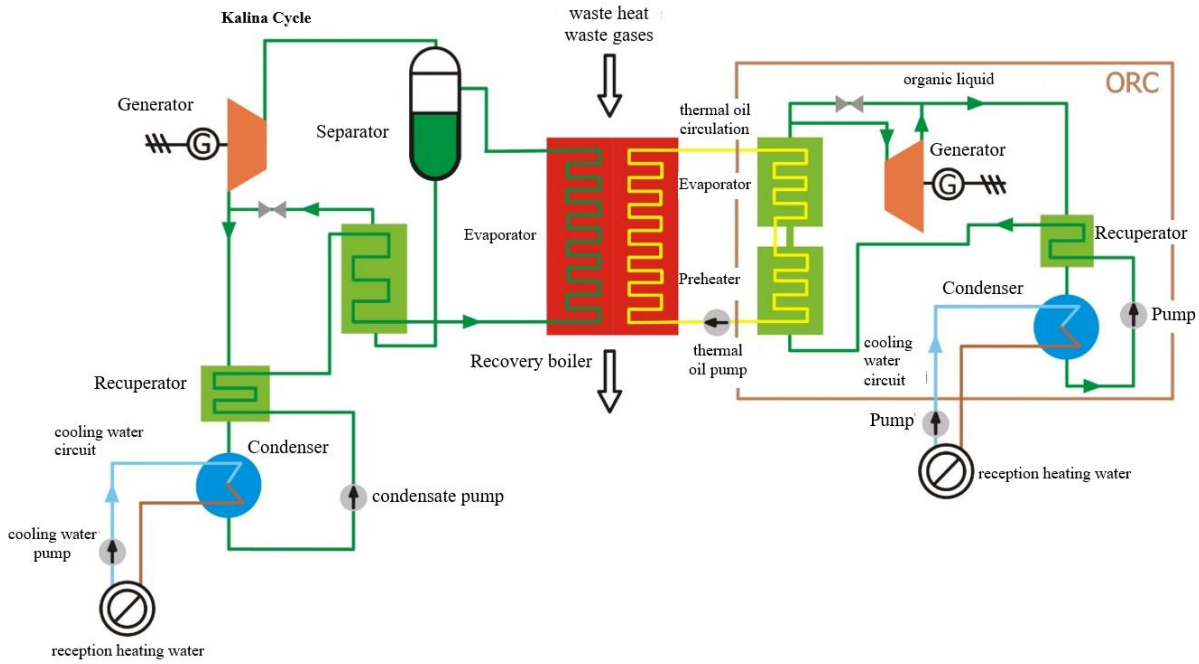


Fig. 1. Process scheme of the ORC and Kalina system.

Source: Tomasiak J., Duda J., „Poprawa efektywności energetycznej procesów technologicznych poprzez zastosowanie układu ORC", „Innowacje w zarządzaniu i inżynierii produkcji" Knosala R. (red.), Oficyna Wydawnicza Polskiego Towarzystw Zarządzania Produkcją, Opole 2016, pp. 514-523.

3. SUPERSTRUCTURE OF THE TECHNOLOGICAL PROCESS OF BURNING CEMENT CLINKER IN A ROTARY KILN WITH THE WHR - ORC SYSTEM

The cement industry, like the power industry, belongs to the group of energy-consuming and environmentally harmful industries. The environmental inconvenience of cement production results mainly from the energy-consuming process of burning clinker in a rotary kiln, which is characterized by high carbon dioxide emissions. Fig.2 shows a process scheme of a rotary kiln.

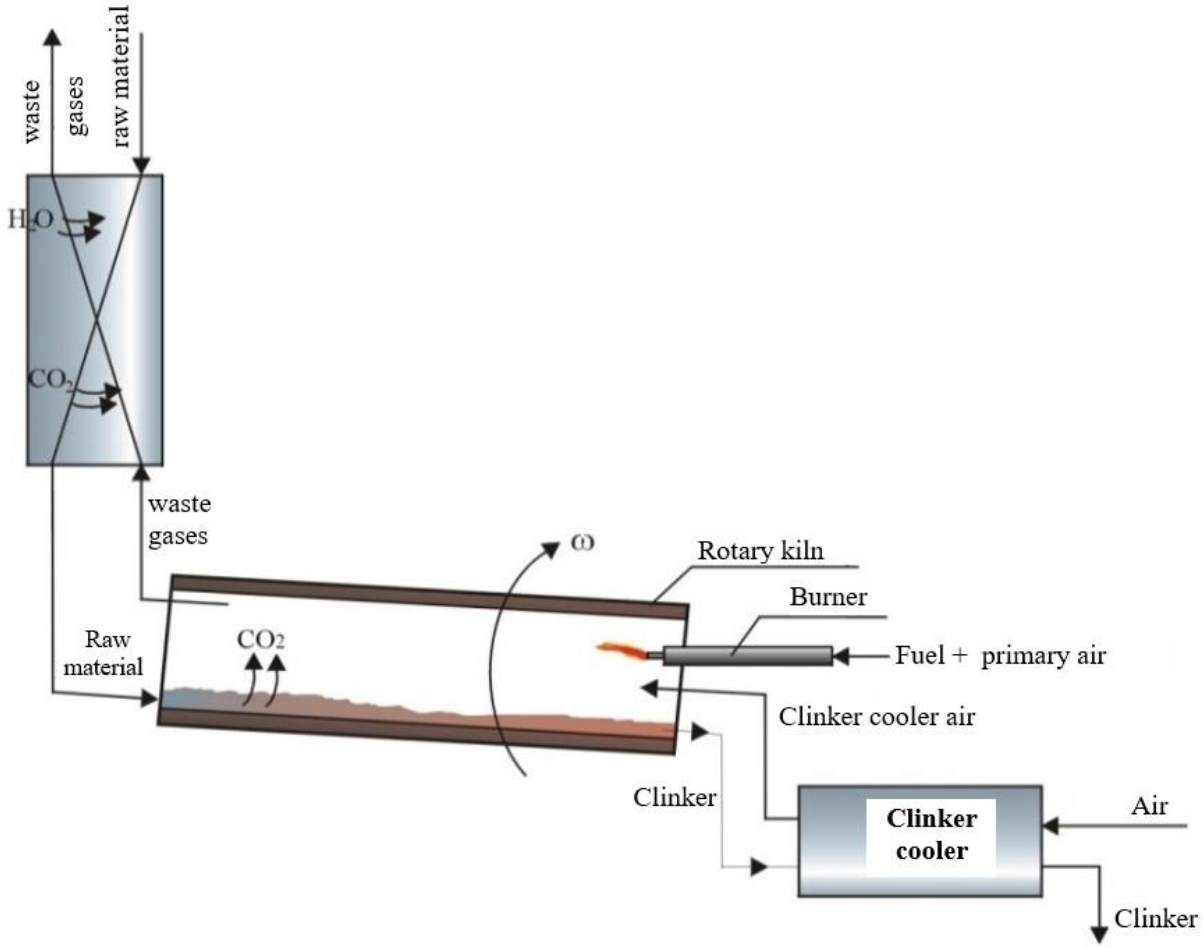


Fig. 2. Process scheme of the clinker burning process.

Source: Duda J., Tomasiak J. 2015, „Redukcja emisji CO2 w procesie produkcji cementu", *Innowacje w zarządzaniu i inżynierii produkcji* pod redakcją R. Knosali, Oficyna Wydawnicza Polskiego Towarzystwa Zarządzania Produkcją, Opole, pp.384-395.

The limitation of GHG emissions (including CO_2) in the cement industry is facing problems relating both to the process complexity and to emission sources. The total CO_2 emission during cement production is the sum of emissions coming from fuel combustion (CO_2^P – from fuel) and limestone calcination (CO_2^S – from resource). Pulverized limestone constitutes the major part of feed (substrates) [4]. So,

$$\sum CO_2 = CO_2^P + CO_2^S \quad (1)$$

$$CO_2^S = 0{,}78\ CaO^S + 1{,}09\ MgO^S \quad (2)$$

$$G_{CO_2}^S = \frac{G_S \times CO_2^S}{100} \text{ [kg } CO_2\text{/kg of clinker.]} \quad (3)$$

where:

CaO^S and MgO^S - shares of calcium and magnesium oxides in kiln feed in mass %, and G_S – coefficient of feed use per 1 kg of clinker.

It was found that production of 1 Mg of cement clinker leads to emission of 865 kg of CO_2 (ie ~ 680 kg CO_2 per 1 Mg of cement). More than 60 % of this CO_2, ie 535 kg, is related to lime calcination; the rest ~ 330 kg comes from fuel combustion.

The development of new dry firing techniques, in rotary kilns with a multi-stage cyclone heat exchanger, allowed for a significant reduction in heat consumption. However, still with low efficiency (approx.55 %) of this process is determined by high waste heat losses. With the high-temperature technological process, such as the clinker burning process, there is always a loss of energy to the environment. It is energy related to waste products from the process, exhaust gases or convection and heat radiation losses from process equipment to the environment. A properly implemented technological process should be characterized by a low level of waste energy, the use of which in the process is no longer economically profitable or there are no technical methods to reduce it. An example of such technology is the process of burning cement clinker in a rotary kiln, where, thanks to the implementation of new innovative solutions, heat consumption has already been achieved at a level close to the theoretical one. Therefore, the only way to reduce CO_2 emissions is the use of waste enthalpy outside the firing process. Fig.3 shows the sources of waste heat from the clinker burning process and the methods of use.

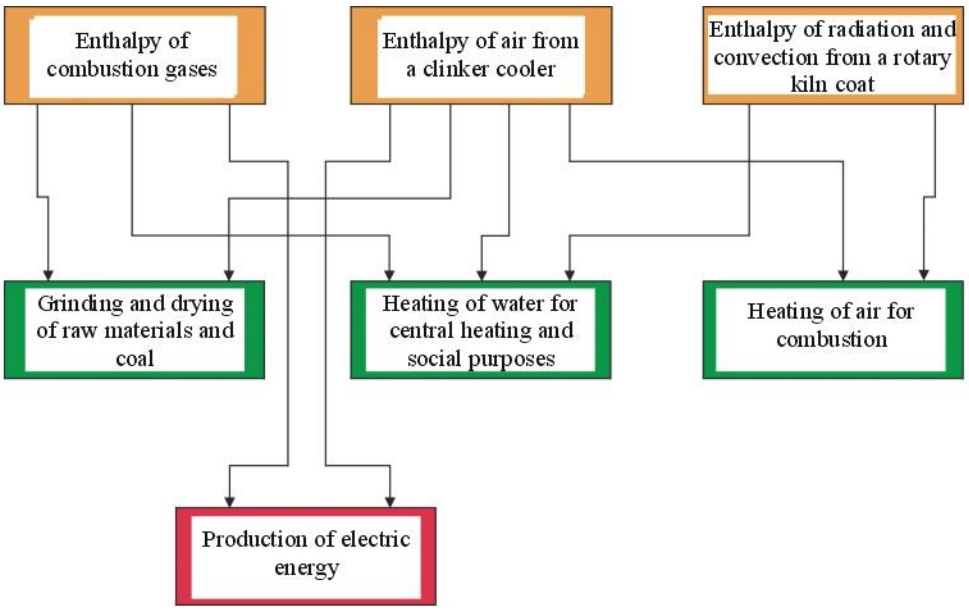


Fig. 3. Sources of waste heat from the clinker burning process and methods for its recovery.

Source: Tomasiak J., Duda J., „Wpływ innowacyjnych technik WHR na poprawę efektywności energetycznej procesów technologicznych, *Innowacje w zarządzaniu i inżynierii produkcji* pod redakcją R. Knosali, Oficyna Wydawnicza Polskiego Towarzystwa Zarządzania Produkcją, Opole 2015, pp. 510-519.

In practice, the use of waste heat from the burnout process comes down to the use of the enthalpy of the exhaust gases and the excess air from the clinker cooler for drying raw materials and coal. Due to the lower and lower humidity of raw materials and fuels, the use of this heat is limited. Therefore, research is being conducted on other methods of waste enthalpy use. The most frequently used methods include using it to produce hot water or steam for heating and social purposes. In Poland, due to the long distances of cement plants from housing estates and the resulting high costs of supplying the generated heat to customers, this method has not been used.

In recent years, mainly due to the World Commission for Environment and Development, which presented the assumptions of the so-called sustainable development policy, the issue of waste heat utilization in the clinker burning process has become topical again. Considering the constant increase in

electricity prices and increasingly stringent emission standards, the combination of cement production with electricity generation is a future-proof solution. The use of waste heat for the production of electricity is in line with the assumptions of the country's energy policy and corresponds to the current trends in the world, consisting in the development of small sources of energy production in combination with another thermal process. According to available research results and cost analysis, the best solution for a waste heat source with a temperature above 650 K is the classic Clausius-Rankine cycle. However, for the so-called low-temperature sources (<600 K), the ORC or Kalina cycle is recommended, which are characterized by lower boiling points of the working liquid. In the climatic conditions of the EU, where due to the relatively high humidity of carbonate raw materials and coal-fuel, it is required to use some of the waste heat for drying these materials, the only solution is to use the ORC system or the Kalina cycle. Fig.4 shows a diagram of the WHR-ORC installation that provides heat for drying and for electricity production. In the presented solution, the enthalpy of exhaust gases from the rotary kiln with a temperature of approx. 653 K is used in a recovery boiler to heat up thermo-oil. Due to the moisture content of the limestone raw material (national average approx.6 %) and the required gas temperature at the inlet to the drying and grinding mill approx. 500 K, excess air from the clinker cooler is additionally supplied to the waste gases from the recovery boiler. With higher moisture contents in the raw material, it is possible to increase the proportion of excess air in the mill gases, or to reduce the power of electricity produced by lowering the temperature of the thermo-oil. The ORC system, compared to the classic CR, is characterized by a constant efficiency in a very wide range of load changes. The association of the clinker burning process with the production of electricity can be compared with cogeneration in the commercial power industry, consisting in the joint production of heat and energy. In addition to cement clinker, the product of such a combination is the "Clean Energy", the production of which takes place without the combustion of fuel and the emission of harmful gases. Therefore, it can be assumed that by producing electricity from waste heat, a cement plant indirectly reduces carbon dioxide emissions resulting from coal combustion in a coal-fired power plant by approx.800 g of CO_2/kWh. The association of the production process with energy generation is nowadays more and more used technology in the world. Economic and ecological benefits speak for such a solution.

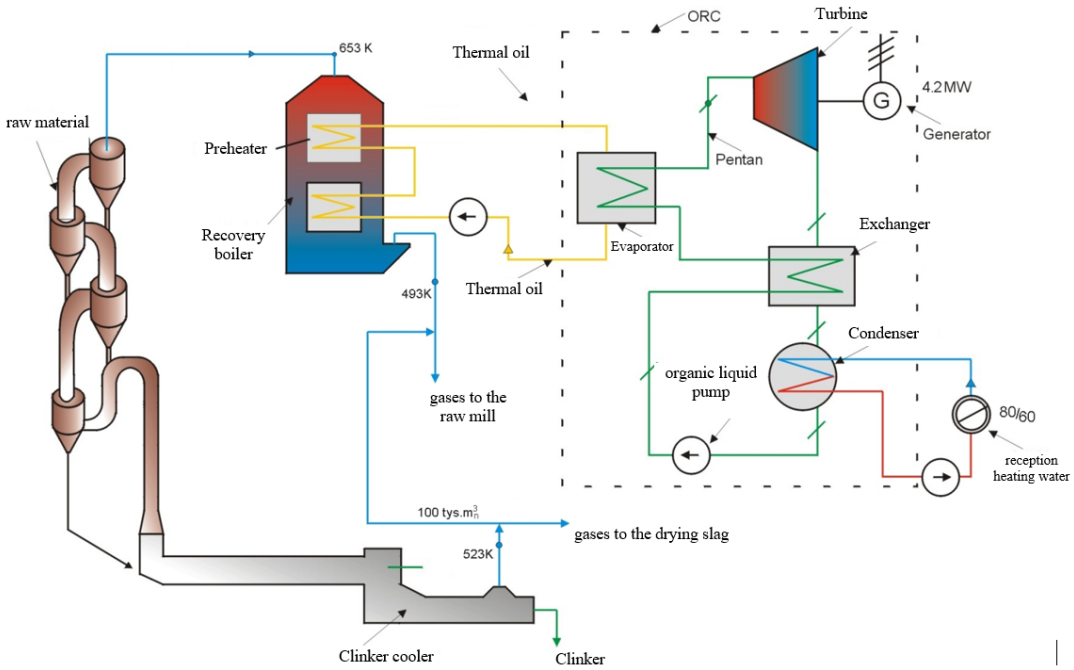


Fig. 4. Scheme of a kiln with an installation for generating electricity in the ORC cycle.

Source: Tomasiak J., Duda J., „Wpływ innowacyjnych technik WHR na poprawę efektywności energetycznej procesów technologicznych, *Innowacje w zarządzaniu i inżynierii produkcji* pod redakcją R. Knosali, Oficyna Wydawnicza Polskiego Towarzystwa Zarządzania Produkcją, Opole 2015, pp. 510-519.

Generating energy in a production plant from waste heat coming from the technological process, in addition to improving the efficiency of the process, allows to eliminate energy transmission losses, reduce the consumption of non-renewable fuels and reduce GHG emissions. The energy produced by this method indirectly reduces CO_2 emissions by the amount of emissions that results from producing a similar amount of energy in a coal-fired power plant. As it results from the literature data and own research, the power of energy generated in WHR systems in a cement plant depends on: burning technology - a waste heat source, its size, the technique used to use the available waste enthalpy, moisture of raw materials. This capacity ranges from 25 - 45 kWh/Mg cl.

4. CONCLUSION

Apart from economic effects (reduction of heat losses), the combination of the technological process with the WHR system, similar to cogeneration in the power industry, also has a beneficial effect on reducing greenhouse gas emissions. As results from the presented status of activities aimed at reducing CO_2 emissions, many technological processes already have limited technical possibilities to further reduce these emissions. The presented process of burning cement clinker is an example of such a technology. An extension of the technological process with the WHR system and the production of "clean energy" may be the way to indirectly reduce CO_2 emissions. Generating energy in the place where it is consumed has a large impact on the production efficiency and reducing the harmful impact on the environment. WHR technology has found great application especially in high-temperature processes that are characterized by high heat losses. New low-temperature electricity generation techniques in ORC and Kalina cycles have also found great application in installations with much smaller waste heat sources of a few MW. Taking into account the previous experience in the operation of ORC and Kalina systems and model tests of new solutions in the Kalina cycle, it can be concluded that these are future-proof solutions for industry and heating. The combination of the technological process with electricity generation is consistent with the policy of efficient fuel and energy management and the development of distributed energy sources.

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