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Combating climate change with hydrogen

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Abstract
Replacing fossil fuels with hydrogen helps us cut our carbon footprint and turn into green transportation. Hydrogen is an essential fuel for our secure and clean energy future. Hydrogen will be the future fuel, and gradually it will replace all current fossil fuels. The present work provides an overview of combating climate change with hydrogen as an alternative fuel for transportation, which can be used in internal combustion engines and fuel cells.

Keywords: Climate change; Hydrogen; Alternative fuel; Clean energy; Renewable energy.

1. Climate change

Burning fossil fuels for energy is mainly responsible for rising carbon dioxide concentrations. Fossil fuels contain carbon that plants pull out of the atmosphere through photosynthesis over many millions of years; when we use fossil fuels to produce energy, we return that carbon to the atmosphere in just a few hundred years. Carbon dioxide absorbs energy at a variety of wavelengths between 2,000 and 15,000 nanometers. As CO_2 soaks up this infrared energy, it vibrates and re-emits the infrared energy back in all directions. About half of that energy goes out into space, and almost half of it returns to Earth as heat, contributing to the ‘greenhouse effect.’ As carbon dioxide and other greenhouse gases heat up the planet, more water evaporates into the atmosphere, which in turn raises the temperature further. Figure 1 shows the change in average surface air temperature since the industrial revolution, plus drivers for that change. Human activity has caused increased temperatures, with natural forces adding some variability.

From the year of 1750 to 2020, 440 ± 20 Pg C (1 Pg C = 10^{15} g C) were emitted as CO_2 from fossil fuel burning [1]. For 2020 alone, global fossil fuel emissions reached 10 ± 0.5 Pg C yr−1 for the first time in history [1]. About half of the CO_2 emitted since 1750 remains in the atmosphere. The rest of it has partially dissolved in the world’s ocean. While the terrestrial biosphere is currently also a sink for fossil fuel CO_2, the cumulative emissions of CO_2 from land use changes such as deforestation cancel terrestrial uptake over the 1750-2020 period.

Each year we put more carbon dioxide into the atmosphere than natural processes can remove, which means the net global amount of carbon dioxide rises. The more we overshoot what natural processes remove, the faster the annual growth rate (Figure 2). In the 1960s, the global growth rate of atmospheric carbon dioxide was roughly 0.6 ± 0.1 ppm per year. Between 2009-2018, however, the growth rate has been 2.3 ppm per year. The annual rate of increase in atmospheric carbon dioxide over the past 60 years is about 100 times faster than previous natural increases, such as those that occurred at the end of the last ice age 11,000-17,000 years ago.

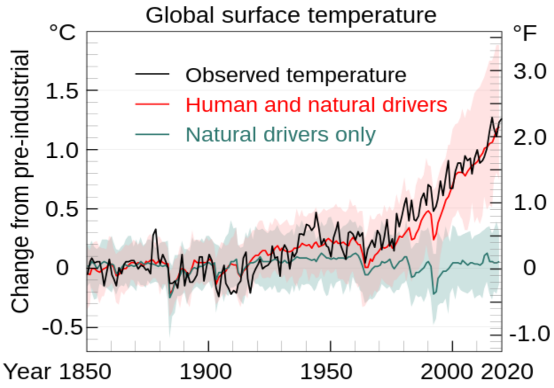

Figure 1. Global change in average surface air temperature since the industrial revolution.

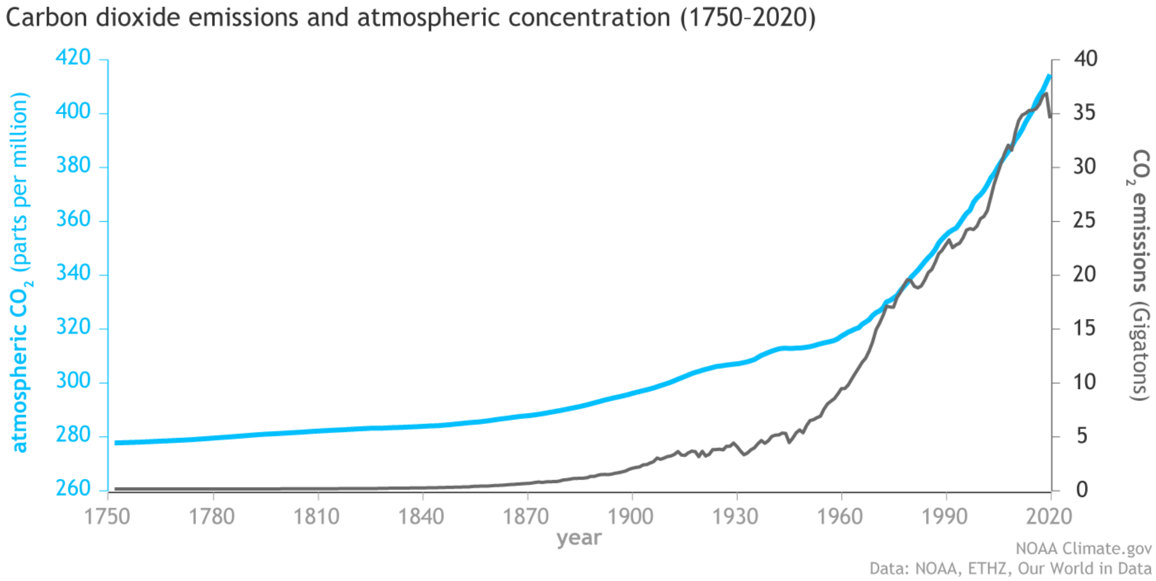

Figure 2. Carbon dioxide emissions and atmospheric concentration for a period from 1750 to 2020.

Carbon dioxide is a greenhouse gas: a gas that absorbs and radiates heat. Warmed by sunlight, Earth's land and ocean surfaces continuously radiate thermal infrared energy (heat). Unlike oxygen or nitrogen (which make up most of our atmosphere), greenhouse gases absorb that heat and release it gradually over time, like bricks in a fireplace after the fire goes out. Without this natural greenhouse effect, Earth's average annual temperature would be below freezing instead of close to 60°F. But increases in greenhouse gases have tipped the Earth's energy budget out of balance, trapping additional heat and raising Earth's average temperature.

Carbon dioxide is the most important of Earth's long-lived greenhouse gases. It absorbs less heat per molecule than the greenhouse gases methane or nitrous oxide, but it's more abundant, and it stays in the atmosphere much longer. Increases in atmospheric carbon dioxide are responsible for about two-thirds of the total energy imbalance that is causing Earth's temperature to rise.

Another reason carbon dioxide is important in the Earth system is that it dissolves into the ocean like the fizz in a can of soda. It reacts with water molecules, producing carbonic acid and lowering the ocean's pH (raising its acidity). Since the start of the Industrial Revolution, the pH of the ocean's surface waters has dropped from 8.21 to 8.10. This drop in pH is called ocean acidification.

A drop of 0.1 may not seem like a lot, but the pH scale is logarithmic; a 1-unit drop in pH means a tenfold increase in acidity. A change of 0.1 means a roughly 30% increase in acidity. Increasing acidity interferes with the ability of marine life to extract calcium from the water to build their shells and skeletons.

Figures (3-9) show the measured data on the change in carbon dioxide concentration and its accumulation.

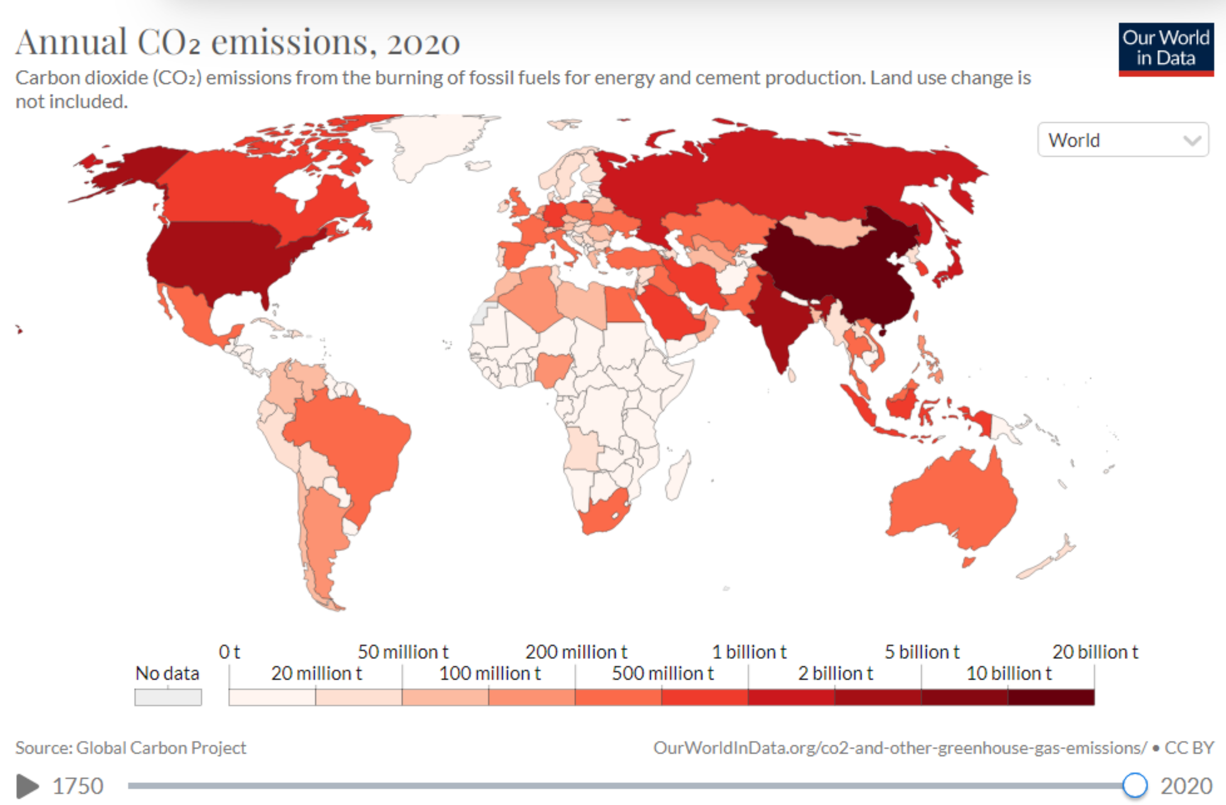

Figure 3. Annual CO_2 emissions, 2020.

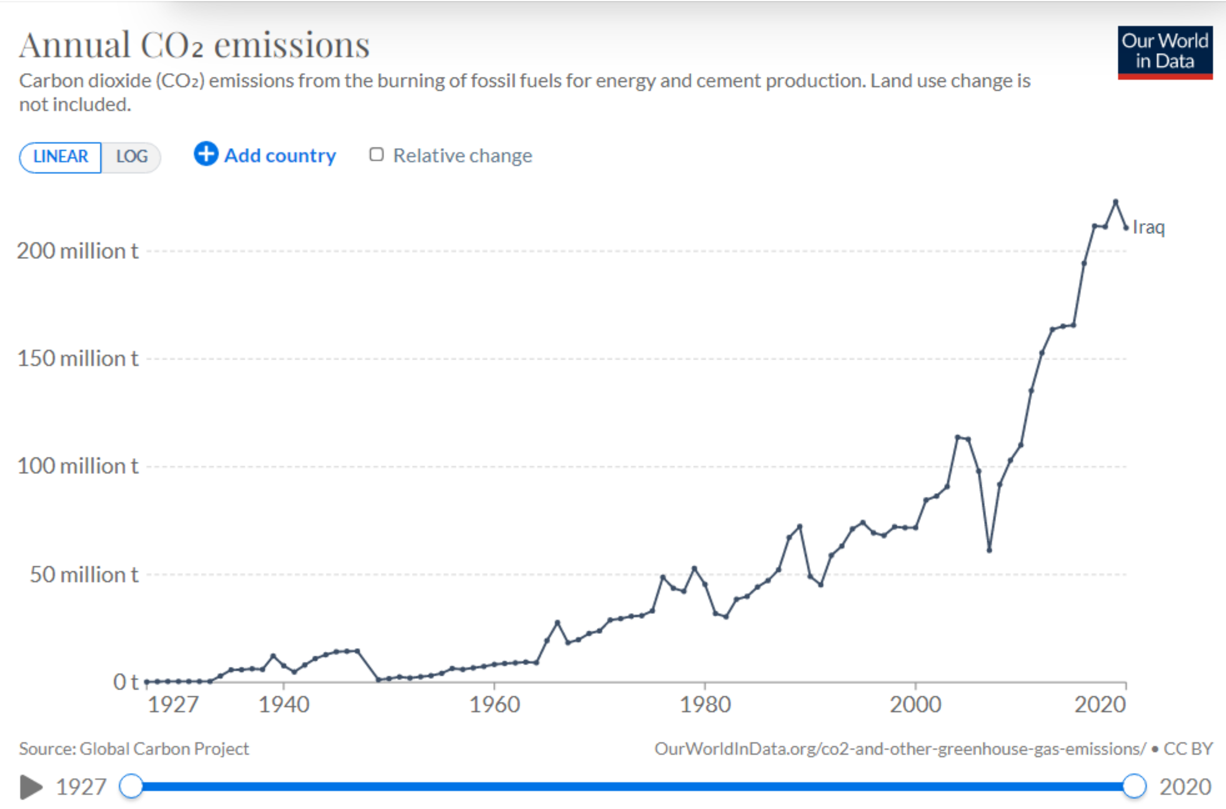

Figure 4. Annual CO_2 emissions for a period from 1927 to 2020.

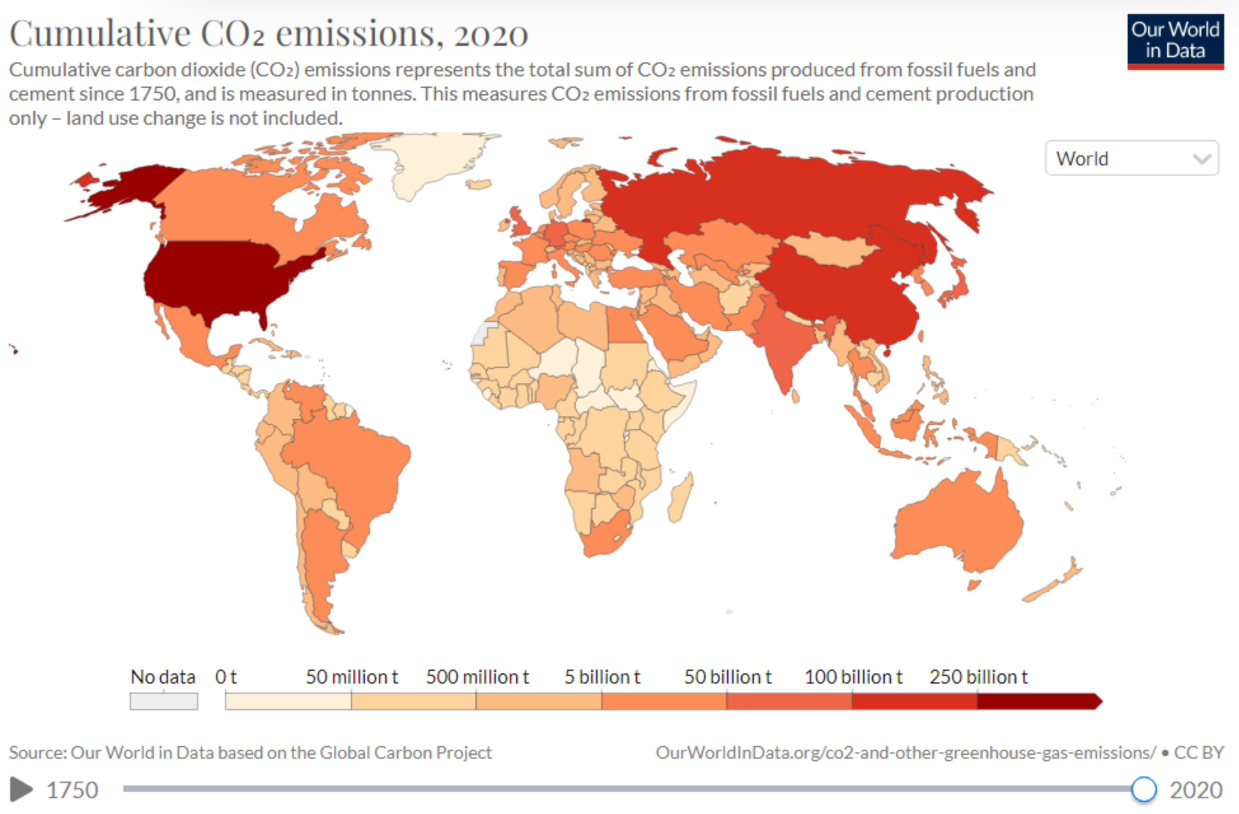

Figure 5. Cumulative CO_2 emissions, 2020.

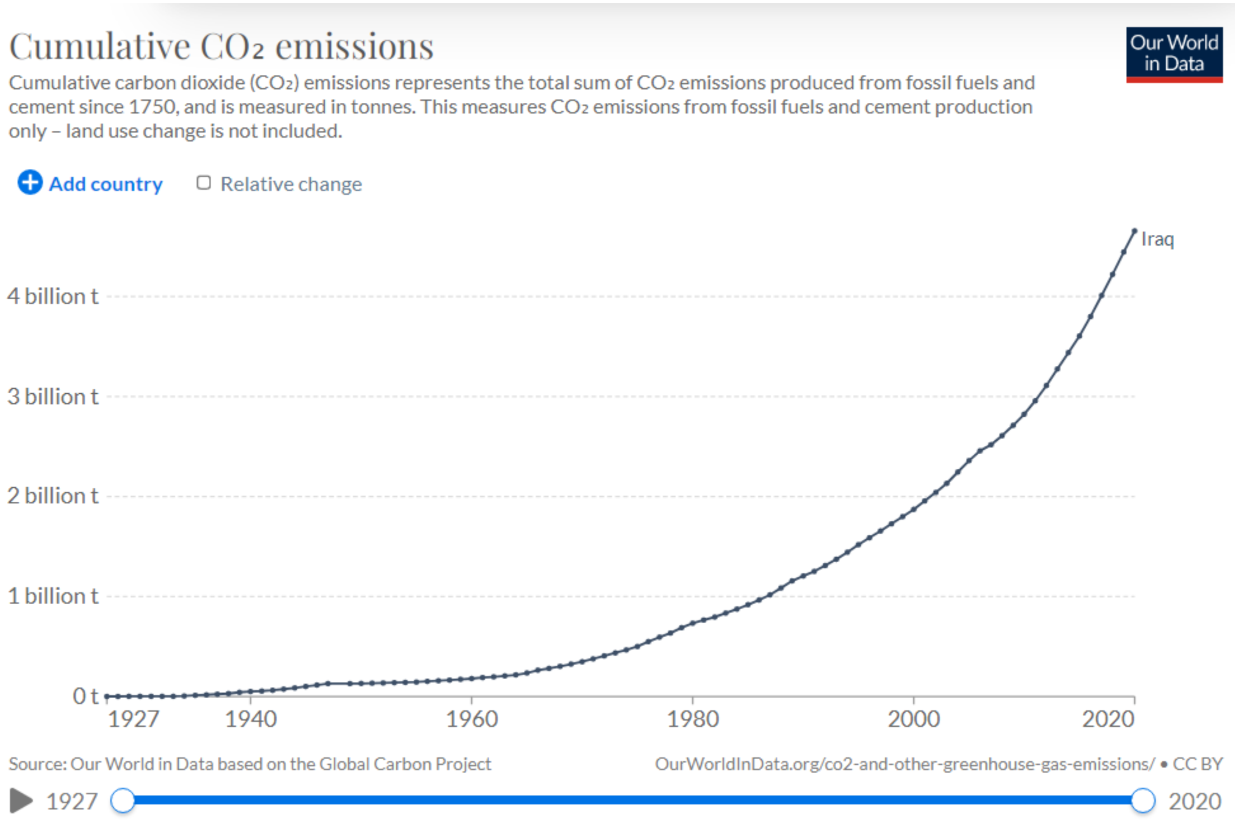

Figure 6. Cumulative CO_2 emissions for a period from 1927 to 2020.

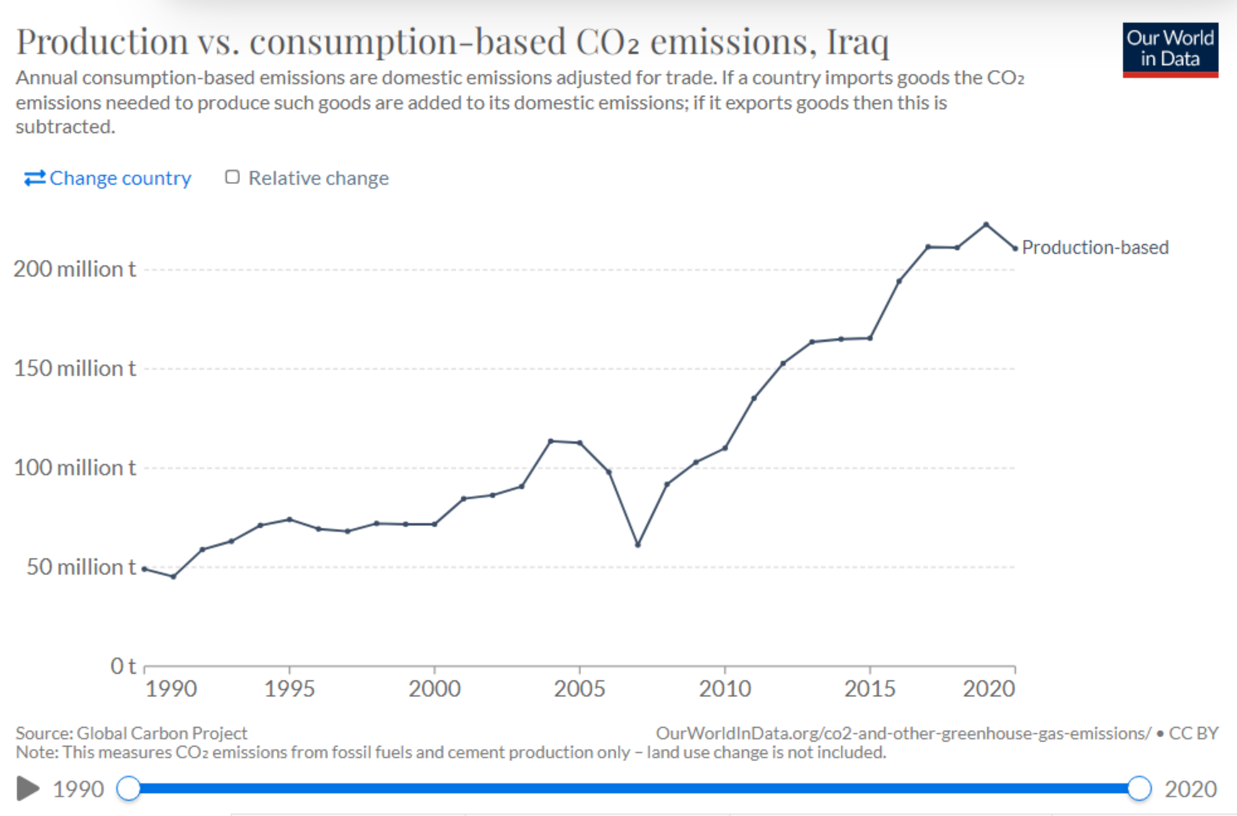

Figure 7. Production vs. consumption-based CO_2 emission, Iraq.

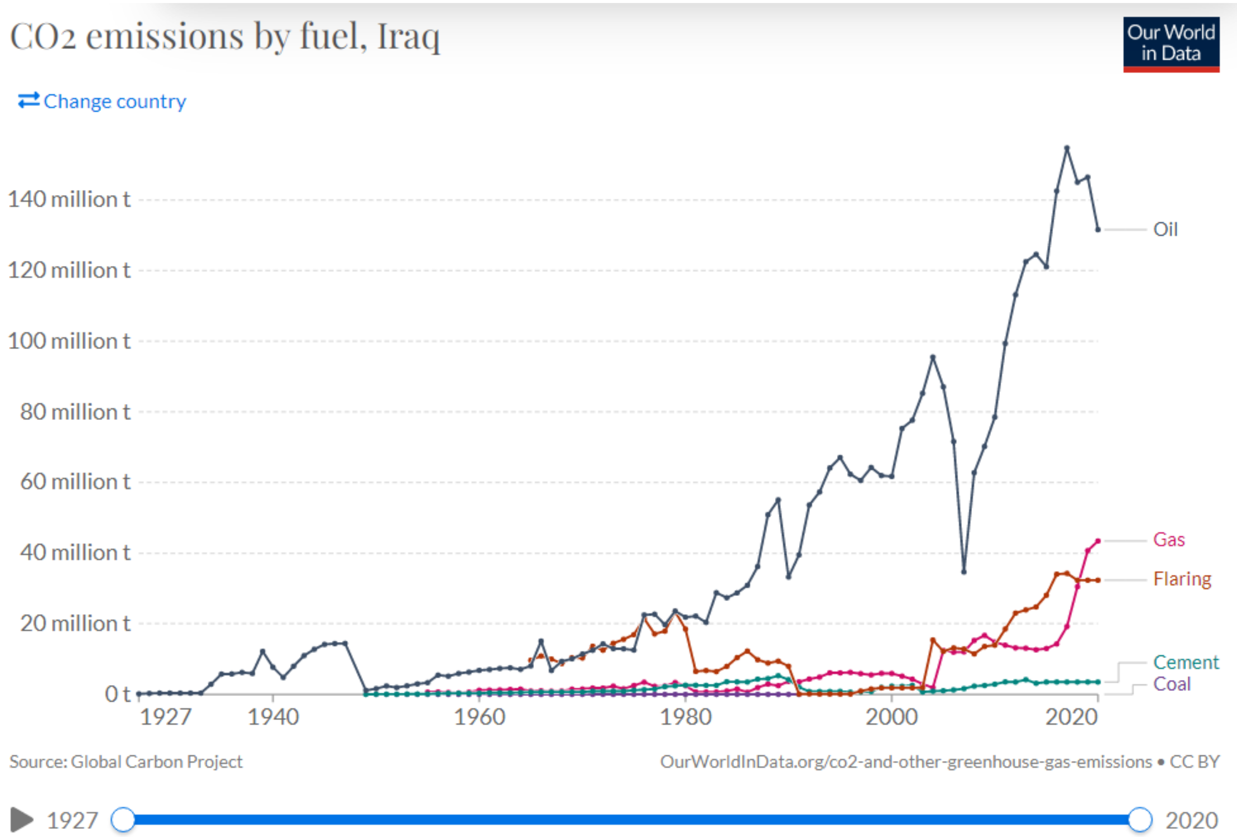

Figure 8. CO_2 emissions by fuel, Iraq.

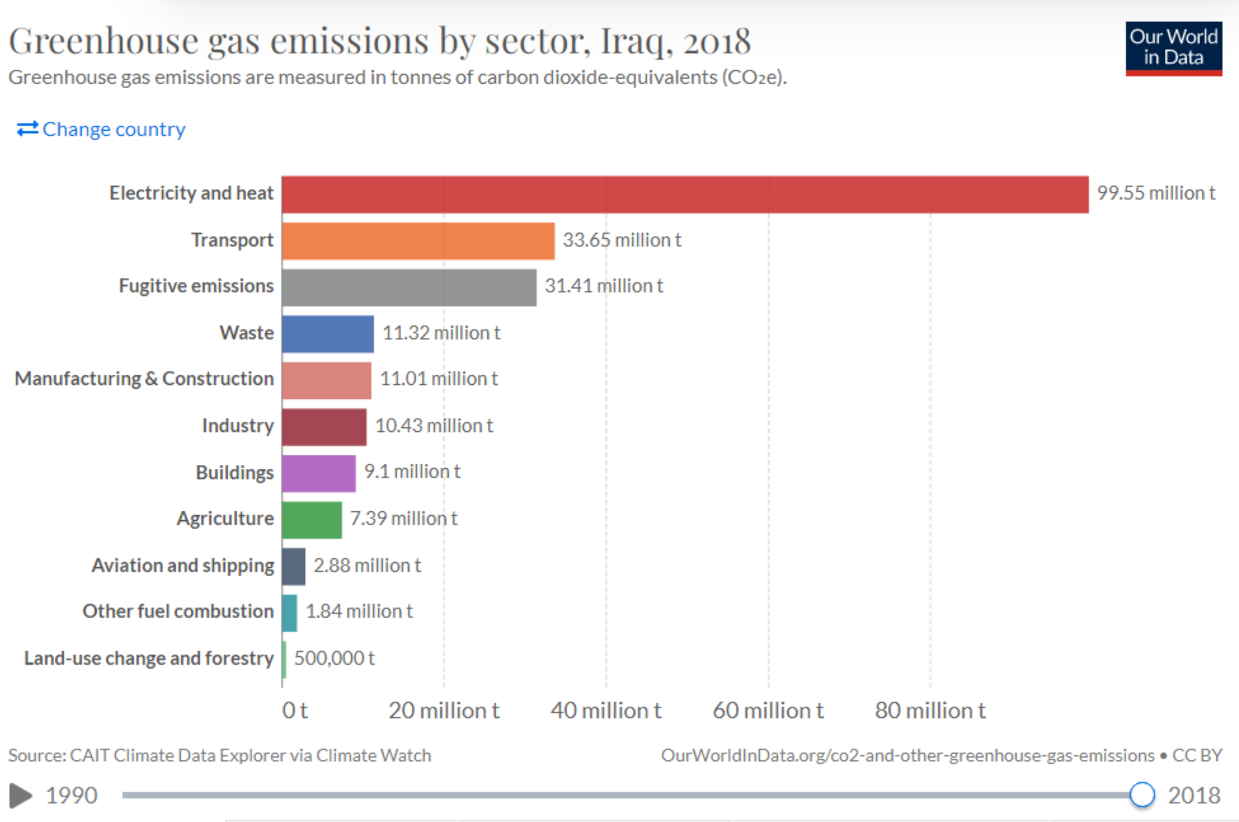

Figure 9. Greenhouse gas emissions by sevtor, Iraq, 2018.

2. Hydrogen fuel

Hydrogen is abundant, being the most common element in the universe. The sun consumes 600 million tons of it each second. But unlike oil, large reservoirs of hydrogen are not to be found on earth. The hydrogen atoms are bound together in molecules with other elements, and it takes energy to extract the hydrogen so it can be used for combustion or fuel cells. Hydrogen is not a primary energy source, but it can be viewed as a means of exchange for getting energy to where it is needed, much like electricity. Hydrogen is a sustainable, non-polluting source of power that could be used in mobile and stationary applications. As an energy carrier, it could increase our energy diversity and security by reducing our dependence on hydrocarbon-based fuels. Although hydrogen is the simplest element and most plentiful gas in the universe, it never occurs by itself but is always combined with other elements such as oxygen and carbon. But once it has been separated, hydrogen is an extremely clean energy carrier [1]. Hydrogen can be extracted from fossil fuels and biomass, from water, or from a mix of both.

3. Hydrogen fuel storage systems

Hydrogen as an energy carrier must be stored to overcome daily and seasonal discrepancies between energy source availability and demand. Hydrogen can be stored physically as either a gas or a liquid. Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar [5,000–10,000 psi] tank pressure). Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is (−252.8°C). Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption) [1].
The most commonly used method for hydrogen storage in fuel cell vehicles is compressed hydrogen tanks. Several vehicles (e.g. Honda FCV, Toyota FCV, Mercedes-Benz F-Cell, Hyundai FCV, and GM FCV) with such tanks are already in use today. The most important consideration for compressed gas is the material composing the tank. It must be lightweight, inexpensive and sufficiently strong to meet the required stress, strain and safety specifications. In addition, thermal conductivity of the material must be high enough to manage exothermic heat during filling the tank.

When hydrogen is stored as liquid at 1 atm, it must be maintained below its boiling point (−252.8°C). Therefore, effective thermal insulation is essential to maximize the efficiency of the liquid hydrogen tank. Therefore, typical liquid hydrogen tanks consist of metallic double-walled container, where the inner and outer walls are separated by vacuum for thermal insulation purposes. Despite improved volumetric density, liquid hydrogen storage is not frequently used for several reasons. One of main issues is hydrogen boil-off. The liquid hydrogen can evaporate even with highly insulated tank, which causes hydrogen loss. In addition, the boil-off occurs even when the system is dormant and increases the pressure of the tank which must be vented to prevent rupture. Apart from cost and energy efficiency penalty due to hydrogen loss, the boil-off also presents safety concerns, particularly for vehicles parked in confined space such as containers and parking garages. Second, 30-35% of energy value of hydrogen is required to liquefy it, which is about 3 times larger than needed for compressed H_2 tank [1].

As noted above, compressed tank requires a relatively large volume while liquid hydrogen can vaporize to cause loss of hydrogen as well as safety concerns. Consequently, studies of physical hydrogen storage have currently shifted to cryo-compressed H_2, which combines compression and cryogenic storage. The volumetric density of hydrogen can be increased by pressurizing liquid hydrogen at 20 K from 70 g/L at 1 bar to 87 g/L at 240 bars, which reduces the requirement for expensive carbon fiber composite. In addition, it can decrease evaporative loss of hydrogen as well as extend the dormancy period in insulated pressure vessels [1].

Metal hydride tank is a container loading with hydrogen storage alloy powder, heat exchange parts, and gas transport components. The container body materials are generally aluminum alloy or stainless steel. Hydrogen is stored in the form of so-called “metal hydride”. Most metals or alloys can react with hydrogen to form new compounds, which are named as metal hydrides. The formation of metal hydride is an exothermic process associated with heat releasing. With sufficient heat supply, hydrogen can be released from the as-formed metal hydride. Some metal hydrides have the potential for reversible on-board hydrogen storage and release hydrogen at the relatively low temperatures and pressures required for fuel cells [1].

As compared to conventional metal hydrides, complex metal hydrides offer the potential to improve gravimetric hydrogen capacity. However, complex metal hydrides still provide relatively low hydrogen capacity and slow hydrogen uptake and release kinetics. Many different types of metal hydrides have been studied as means of hydrogen storage. However, superior hydrogen release properties (yield and kinetics) are obtained at temperatures much higher than PEM fuel cell operation conditions.

High surface area sorbents based on metal-organic frameworks have been considered as promising materials for hydrogen storage ever due to their high porosity and controllable structural characteristics. The metal-organic frame works are crystalline and micro porous solids composed of metal ions or clusters linked with organic molecules and typically have surface area greater than 3000 m^2/g. Despite reversible nature of the hydrogen absorption/desorption process for high surface area sorbents and carbon-based materials, they suffer from lower hydrogen capacity, especially under mild operating conditions.

As compared to metal hydrides, chemical hydrides offer higher energy densities since they contain lighter elements. In addition, they can release hydrogen under relatively mild operating conditions. The dehydrogenation reactions, however, are irreversible, so the resulting products have to be regenerated off-board the vehicle.

In conclusion, although hydrogen has high gravimetric energy density, its volumetric energy density is poor, which presents a significant barrier for use of hydrogen on-board fuel cell vehicles. Current approaches for on-board hydrogen storage include compressed hydrogen gas, cryogenic and liquid hydrogen, sorbents, metal hydrides, and chemical hydrides. The advantages and disadvantages for each approach are summarized in Table 1.

Technologies for hydrogen conversion into other useful energy forms have already been developed and demonstrated. In almost all cases hydrogen is converted more efficiently than any other fuel, and more important, hydrogen conversion creates little or no emissions (mainly water or water vapor). These technologies are the driving force for development of technologies for hydrogen production and storage [2].

Table 1. Advantages and disadvantages of different hydrogen storage approaches [1].

H_2 storage system	Advantages	Disadvantages
Compressed H_2	• Commercially available.	• Low volumetric capacity. • High compression energy. • Heat management during charging required.
Liquid H_2	• Commercially available.	• H_2 loss. • Safety issue. • High liquefaction energy. • Heat management to reduce boil-off.
Cryo-compressed	• High volumetric capacity.	• High compression/liquefaction energy.
Metal hydride	• Reversible on-board.	• Low gravimetric/volumetric capacity. • Heat management during charging required. • High operating temperature for H_2 release.
Sorbent and carbon-based materials	• Reversible on-board.	• Low volumetric density. • Loss of useable H_2. • Low operating temperature for H_2 uptake.
Chemical hydride	• Good volumetric capacity. • Proper operating temperatures.	• Thermal management required. • Off-board regeneration.

4. Safety aspects of hydrogen as fuel

Like any other fuel or energy carrier, hydrogen poses risks if not properly handled or controlled. The risk of hydrogen, therefore, must be considered relative to the common fuels such as gasoline, alcohol, propane, or natural gas. The specific physical characteristics of hydrogen are quite different from those common fuels. Some of these properties make hydrogen potentially less hazardous, whereas other hydrogen characteristics could theoretically make it more dangerous in certain situations. Because hydrogen has the smallest molecule, it has a greater tendency to escape through small openings than other liquid or gaseous fuels. If a leak should occur for whatever reason, hydrogen will disperse much faster than any other fuel, thus reducing the hazard levels. Hydrogen is both more buoyant and more diffusive than gasoline, propane, or natural gas [3].

Hydrogen/air mixture can burn in relatively wide volume ratios, between 4% and 75% of hydrogen in air. Other fuels have much lower flammability ranges, viz., natural gas 5.3-15%, propane 2.1-10%, and gasoline 1-7.8%. However, this range has little practical value. In many actual leak situations the key parameter that determines if a leak would ignite is the lower flammability limit, and hydrogen's lower flammability limit is 4 times higher than that of gasoline, 1.9 times higher than that of propane, and slightly lower than that of natural gas [3].

Hydrogen has a very low ignition energy (0.02 mj), about one order of magnitude lower than other fuels. Ignition energy is a function of the fuel/air ratio, and for hydrogen it reaches a minimum at about 25-30% hydrogen content in air. At the lower flammability limit (LFL), hydrogen ignition energy is comparable to that of natural gas [3].

Hydrogen has a flame velocity 7 times faster than that of natural gas or gasoline. A hydrogen flame would therefore be more likely to progress to a deflagration or even a detonation than other fuels. However, the likelihood of a detonation depends in a complex manner on the exact fuel/air ratio, the temperature, and particularly the geometry of the confined space. Hydrogen detonation in open atmosphere is highly unlikely.

The lower detonability fuel/air ratio for hydrogen is 13-18%, which is two times higher than that of natural gas and 12 times higher than that of gasoline. Because the lower flammability limit is 4%, an explosion is possible only under the most unusual scenarios, for example, hydrogen would first have to accumulate and reach 13% concentration in a closed space without ignition, and at that point an ignition source would have to be triggered. Should an explosion occur, hydrogen has the lowest explosive energy

per unit of stored energy of any fuel, and a given volume of hydrogen would have 22 times less explosive energy than the same volume filled with gasoline vapor [3].
Hydrogen flame is nearly invisible, which may be dangerous, because people in the vicinity of a hydrogen flame may not even realize there is a fire. This may be remedied by adding chemicals that will provide the necessary luminosity. The low emissivity of hydrogen flames means that nearby materials and people will be much less likely to ignite or be hurt by radiant heat transfer. The fumes and soot from a gasoline fire pose a risk to anyone inhaling the smoke, whereas hydrogen fires produce only water vapor (unless secondary materials begin to burn).
Liquid hydrogen presents another set of safety issues, such as risk of cold burns, and the increased duration of leaked cryogenic fuel. A large spill of liquid hydrogen has some characteristics of a gasoline spill; however, it will dissipate much faster. Another potential danger is a violent explosion of a boiling liquid expanding vapor in case of a pressure relief valve failure.
Hydrogen on-board a vehicle may pose a safety hazard. Such hazards should be considered in situations when the vehicle is inoperable, when the vehicle is in normal operation, and in collisions. Usually, potential hazards are due to fire, explosion, or toxicity. The latter can be ignored, because neither hydrogen nor its fumes in case of fire are toxic. Hydrogen as a source of fire or explosion may come from the fuel storage, from the fuel supply lines, or from the fuel cell itself. The fuel cell poses the least hazard, although in a fuel cell hydrogen and oxygen are separated by a very thin polymer membrane. In case of membrane rupture hydrogen and oxygen would combine, and the fuel cell would immediately lose its potential, which should be easily detected by a control system. In such a case the supply lines would be immediately disconnected.
In conclusion, hydrogen appears to pose risks of the same order of magnitude as other fuels. In spite of public perception, in many aspects hydrogen is actually a safer fuel than gasoline and natural gas. Table 2 compares hydrogen properties with other fuels and ranks their effect on safety [3].

Table 2. Summary of hydrogen safety related properties compared with other fuels [1, 3].

Property	Compare with other fuels	Risk
Leak probability	Higher than other fuels	Dangerous
Volume of fuel released in leak	Higher than other fuels	Same as other fuels
Energy of fuel released in leak	Lower than other fuels	Safe
Diffusivity and buoyancy	Higher than other fuels	Safe
Lower flammability limit in air	Higher than other fuels	Same as other fuels
Minimum ignition energy	Lower than other fuels	Same as other fuels
Ignition energy at LFL	~Same as other fuels	Same as other fuels
Flame velocity	Higher than other fuels	Dangerous
Lower detonability fuel/air ratio	Higher than other fuels	Safe
Explosive energy per energy stored	Lower than other fuels	Safe
Flame visibility	Lower than other fuels	Dangerous
Flame emissivity	Lower than other fuels	Safe
Flame fumes toxicity	Lower than other fuels	Safe
Fuel toxicity	Lower than other fuels	Safe

5. Hydrogen as an internal combustion engine fuel

Hydrogen is an alternative fuel resource that can be produced through the expenditure of energy as a replacement for declining reserves of conventional fossil fuels. It has long been recognized as a fuel has some unique and highly desirable properties for application in engines. These features give hydrogen excellent potential as a fuel to meet the ever more stringent environmental controls of exhaust emissions from combustion devices, including the reduction of greenhouse gas emissions [3, 4].

The use of hydrogen as an internal combustion engine fuel, as a primary or supplementary fuel, appears to promise a significant improvement in the performance of a spark ignition engine. Besides being the cleanest burning chemical fuel, hydrogen can be produced from water (using non-fossil energy) and conversely, on combustion forms water again by closed cycle. The self-ignition temperature of the hydrogen/air mixture is greater than that of the other hydrocarbon fuels and, therefore a small amount of hydrogen addition produces an antiknock quality of fuel. Hydrogen is characterized by having the highest energy-mass coefficient of the chemical fuel and in terms of mass energy consumption it exceeds the conventional gasoline fuel by about 3 times, alcohol 5 to 6 times, methane and propane 2.5 times. Therefore the results clearly establish that the supplemental hydrogen can increase the effective efficiency of the engine and reduce the specific fuel consumption.
A small amount of hydrogen mixed with hydrocarbon fuel and air produces a combustible mixture, which can be burned in a conventional spark ignition engine at an equivalence ratio below the lean flammability limit of hydrocarbon fuel/air mixture. The resulting ultra-lean combustion produces low flame temperature and leads directly to lower heat transfer to the walls, higher engine efficiency and lower exhaust of CO and NOx. The burning velocity of hydrogen/air mixture is about seven times higher than that of all hydrocarbon-fuel/air mixture. As the burning velocity rises, the actual indicator diagram approaches closer to the ideal diagram and a higher thermodynamic efficiency is achieved. The high molecular diffusivity of the hydrogen into the air improves the mixture uniformity and hence the combustion efficiency and cycle-to-cycle variation. The using of gaseous fuel (rather than a liquid fuel) for short periods during cold start and warm-up, avoids problems of cold fuel evaporation, uneven distribution of the fuel to the different cylinders due to the presence of a liquid film on the walls of the intake manifold and to unwanted large variations in supplied air-fuel ratio during transient conditions such as acceleration and deceleration. Table 3 shows the properties of hydrogen and the hydrocarbon fuels [3].

Table 3. Comparison properties of hydrogen and hydrocarbon fuels.

Property	Hydrogen	Methane	Propane	Ethanol	Methanol	Gasoline
Chemical Formula	H_2	CH_4	C_3H_8	C_2H_5OH	CH_3OH	C_8H_{18}
Molecular Weight	2.02	16.04	44.1	46.07	32.04	102
Molar carbon to hydrogen ratio	0.000	0.250	0.375	0.333	0.250	0.444
Stoichiometric air/fuel ratio, mass	34.32	17.20	15.67	9.00	6.45	15.11
Latent heat of vaporization (kJ/kg)	446	509	449	921	1176	348
Lower heating value (MJ/kg)	119.93	50.02	46.40	26.86	19.93	44.50
Flammability limits (% by volume)	4.1-74	5.3-15	2.2-9.5	4.3-19	7.3-36	1.4-6.7
Self-ignition temperature (oK)	855	813	755	696	737	530
Combustion speed in air (m/s)	2.933	0.355	0.432	0.455	0.455	0.356
Octane number (R+M)/2	130+ (R)	120+	104	100	100	86-94

Flexible-fuel engines are designed to use several fuels. Flexible-fuel engines are able to use a variable mixture of two or more different fuels, as long as they are alike physically [4]. Vehicles with flexible-fuel engines are not in widespread use since dedicated-fuel vehicles that operate on a single fuel are typically cheaper. Most gasoline-powered engines can be converted to dual-fuel engines with natural gas/propane or hydrogen for example [5]. The conversion does not require the removal of any of the original equipment. A natural gas/propane or hydrogen pressure tank is added, along with a fuel line to the engine through special mixing equipment [3-5]. A switch selects either gasoline, of gas fuel like hydrogen or natural gas/propane operation [4]. Diesel vehicles can also be converted to a dual-fuel configuration [4, 5].

6. Hydrogen and fuel cells

Fuel Cell system is an advanced power system for the future that is sustainable, clean and environmental friendly. Fuel Cells are electrochemical devices that directly convert the chemical energy of hydrogen fuel into electricity. In general, fuel cells offer many advantages over conventional energy conversion devices. Fuel cells have higher energy efficiencies, silent, vibration free and zero emissions at point of use. One major advantage of hydrogen fuel cells becomes apparent when we compare their efficiencies to the efficiency of a hydrogen internal combustion engine. The efficiency range for the hydrogen fuel cells ranges from 45 to 75%. Whereas, the typical efficiency of an internal combustion engine fueled with hydrogen is on the order of 35% [6-9]. The hydrogen fuel-cells convert compressed hydrogen from their fuel tanks into electricity that powers the electric motor in the vehicle, providing a similar range to vehicles powered by internal combustion engines using hydrogen or fossil fuels.

7. Maximum thermodynamic efficiency

The natural limitation on the thermodynamic efficiency for an ideal Carnot cycle heat engine can be shown as;

$$\eta_{max} = 1 - \frac{T_L}{T_H} \quad (1)$$

where the *TL* and *TH* are the temperatures of heat rejection and heat addition, respectively.

The maximum possible thermodynamic efficiency of a hydrogen PEM fuel cell can be written as;

$$\eta_{max} = 1 - \frac{T\Delta S}{\Delta H} \quad (2)$$

Figure 10 shows a comparison of the maximum thermodynamic efficiency of an ideal hydrogen heat engine and an ideal hydrogen fuel cell with vapour water as the exhaust. The figure shows that the maximum thermodynamic efficiency is not always greater for the hydrogen fuel cell. At high temperatures, the hydrogen heat engine can theoretically be more efficient. The hydrogen fuel cell shows a decreasing efficiency with temperature. However, the figure shows only the maximum possible efficiency, which will not be obtained in practice for the hydrogen heat engine or hydrogen fuel cell. For the hydrogen fuel cell, the efficiency decreases with increasing electrical power, so that it only approaches the theoretical value at open-circuit conditions, where no useful electrical work is produced.

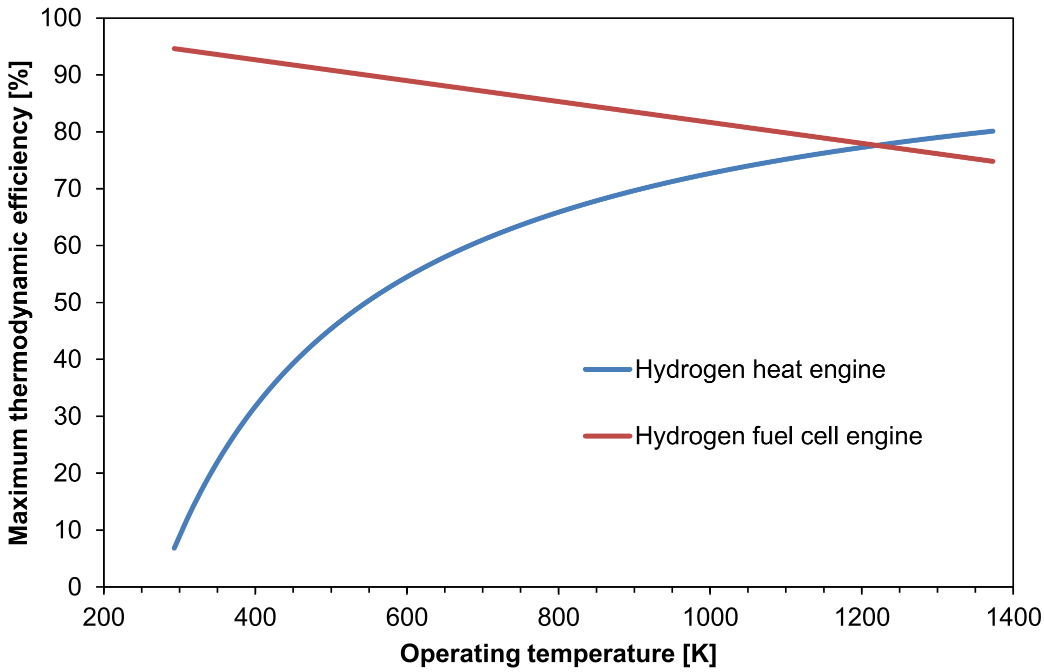

Figure 10. Comparison of maximum thermodynamic efficiency for hydrogen heat engine (Carnot cycle, exhaust to 273 K) and hydrogen fuel cell engine (vapour-phase water, LHV).

8. Conclusions

Hydrogen is one of the energy carriers which can replace fossil fuel, and can be used as fuel in internal combustion engine's vehicles and also in fuel cell vehicles. To use hydrogen as a fuel of internal combustion engine, engine design should be considered for avoiding pre-ignition and abnormal combustion. As a result it can improve engine efficiency, power output and reduce the pollutant emissions. The emission of fuel cell is very low and it work with higher efficiency as compared to conventional internal combustion engines but as penalty, fuel cell vehicles need additional space and weight to install the battery and storage tank, thus increases it production cost.

References

[1] Rebecca Lindsey, Climate Change: Atmospheric Carbon Dioxide, NOAA Climate 2021.

[2] Hannah Ritchie, Max Roser and Pablo Rosado, "CO_2 and Greenhouse Gas Emissions", 2020. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

[3] Maher A.R. Sadiq Al-Baghdadi. Alternative Fuels Research Progress. International Energy and Environment Foundation 2013, (442 pages), ISBN-13: 9781484057711.

[4] Maher A.R. Sadiq Al-Baghdadi. Hydrogen - Gasoline Fueled SI Engine Simulation. International Energy and Environment Foundation 2020, (50 pages), ISBN-13: 9798634169286.

[5] Maher A.R. Sadiq Al-Baghdadi. Green Hydrogen and the Beginning of a New Energy Era. International Journal of Energy and Environment (IJEE) 2021, 12(10), pp. 1-62.

[6] Maher A.R. Sadiq Al-Baghdadi. PEM FUEL CELLS - From Fundamentals to Research Studies. International Energy and Environment Foundation. 2020, (478 pages). ISBN-13: 9798634858883.

[7] Maher A.R. Sadiq Al-Baghdadi. CFD Models for Analysis and Design of PEM Fuel Cells. NOVA SCIENCE PUBLISHERS, INC, 400 Oser Avenue, Suite 1600, Hauppauge, NY 11788-3619 USA. 2008, (202 pages). ISBN-13: 9781604569971.

[8] Maher A.R. Sadiq Al-Baghdadi. CFD Modeling and Analysis of Different Novel Designs of Air-Breathing PEM Fuel Cells. NOVA SCIENCE PUBLISHERS, INC, 400 Oser Avenue, Suite 1600, Hauppauge, NY 11788-3619 USA. 2010, (202 pages). ISBN-13: 9781608764891.

[9] Maher A.R. Sadiq Al-Baghdadi. Al-Baghdadi, Advanced CFD Technology for Design and Optimize Future PEM Fuel Cells with a Higher Power Density and Long Cell Life: A Comprehensive Study (August 20, 2021). http://dx.doi.org/10.2139/ssrn.3908743