Article citation info:
Chojnowski J, Karczewski M, Szamrej GA. Dual-fuel engines using hydrogen-enriched fuels as an ecological source of energy for transport, industry and power engineering. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-176800

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Dual-fuel engines using hydrogen-enriched fuels as an ecological source of energy for transport, industry and power engineering

ARTICLE INFO

Received: 31 May 2023
Revised: 10 December 2023
Accepted: 11 December 2023
Available online: 19 January 2024

Displacing internal combustion engines (ICE) from the passenger car sector does not mean displacing it from all industries and specific applications. Thanks to the analysis of data on compression ignition (CI) engines used in the world, it is possible to prepare ready-made solutions for the most common engines in selected industries or for those whose greenhouse gas emissions will be the largest and most expensive for their owners in the coming years. The basic solution presented in this article gives the possibility of powering the engines with the most ecological currently known alternative engine fuels and using the already existing methane transmission infrastructure around the world. Their greatest advantage is their availability and low carbon content, which allows to minimize carbon dioxide emissions, both by burning hydrogen-enriched fuels and by increasing the efficiency of the engines modified by dual fuel supply system. Properly made external dual-fuel installation allows to improve the thermal efficiency of the CI engine. Work on this issue may help in the development of, for example, high-efficiency flex fuel power generators, which, as the current situation in Ukraine shows, are worthy. Thanks to the diversification of power sources for power generators, the countries is able to increase the reliability and security of energy supplies even in difficult conditions, such as armed conflict or natural disasters.

Key words: *dual-fuel, alternative fuels, hydrogen-enriched fuels, industrial engine*

1. Introduction

1.1. Global CO_2 emissions and energy sources in the world

Improving the protection of the natural environment, reducing the emission of harmful exhaust components and greenhouse gases is a path of development that is of interest to the general public. The idea of using the current technological achievements in the form of Dual Fuel (DF) and Reactivity controlled compression ignition (RCCI) engines proposed in this article, together with the use of ecological fuels blended with hydrogen, is part of the trend of reducing CO_2 emissions into the atmosphere, because it covers all the most emission-intensive economic sectors, which have been marked in the Fig. 1.

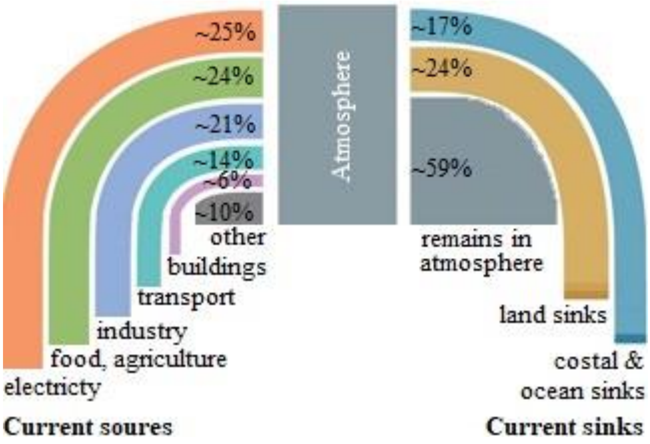


Fig. 1. Sources of CO_2 emissions to the atmosphere in the world [52]

The largest CO_2 emitters use mainly natural gas (NG), coal and oil to generate energy (Fig. 2).

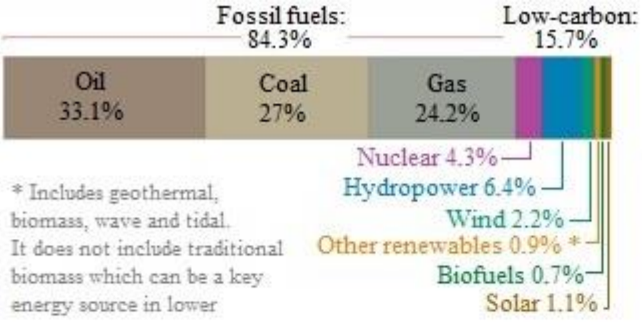


Fig. 2. Total world energy mix (electricity, transport & heat) [3, 52]

The idea presented in this article, which will make it possible to replace them with hydrogen in internal combustion engines, can reduce the consumption of two of these fuels.

1.2. Worldwide use of ICE in industrial applications

The use of combustion engines in power systems plays a key role in maintaining system continuity in various emergency situations, including armed conflicts, natural disasters and weather anomalies. These engines serve as backup power sources and ensure reliable electricity generation in the event of failure of the basic power infrastructure and will important in stabilizing electricity grids with a large share of uncontrollable renewable energy sources [9, 19].

In times of armed conflict or war, the electrical network may become the target of disruption or destruction. In such scenarios, internal combustion engines provide power continuity. These engines can be integrated with stand-alone power generators or connected to the grid through synchronized operation with existing power plants [9, 19].

In the event of natural disasters such as earthquakes, hurricanes or floods, the electrical infrastructure is exposed to severe damage, leading to power outages. Combustion engines, equipped with suitable generators, can be quickly deployed to affected areas to restore electricity. Their mobility and flexibility allow them to be stationed near critical facilities such as hospitals, emergency response centers or communication networks, ensuring that essential services continue to function [9, 19].

Weather anomalies such as extreme heat waves, periods of frost or storms can also stress the power grid and potentially cause blackouts. During such events, internal combustion engines may be run as peak power plants to meet the increased demand. These engines can quickly increase energy production and stabilize the grid, compensating for fluctuating renewable energy sources or reduced efficiency of conventional power plants affected by extreme conditions. Figure 3 shows the process of stabilizing the power system in New England USA at the beginning of 2023 [10, 51, 53].

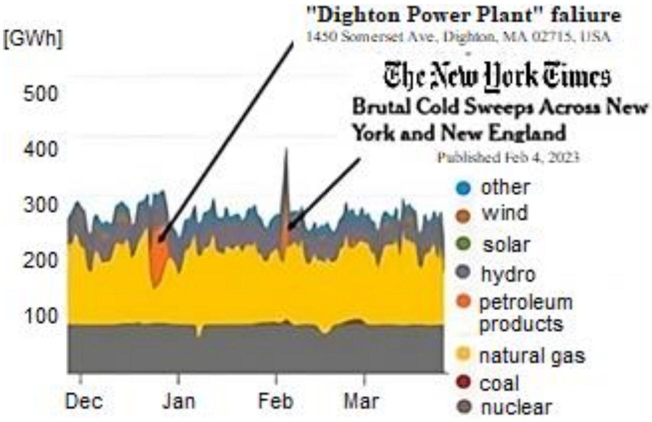


Fig. 3. Graph of the use of electrical energy sources for New England, USA in the period from 12.2022 to 4.2023, with marked anomalies where it was necessary to use emergency generators using ICE [10, 51]

The chart above showing the daily production of electricity by energy source shows two crises in which internal combustion engines were used as an intervention, which in the event of a failure of the Dighton natural gas power plant, and later during severe frosts in New England, over 5 GW of power installed in power generators was launched [51, 53].

In addition, the availability of fuel storage facilities for internal combustion engines allows them to operate independently of external power sources for extended periods of time. This self-sufficiency becomes invaluable in situations where the primary power supply is cut off for various reasons, such as damaged transmission lines or disruptions in fuel supplies. To increase the resilience of power systems in emergency situations, it is essential to have a well-maintained fleet of ICE with regular fuel supply and maintenance procedures. Proper training and preparedness are critical to the successful deployment and operation of these engines in emergency situations. However, it should be noted that while internal combustion engines provide a reliable backup power solution, they come with emissions and environmental concerns. To mitigate these problems, efforts must be made to minimize their use and shift to cleaner and more sustainable alternatives such as renewables, energy storage systems and microgrids. Nevertheless, in the context of maintaining the continuity of the system in emergency situations, internal combustion engines continue to play an important role until more sustainable solutions become commonplace and available.

In total, there are 34,937 electricity generation installations installed in the world. Diesel oil and derived fuels are used in 3626 power plants with a total installed capacity of approximately 250 GW, including approximately 800 of these installations also running on natural gas, and additionally 3697 power plants with natural gas turbine engines with a capacity of max. 1.2 TW. For comparison, 127 GW of capacity is installed in pumped storage power plants around the world [11, 12, 56]. This shows how important the internal combustion engines play in the power system.

As far as industry and heavy industry are concerned, the authors of this article are currently unable to find data on the global use of internal combustion engines, however, legislative changes in the United States (US) and European Union (EU) will lead to a reduction in CO_2 emissions from these engines in the near future and will force entities using them to disclosure.

1.3. Worldwide use of ICE in transport

Combustion engines also continue to play a key role in transport. There are currently around 350 million [16, 55] diesel engines in goods transport vehicles. There are a total of 450 million cars with such engines on land, and about 50,000 heavy transport ships (over 1000 tons of load capacity) and a total of over 2 million various types of ships and ships powered by diesel engines [32]. In 2018, 8×10^{18} Joules of energy contained in the fuel were needed to power marine transport with diesel fuels and its derivatives, and in total it is already 10×10^{18} joules of energy when adding this value with the demand for natural gas as shown in Fig. 4 [21, 32].

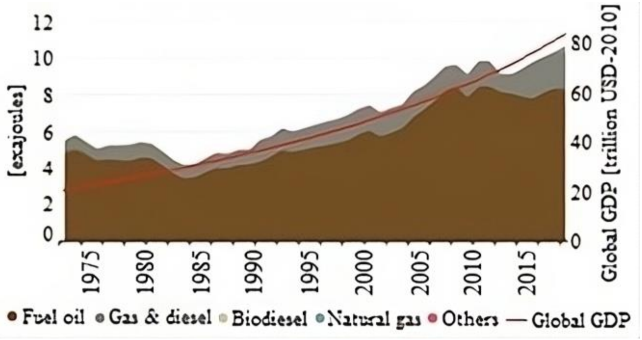


Fig. 4. Estimated energy demand contained in water transport fuel in the world [21]

In the case of road vehicles, the possibility of reducing carbon dioxide emissions is even higher than in the case of energy, industry or water transport, due to the possibility of additionally increasing the efficiency of the engine operating on two fuels and reducing the emission of harmful exhaust components. Carbon dioxide emissions in road transport are more than 2.5 times higher than in sea transport and account for nearly 30% of all carbon dioxide emissions from transport [40]. Despite legislative efforts and the hard work of constructors and engineers building motor vehicles, due to, among others, consumption, they did not ultimately contribute to drastic decreases in emissions, as shown in the Fig. 5. Consider here is the best-executed scenario of actions, i.e. the effect of reforms in the EU. In the European Union, the trend of reducing carbon dioxide emissions is the strongest compared to other countries in the world. As you can see in the graph in Fig. 5, emissions in the last decade began to decrease (very slightly, and the decrease in 2020 was the result of the pandemic), which, however, is not yet the effect that could be achieved by using alternative fuels proposed by our team, which, as mentioned , can significantly exceed the 35% reduction compared to diesel emissions, thanks also to the increase in efficiency of the engine operating in dual-fuel mode [8, 40].

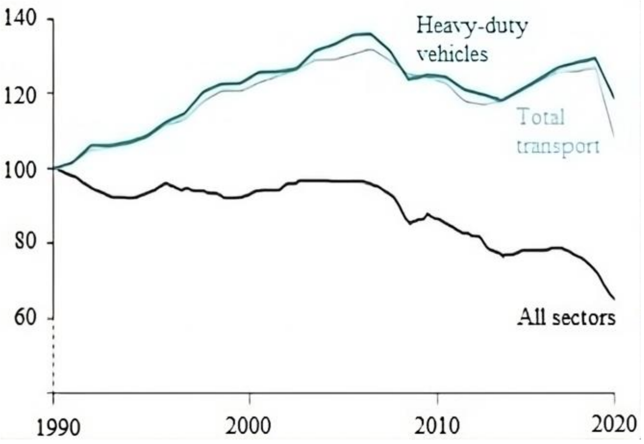


Fig. 5. Relative CO_2 emissions from transport since 1990 in EU [8]

2. Material and methods

2.1. Hydrogen enriched fuels

Hydrogen-enriched fuels may be the key to reducing carbon dioxide emissions generated in the combustion process in internal combustion engines. Their current development has been very intensive for several years, and after the EU decision to limit the sale of combustion cars by 2035 [7, 46], work on low- and zero-emission fuels has accelerated even further. Their production may allow the operation of new cars with ICE powered only by those fuels which total greenhouse gas (GHG) emissions over the entire use cycle will be zero. Many car manufacturers believe that they can determine the future of automotive development, the aviation and maritime industries already treat them as the only source of energy to maintain their transport fleet in the future in the form of zero-emission means of transport [18]. The lack of real alternatives means that industries that need large energy resources invest in this technology in a way that is not only declarative – like the automotive industry – but also fully real, already implementing a huge number of investments related to their use [15, 23, 57]. The existing research methodology still mainly takes into account how many substances the engine actually emits in the place where it is used. In addition to carbon dioxide and water, each of the other substances that affect the natural environment can be neutralized in the exhaust gas catalytic reactor, which is why carbon dioxide, which is the basic greenhouse gas produced in the combustion process, is the focus of reducing emissions in internal combustion engines. The currently used fuels are able to reduce the level of carbon dioxide emissions. Its complete elimination can be done using pure hydrogen or substances binding it with elements other than carbon dioxide, such as ammonia. The use of pure hydrogen or ammonia is currently used, but in a very limited form [47], and it is easier to introduce fuels that can directly replace fuels distributed in the current infrastructure, such as Hydrogen enriched Compressed Natural Gas (HCNG) also in configuration with fully renewable biomethane – replace fossil Compressed Natural Gas (CNG), or Hydro-treated Vegetable Oil (HVO) – replacing diesel, and methanol – replacing gasoline. The possibility of their hydrogenation translates directly into the level of carbon dioxide emissions during their combustion. In addition, both of these fuels come from renewable energy sources such as biogas for HCNG and vegetable oil for HVO. Their total carbon footprint is very low, it can be practically zero when hydrogen is obtained from green energy sources. The methods of obtaining hydrogen are varied and, depending on the energy source used for its production, it may be characterized by a different degree of GHG emissions.

For the purposes of our considerations, green hydrogen should be taken into account, because the EU directs its industry and energy sector to the production of such hydrogen. Green hydrogen is hydrogen whose total carbon footprint does not exceed 2 kg of CO_2 equivalent per kg of hydrogen produced. Hydrogen produced from renewable energy sources has a zero-carbon footprint, and combining it with biogas we get a fuel whose carbon footprint will be practically zero – HCNG is a mixture of natural gas and hydrogen with proportions set by the manufacturer of this fuel, with limitations resulting primarily from the technical capabilities of the system distribution of this fuel. The distribution of natural gas is easier than the distribution of hydrogen and its high content in this fuel causes a number of changes in its properties, making it impossible to distribute it through the natural gas distribution system [42]. However, the hydrogen content can reach up to 50% of the mixture volume, which is a noticeable share of hydrogen in this fuel and allows to reduce carbon dioxide emissions to the atmosphere during its combustion compared to pure natural gas or methane [38].

HVO, on the other hand, reduces carbon dioxide emissions both by reducing the chemical share of carbon in this fuel in favor of hydrogen and by using plant substances in the process of its production, thanks to which practically all carbon dioxide emitted to the atmosphere was previously absorbed by the plants from which this fuel was created [4].

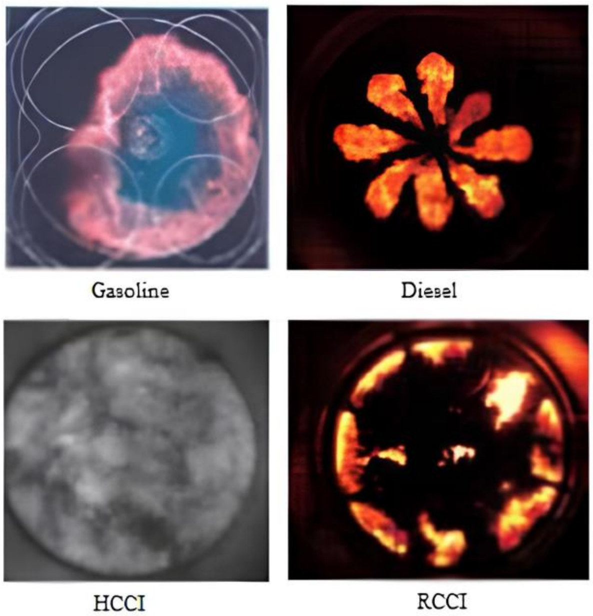
The situation is similar with methanol, which, although it is not an additionally hydrogenated fuel, its production is based primarily on agricultural production from plants that quantitatively absorb most of the carbon dioxide that is emitted in the process of burning this fuel [35].

In another article by the authors of this publication entitled "A review of low-CO_2 emission fuels for a dual-fuel RCCI engine" [25] a list was developed, which selected fuels with the lowest potential for carbon dioxide emissions into the atmosphere, and on its basis, those with the greatest potential to reduce CO_2 emissions from internal combustion engines in the future were selected. It clearly shows that the emission for HCNG is the lowest of all fuels, and its decrease is proportional to the hydrogen content in this fuel. Further opportunities to increase the concentration of hydrogen in the mixture will increase along with the development of distribution technology and the development of hydrogen networks, which will allow for a gradual transition to pure hydrogen in such installations in the future, which will be related to the EU “FIT for 55” assumptions [50]. Table 1 below shows part of the developed table.

However, only two hydrogen-enriched fuels, HCNG and HVO, were selected for the purpose of this work. This is due to the analysis carried out by the authors in a number of their articles [25, 48, 49] in which we presented the concept of using dual-fuel engines in the future, whose overall efficiency exceeds both conventional CI and Spark Ignition (SI) engines, and the flexibility of fuel use is practically unlimited. These engines require both high-octane and high-cetane fuels at the same time, which means that two fuels with diametrically opposed properties must be used. The selection of two fuels with the lowest carbon dioxide emissions allows you to determine how low carbon dioxide emissions will be possible in the future for ICE, the use of which in the power industry and heavy industry will not be phased out in Europe by 2050 [25, 48].

2.2. Principle of operation and advantages of a dual-fuel engine

To ignite the mixture of air and high-octane fuel, a dual-fuel engine uses high-cetane fuel injected directly into the combustion chamber just before its self-ignition, causing further combustion of the entire mixture located in the space above the piston. In a variant of the dual-fuel engine, called the RCCI engine (Reactivity Controlled Compression Ignition), the self-ignition of the high-cetane fuel, in this case the high-reactive fuel, causes the auto-ignition of a homogeneous mixture of the high-octane fuel, called the low-reactive fuel, with air. The RCCI engine is a DF engine variant of the Homogeneous Charge Compression Ignition (HCCI) engine, which is characterized by higher thermal efficiency than a classic dual-fuel engine or a standard CI diesel engine. Figure 6 below shows the view of the combustion process in the chamber operation of the Gasoline, Diesel, HCCI and RCCI dual fuel engine.



Gasoline Diesel

HCCI RCCI

Fig. 6. A view of the combustion process in the chamber during operation of the Gasoline, Diesel, HCCI and RCCI dual fuel engine [22]

In industry, maritime transport and energy, DF engines have been the main source of propulsion for years. This is due to the possibility of using cheaper and less emission-intensive fuels such as CNG, Liquefied Natural Gas (LNG) or bio-CNG/LNG. Their use in SI engines is less economical due to the lower efficiency of these engines compared to dual-fuel engines. Engines on an industrial scale usually work only with necessary breaks, so the higher efficiency of a given solution translates directly into the economy of operation of a given engine and this indicator is crucial in this type of application. DF engines, especially RCCI engines, achieve higher efficiency thanks to a very even temperature distribution in the combustion chamber and a lower maximum combustion temperature. The following Fig. 7 shows an example of the temperature distribution in an RCCI engine and a classic CI engine.

Table 1. Selected fuels properties (full table available at [25])

		Petrol	Diesel	HVO	M100	CNG	HCNG15	HCNG30	HCNG50
C/H ratio	% of weight	9	7.26/6.73	5.49	3	3	2.77	2.52	2.15
	molecular	~3:4	~3:5	0.46	1:4	1:4	0.23/0.24	0.21/0.22	0.18/0.19
Hydrogen weight content [%]		10	12/(12.96)	15.4	12.5	25	26.5 (25.75)	28.39 (26.5)	31.75 (27.5)
Carbon weight content [%]		69–70	69–74	~70	~70	56.1–55.35	55–54.3	53.56–52.85	51.05–50.37
CH_4 emission potential		Low	Low	Low	Low	Very high	High	High	Medium/ high
N_2O emission potential		Very high	Medium	Low	High	Medium	Low	Low	low
Mainly emission potential		HC, CO, CO_2, NO_2, NO_x	HC, CO, CO_2, NO_2, NO_x	HC, CO, NO_2, NO_x	HC, NO_2, NO_x	CH_4, NO_2, NO_x	CH_4, NO_2, NO_x	CH_4, NO_2, NO_x	NO_2, NO_x

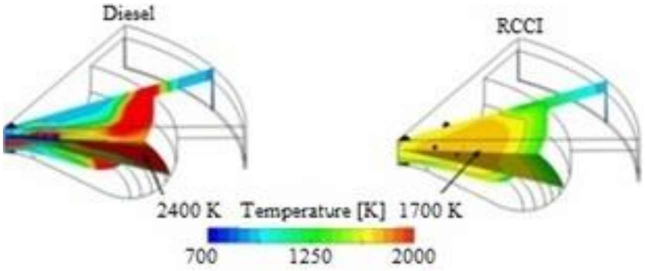


Fig. 7. Temperature distribution in the combustion chamber for diesel only and RCCI [45]

The high efficiency of these engines also results from the possibility of using the entire space above the piston as a combustion chamber, which in a classic CI engine is limited to a small combustion chamber located in the piston. The time needed for a good mixing of low-reactive fuel with air is provided by indirectly supplying this fuel to the intake manifold, or a series of high-pressure injections directly into the combustion chamber in various phases of engine operation called Direct Dual Fuel Stratification (DDFS) [5, 17].

This strategy is used in more advanced solutions, and both methods of powering the dual-fuel engine can also be mixed to improve the results.

Dual-fuel engines are also characterized by extraordinary fuel flexibility – they can be used with all fuels that can be used in classic SI and CI engines. This allows for an emergency change of the fuel used in the engines in the event of difficulties with the supply of the standard power source, and it is also easy to adapt the engine to burn more ecological fuels when they become widely available. among others for this reason, HCNG is such a good example of a fuel evolving towards an ecological fuel of the future, from which it will be easy to switch to clean, green hydrogen, and the highly reactive fuel, which in our considerations is HVO [4, 14], in the future may be a zero-emission e-fuel that can be used in these engines with only minimal or zero emission fuels and use them with higher efficiency than SI engines and in some cases also fuel cells [16].

3. Potential and reasons for the use of dual-fuel engines using hydrogen-enriched fuels

It should be remembered that the engines used in the power industry, maritime transport or industry have a much higher efficiency than high-speed SI and CI engines. The most efficient engines already achieve an efficiency of 54.6% [30, 31, 44, 54]. Overall efficiency of up to 55% in low-speed engines is no longer uncommon, and designers predict that thanks to RCCI technology in engines of this type it will be possible to achieve values of 60% [44]. Such performance makes engines of this type an attractive alternative to turbine engines, fuel cells or batteries that allow the development of electromobility. Hydrogen, which is not only a fuel, but also a storage of energy generated from electricity sources, combusted in internal combustion engines, allows for the recovery of this energy when it is needed. The graph below in Fig. 8 below shows the electricity production in the power system, which shows the scenarios for different capacities of installed PV installations.

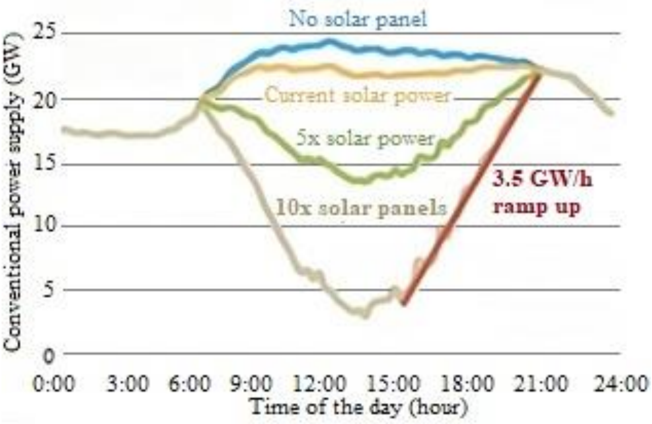


Fig. 8. Scenarios of electricity production using PV in the energy mix (based on [26])

The figure above shows how the power of the installed photovoltaic installations in the power grid affects production during the day. The visible decrease in production from conventional sources around noon is problematic for the system operators and for this reason the need to store the energy produced during this period will increase. A network constructed in this way will require energy to be delivered in the period when Renewable Energy Source (RES) does not operate with high power and its storage in the period when it is operating. One of the methods of energy storage is the production of hydrogen and its subsequent use, e.g. in internal combustion engines. Thanks to the possibility of using the existing natural gas distribution network, it is possible to distribute hydrogen to the target customer in the form of HCNG fuel. In combustion engines, the use of liquid fuels also allows the combustion of green hydrogen, because fuels enriched with it, such as HVO, can use for this process green hydrogen produced during the surplus of electricity production from RES. Due to the possibilities offered by DF ICE in the use of green energy sources, simulations have been developed showing the level of carbon dioxide emissions depending on the hydrogen content in HCNG, at various degrees of replacement [5] of high-reactivity fuel with low-reactivity fuel. The graph below in Fig. 9 shows the effect of the hydrogen content on the carbon dioxide emissions during complete combustion of HCNG.

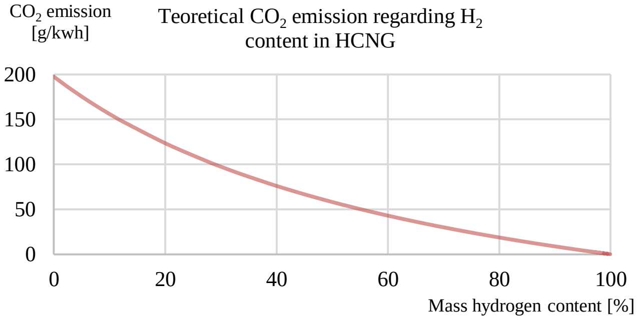


Fig. 9. Impact of hydrogen content on CO_2 emissions from HCNG combustion

The influence of hydrogen content on carbon dioxide emissions visible in the graph in Fig. 9 clearly shows that with the initial increase in hydrogen content at low concentrations, carbon dioxide emission decreases more intensively than with high hydrogen content in the mixture. This shows how important it may be to add methane, even with a small amount of hydrogen, to improve the ecological parameters of this fuel.

The chart on the Fig. 10 below shows the level of carbon dioxide emissions for various types of ICE and the fuels used in them, with the assumed values of overall efficiency of SI engines fueled with gasoline at the level of 36.4% [54], SI fueled with CNG at the level of 39% [27, 37], CI fueled with oil or HVO of 44% [37], DF of 45% [37], and RCCI of 46% [43].

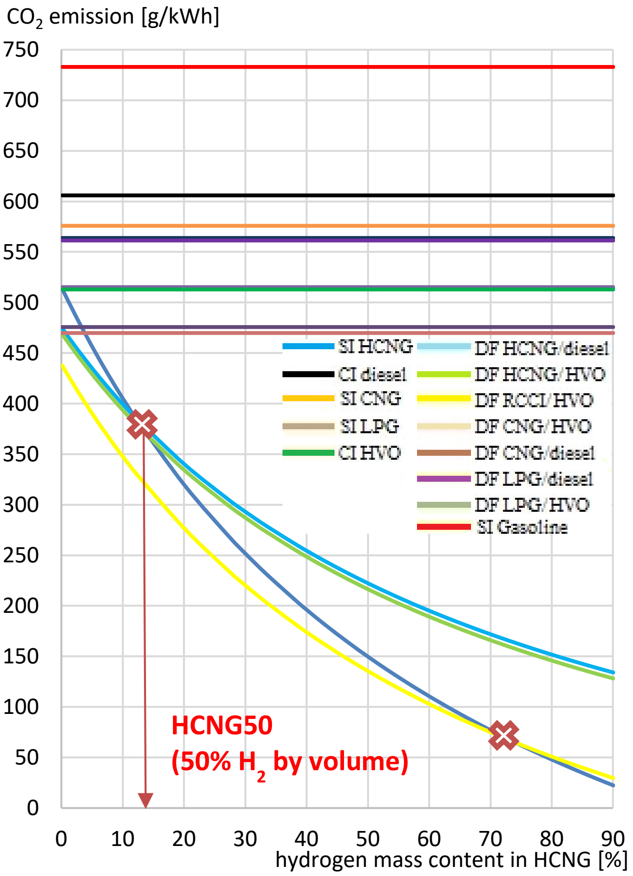


Fig. 10. Carbon dioxide emission intensity for different types of engines and different types of fuels used as a function of hydrogen content in HCNG fuel with maximal fuel replacement in DF mode at the 80% level for CNG & HCNG fuel and 35% for LPG

The graph above clearly shows the impact of the hydrogen content in HCNG on carbon dioxide emissions and shows the advantage of DF engines in the range where the hydrogen concentration in the HCNG mixture does not exceed 50% of the volume content in the mixture (~12% of the mass content). This is the limit value at which hydrogen can be mixed with NG without serious consequences related to the safety and impact of this fuel on the corrosiveness of steel [34] and other serious problems with combustion and distribution [1, 2, 13, 14, 20, 24, 29, 33, 36, 39, 41]. These hydrogen contents in HCNG constitute a mixture that can be effectively used in combustion engines, as determined in many tests [14, 20, 24]. To better understand the advantages of using two different types of engines in specific operating conditions, three additional simulations, presented in the charts below were presented and analyzed. Figure 11 and 12 represent engine used in transport, Fig. 13 represent the same type of engines but used in power engineering or industry.

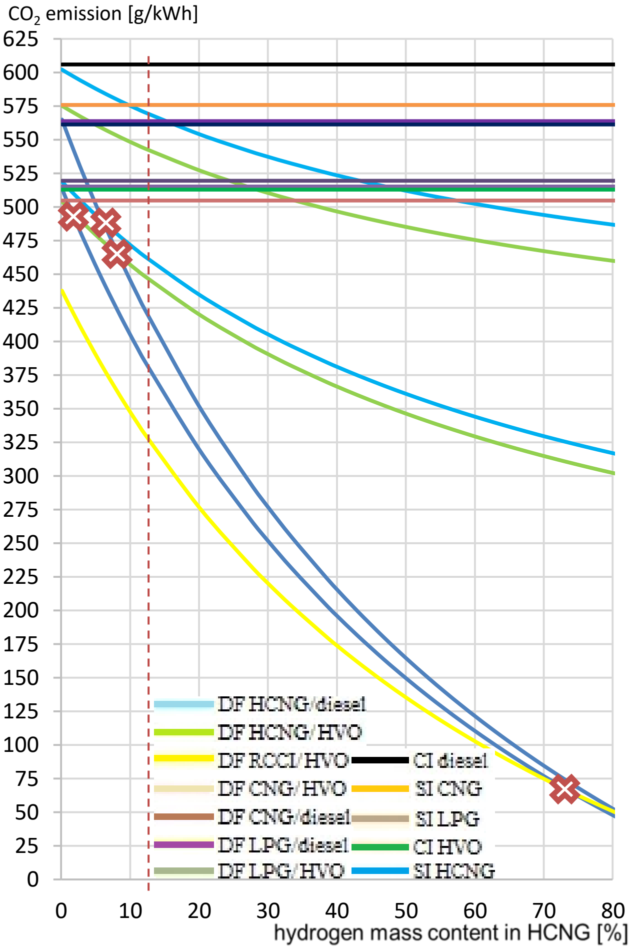


Fig. 11. Carbon dioxide emission intensity for different types of engines and different types of fuels used as a function of hydrogen content in HCNG fuel with maximal fuel replacement in DF mode at the 80% level and 50% level for CNG & HCNG fuel and 35% for LPG and different efficiency for engines using HCNG fuel

Lines of the same color symbolize the range in which an engine of a given type can operate when powered by a specific fuel. The line with the lowest achieved CO_2 emissions symbolizes the optimal operating point at which the engine operates, at which the assumed replacement rate is 80% and the maximum efficiency, as written earlier, is 45%. The line of the same color with the higher emission value shows the engine operating condition in which the maximum efficiency is reduced by 10%, which in this case results from the reduction of the engine speed, while the degree of replacement decreases in the square of its maximum value, i.e. for the maximum replacement of 50% it drops to 25%, and for 80% it drops to 64%. These values correspond to the values achieved on two types of gas installations that are most often used in DF engines. Lower replacement values allow the engine to operate at low load without the risk of knocking combustion. Both of these factors are taken into account in the emissions calculation for the line representing the maximum emissions during normal operation of the described engine. Dotted line shows the HCNG50 level.

Figure 11 shows that only when operating optimally (with high efficiency and degree of replacement), a DF engine is able to produce lower CO_2 emissions than an SI engine using HCNG fuel with a low H_2 content (< 50% V/V). The low replacement degree, which is characteristic of low-advanced and inexpensive gas installations, means that the use of SI engines actually becomes a more ecological solution, despite their lower overall efficiency. The graphs below (Fig. 12) show the CO_2 emissions with maximum replacement of a DF engine of 50% and 80%. The emission crossover points for the SI & DF engines show the H_2 content of HCNG at which CO_2 emissions are equal.

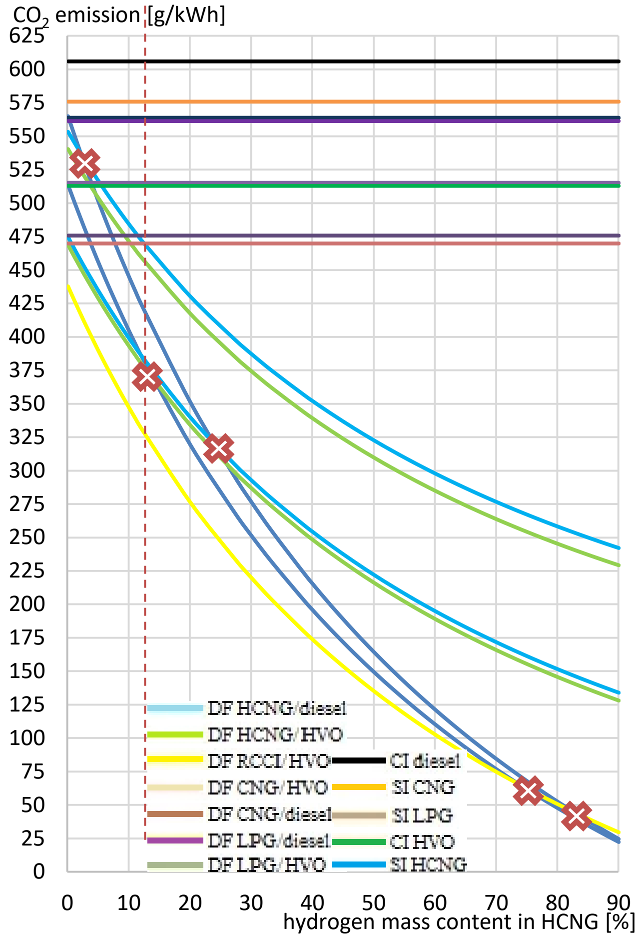


Fig. 12. Carbon dioxide emission intensity for different types of engines and different types of fuels used as a function of hydrogen content in HCNG fuel with maximal fuel replacement in DF mode at the 80% level for CNG & HCNG fuel and 35% for LPG

This clearly shows what type of engine is worth to use when HCNG fuel with a bit higher H_2 content is available. We can clearly see the contents, which SI engines prepared for gas fuel are a less emission-intensive option than DF engines. Even the use of HVO does not significantly change this situation and only when operating at the highest efficiency similar CO_2 emission values for both engine types are achieved. The level at which the RCCI engine is more emissive than the SI engine is a value very close to using pure H_2 with an admixture of NG, not NG with an admixture of H_2, and is beyond the reach of the currently used transmission infrastructure.

For the HCNG fuel at the level of hydrogen mass content around 5% (~20% V/V) the CO_2 emission is similar in DF HCNG fueled engines and SI HCNG engines. HCNG with a low H_2 content between 5–20% V/V is the popular option for the nearest future, what stands DF engines as the more ecological than SI engines, fueled by that kind of HCNG fuel mix.

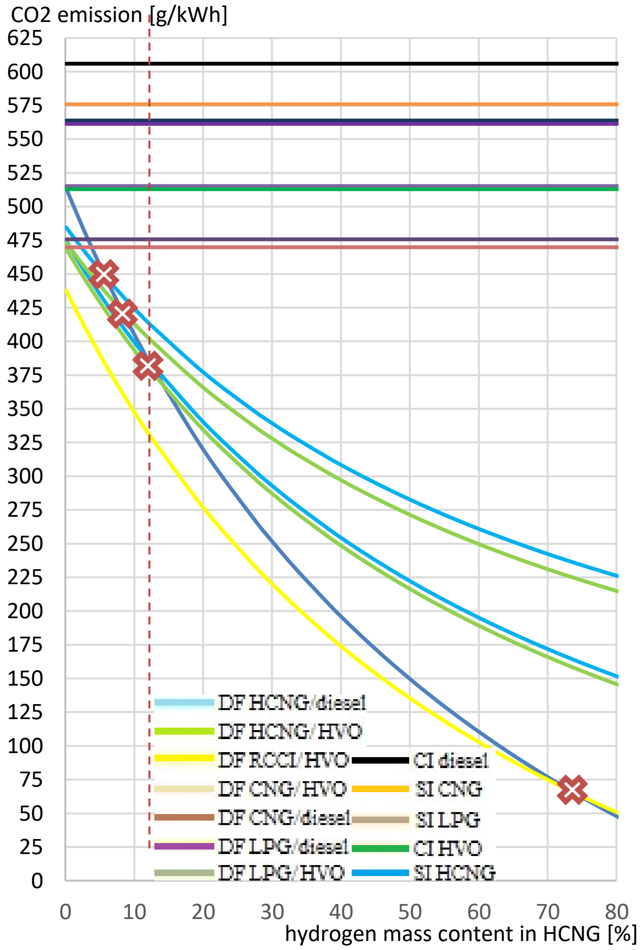


Fig. 13. Carbon dioxide emission intensity for different types of engines and different types of fuels used as a function of hydrogen content in HCNG fuel with maximal fuel replacement in DF mode at the 80% level and 50% level for CNG & HCNG fuel and 35% for LPG

The third graph shows a stationary engine operating at constant speed but with different loads. In the scope of operation of this engine, only the impact of changing the degree of fuel replacement was taken into account, and it was assumed that a higher generation gas installation was used, allowing for achieving high degrees of replacement, which in continuous operation as a power generator has its economic justification. A smaller range of CO_2 emissions in which the engine operates is visible. This allows to see more clearly when such an engine is emitting a similar amount of CO_2 as an equivalent SI engine where their emissions levels are crossing. For HCNG with H_2 mass content below 10%, it can be seen that even in the least optimal operating range, DF engines have a similar emission level to SI engines. The impact of the use of HVO is also more clearly visible here, which, with a reduced degree of replacement, significantly reduces the level of CO_2 emissions.

This proves that until the infrastructure for supplying hydrogen to end users is in place, dual-fuel engines will have an advantage over SI engines. When pure hydrogen can be distributed and burned in engines as the only fuel, or with highly reactive fuel, which is completely zero-emission.

4. Conclusions

In industrial engines, low-emission fuels will be of great importance due to their common occurrence in the power plants, industry and maritime transport, and the amount of fuel they consume. The cost-critical nature of these industries adds to the importance of the efficiency of the engines used in these industries. Therefore, our simulations allow us to determine the limits according to which we can be guided in the application of given types of engines, where dual-fuel engines should be used when using HCNG 0–50 fuel, while in cases where ammonia or pure hydrogen would be used, it would be more favorable for environmental reasons would be the use of CI engines.

Summing up, the presented solution can provide:

- reduction of CO_2 emissions in operating installations using internal combustion engines by over 35%
- lowering the operating costs of enterprises; flexibility in the use of different fuels
- increasing the operational reliability of the power system
- improving the structure of the energy mix
- increasing the potential for further development of green energy sources in the existing energy infrastructure
- extending the lifetime of internal combustion engines already produced and the existing power generation structure
- the use of a gas installation in DF engines, which allows for low levels of fuel substitution, leads to performance that is uncompetitive compared to SI engines in terms of CO_2 emissions
- stationary engines whose speed is constant and the load is always high enough to ensure that these engines operate with relatively high overall efficiency make their use justified at any available HCNG concentration
- the RCCI engines allows a reduction in CO_2 emissions practically over the entire range of H_2 content in HCNG compared to SI engines. When RCCI engines become widely available, the use of hydrogen-enriched fuels in fueling should become the standard.

Acknowledgements

This work was financed by Military University of Technology under University Research Grant UGB 22-833/2023.

Nomenclature

CI	compression ignition
CNG	compressed natural gas
CO_2	carbon dioxide
DDFS	direct dual fuel stratification
DF	dual fuel
EU	European Union
ICE	internal combusiton engines
GHG	greenhouse gas
HCCI	homogeneous charge compression ignition
HCNG	hydrogen enriched compressed natural gas
HVO	hydro-treated vegetable oil
H_2	hydrogen
LNG	liquefied natural gas
NG	natural gas
PV	photovoltaics
RES	renewable energy source
RCCI	reactivity controlled compression ignition
SI	spark ignition
UGB	university research grant
US	United States

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