GECF

# HYDROGEN SCENARIO

NOVEMBER 2019

GECF


Tornado Tower, 47th & 48th Floors, West Bay
Doha, Qatar
P.O. Box 23753
www.gecf.org
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# About the GECF

The Gas Exporting Countries Forum (the GECF or the Forum) is an intergovernmental organisation established in May 2001 in Tehran, Islamic Republic of Iran. The GECF Statute and the Agreement on its functioning were signed in 2008, in Moscow, Russia. It became a full-fledged organization in 2008 with its permanent Secretariat based in Doha, Qatar.

The GECF comprises twelve Members and eight Observer Members (hereafter referred to as GECF Countries). The Member Countries of the Forum, are Algeria, Bolivia, Egypt, Equatorial Guinea, Iran, Libya, Nigeria, Qatar, Russia, Trinidad and Tobago, the United Arab Emirates and Venezuela (hereafter referred to as Members). Angola, Azerbaijan, Iraq, Kazakhstan, Norway, Oman and Peru have the status of Observer Members (hereafter referred to as Observers).

The GECF is a gathering of the world's leading gas producers, whose objective is to increase the level of coordination and to strengthen collaboration among Members. The Forum provides a framework for the exchange of views, experiences, information, and data, and for cooperation and collaboration amongst its Members in gas-related matters.

The GECF represents more than two-thirds of the world's proven gas reserves, almost half of global natural gas production, and around two-thirds of gas exports.

In accordance with the GECF Statute, the organization aims to support the sovereign rights of its Member Countries over their natural gas resources and their abilities to develop, preserve and use such resources for the benefit of their peoples, through the exchange of experience, views, information and coordination in gas-related matters.

In accordance with the GECF Long-Term Strategy, adopted during the 18th GECF Ministerial Meeting, the priority objectives of the GECF are as follows:

Objective No. 1: Maximizing gas value, namely to pursue opportunities that support the sustainable maximization of the added value of gas for Member Countries.

Objective No. 2: Developing the GECF View on gas market developments through short-, medium- and long-term market analysis and forecasting.

Objective No. 3: Co-operation, namely to develop effective ways and means for cooperation amongst GECF Member Countries in various areas of common interests.

Objective No. 4: Promotion of natural gas, namely to contribute to meeting future world energy needs, to ensure global sustainable development and to respond to environmental concerns, in particular with regard to climate change.

Objective No. 5: International positioning of the GECF as a globally recognized intergovernmental organization, which is a reference institution for gas market expertise and a benchmark for the positions of gas exporting countries.

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# Key findings

In order to assess the impacts of prospective hydrogen penetration on the global energy landscape, the GECF Energy Economics and Forecasting Department (EEFD) has formulated the Hydrogen Scenario (HS). The Hydrogen Scenario builds upon ambitious yet realistic assumptions about the advancement of hydrogen through global energy supply chains and, ultimately, end-use sectors.

Blue hydrogen, or hydrogen that is produced from natural gas in combination with carbon capture, utilization and storage (CCUS) technologies, represents a significant emerging opportunity for reducing the global carbon budget. The objective of this report is to present these findings and their underlying assumptions to GECF Member Countries, which, as will be demonstrated throughout this technical report, have an opportunity to increase export potential in support of hydrogen development.

**+600 bcm**

By 2050, in Hydrogen Scenario, more than 600 bcm of natural gas is expected to be annually used to produce hydrogen mostly in the form of blue hydrogen, a 47% contribution.

**26%**

By 2050, 26% of total hydrogen demand will be met with electrolysis in the Hydrogen Scenario, mostly from renewable electricity. This green bydrogen will serve as a perfect complement to blue hydrogen produced from natural gas.

**55 Gt C02**

Hydrogen deployment will result in annual emission reductions of 3.5 GtCO2 by 2050 compared with the Reference Case. This translates to a cumulative total of more than 55GtCO2 from 2018 to 2050.

**29%**

The share of natural gas in primary energy consumption will increase to 29% by 2050 compared with 27% in the Reference Case, and a 6% increase from today's value.



# Executive summary

**Hydrogen is receiving a lot of attention because of the benefits that it can bring to the whole energy system.** Hydrogen is a clean fuel and can be transformed into electricity through fuel-cells. It can play a great role in transport, power sectors, residential, commercial, and industry sectors. There are also varied ways to produce hydrogen that make the hydrogen economy even more interesting and at the same time challenging. The world's interest in the hydrogen economy has accelerated in recent years. The year 2018 marked a very impressive year through historical developments, such as Hydrogen Energy Ministerial Meeting that was the first ministerial meeting on this subject in October 2018.

**Hydrogen will gain shares in the global energy system due to the varied benefits that it has to offer.** The advantages include but are not limited to: net zero emission, the varied application range in most end-use sectors (including electrification in high-grade industrial heat or in heavy transport) and in off-grid or distributed generation, and increased energy security.

**Natural gas can contribute significantly to hydrogen production when carbon capturing measures are employed, especially pre-combustion capturing.** Blue hydrogen, by definition, includes carbon capturing and promises a very economical way to meet hydrogen demand.

**The EEFD has developed a dedicated scenario named the Hydrogen Scenario (HS) to assess the impact of the hydrogen economy on the total energy system, specifically on the natural gas supply chain.** Within the framework of the HS, several assumptions are imposed on energy consuming sectors like transport, industry, commercial, residential, etc.

The results of the Hydrogen Scenario suggest that natural gas can maintain its position in hydrogen production provided that CCS measures are employed. The results show natural gas can contribute to around 47% of hydrogen production compared with 26% for electricity from renewable energies. CCS is an inevitable part of these results, so moving to blue hydrogen presents an important opportunity for gas producer and exporter countries to remain competitive in hydrogen production in lieu of climate concerns.

**Hydrogen production and export can be financially lucrative for gas exporting countries; they are considered crucial to the GECF technology roadmap.**

# Introduction

Technology has always been a vital component of energy systems. From the very primary stages of energy production to the last level of consumption, humans use technologies to enable their energy needs. Any progress and development in any part of the energy system could be done through developing a specific technology or substituting technologies. Hence, the vital role of technology on energy systems and, consequently, on human lives is undeniable. To focus on this very crucial issue, the EEFD has developed a dedicated scenario named the Technology Advancement Scenario (TAS). Development of this scenario started in 2018 and covered a variety of advancement assumptions in selected technologies.

This scenario aims to explore the impacts of a set of technological advancements across the whole energy supply chain, as well as consuming sectors. It considers the implementation of some novice and innovative technologies, as well as the advancement of conventional technologies that are readily available. The objective of the TAS is to examine how technology can affect the future energy system and to evaluate the impact of technologies on energy markets. The results of the TAS have already been presented in a subchapter in the GECF Global Gas Outlook (GGO) 2018.

Due to the broad nature of technology, in these type of reports for each version, we select a subject such as hydrogen, CCUS, modern vehicles, smart grids or any other subjects and then try to assess what technologies can be distinguished and what the state of those technologies are. Due to the broadness of the term technology and to give a brighter view to the readers on what we are assessing in the whole energy system, we use our Reference Energy Technology Map (RETM).

This map has been introduced in the 2018 GGO, where we schematically map the position of each technology in the whole energy system. In this report, we introduce the RETM and we will refer it again by highlighting items relevant to the subject. In all versions, we will see the RETM with highlighted boxes that indicate technologies under discussion. We also illustrate other parts of the energy system that can be directly affected by that specific technology.

Hydrogen energy is a centre of attention because of the benefits that it can bring. Hydrogen is considered a cleanest and can be transformed into electricity through fuel-cells. Hence, it can play a great role in transport, power generation, heating and cooling, and industry. There are also varied ways to produce hydrogen that makes hydrogen economy even more interesting and, at the same time, challenging. Currently, the most economical way to produce hydrogen is by reforming from hydrocarbons, like coal and natural gas. Using electric energy to produce hydrogen through electrolysis is possible, but expensive.



Using renewable electricity to produce hydrogen is considered a promising way to deal with the problem of intermittency, as hydrogen can be used for storage. So the hydrogen economy has various advocates among renewable supporters, as well as those who think reforming of fossil fuels is a very good way to control CO2 emission. Hydrogen can also be produced through anaerobic digestion and other chemical interaction that use municipal waste and biomass, but the potential and feasibility of these methods are not well established.

The first chapter of this report is dedicated to presenting recent policy and technology efforts in the way of hydrogen economy development. Afterwards, we focus on the hydrogen energy system. In this chapter, we provide a revision of the GECF RETM with a focus on hydrogen. In the RETM, the technologies considered most impactful for the evolution of hydrogen are highlighted.

In chapter two, a dedicated scenario on the hydrogen economy is introduced. This scenario aims to assess the impact of promoting hydrogen on the whole energy system. Within this scenario, we impose several assumptions on energy consuming sectors, like transport, industry, commercial, residential, etc., and in the results, we can see how they affect the total energy system in terms of the sources used. This chapter ends with the results of the scenario as well as an analysis based on those results.

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CHAPTER

# Hydrogen Scenario: setting the scene

The hydrogen economy within the context of the Reference Energy Technology Map

# Chapter One: Hydrogen Scenario: setting the scene

## The hydrogen economy within the context of the Reference Energy Technology Map

Hydrogen is well-suited for meeting future energy needs. It is considered the cleanest fuel and the way towards a decarbonised economy. However, the production, storage, distribution, and use of this fuel have not considerably developed to compete with fossil fuels. To date, there is no practical established market for hydrogen, and also in the medium-term, it is not expected for hydrogen to get a market to achieve real competitiveness compared with other fossil fuels.

There are varied ways to produce hydrogen. Almost all energy carries, including fossil fuels and renewables, can be used to produce hydrogen. It also can be transformed into electricity and heat with close to zero emissions and also much higher efficiency.

It has been some years that hydrogen is being introduced as the future fuel. But the exact perspective for hydrogen to rise in the system has not yet been clear, and a variety of uncertainty associated with the subject exists. Many types of technologies like fuel-cells have already been practically initiated, introduced, and developed, but so far the economy of hydrogen production along with the technologies for hydrogen consumption in large scales has not let hydrogen gain shares. In 2018 around 84 mtoe of hydrogen was produced and consumed, but mostly as a feedstock in refinery and other chemical plants and not as a fuel.

### Box 1. Meetings, remarks, and other policy measures

The world's interest in the hydrogen economy has accelerated in recent years. The last two years saw a lot of development in technology measures, as well as high-level meetings, and marked a very impressive year by historical developments such as Hydrogen Energy Ministerial Meeting that was the first ministerial meeting on hydrogen , held in October in Tokyo.

Hydrogen is now recognized as a vital part of decarbonisation in line with the Paris Agreement goals. The year 2018 started with two announcements in China and the US in January. The capital city of central China's Hubei province, Wuhan, announced its intentions to become "the hydrogen city" with more than 100 fuel cell manufacturers and up to 100 filling stations. Jeff Brown, the former governor of California, announced a plan to increase the number of hydrogen filling station to 200 in the short-term

The Australian Renewable Energy Agency (ARENA) closed the first funding round of AUD 20 million to support green hydrogen export in February. The UK Department for Business, Energy, and Industrial Strategy also set up a fund of 20 million pounds to advance innovators running the UK's hydrogen economy.

In May 2018, Mission Innovation, in its third ministerial, launched its eighth Innovation Challenge (IC#8) on hydrogen to address the need for its technology development and to promote efforts to make hydrogen cost-competitive. Participants of IC#8 met in Berlin for a "deep-dive workshop." Another workshop was held in Antwerp in March 2019, called "Hydrogen Valleys," and more than 80 representatives from industry, academia, and government participated in the event.



In early June 2018 French minister, Nicolas Hulot, unveiled an ambitious €100m ($116.8m) plan for hydrogen deployment. He also revealed his intention "to make France a world leader in hydrogen technology."

In September 2018 the Hydrogen Council added 14 members and increased the number of its members to 53. In the same month, the Linz Hydrogen Initiative was signed by EU energy ministers as well as some private companies and non-governmental organizations in Europe. The Linz Hydrogen Initiative states that hydrogen will definitely be part of future European energy. International Renewable Energy Agency (IRENA) also published a report on technology outlook for the production of hydrogen from renewable resources in the context of the energy transition.

October 2018 marked a very important milestone in the way of hydrogen economy development when the first hydrogen energy ministerial meeting was held in Tokyo with representatives from more than 20 countries. Japan and New Zealand signed a memorandum of cooperation on the development of the hydrogen economy.

More recent in Jun 2019, participants of Group of Twenty (G20) mattings recognized the opportunities offered by further development of innovative, clean and efficient technologies for energy transitions, including hydrogen as well as, depending on national circumstances, the Carbon Capture, Utilization, and Storage

One of the great advantages of hydrogen is that it can be used in varied application range in most energy sectors such as power, industry, residential, commercial, and transportation. In this regard, it is considered to be as flexible as electricity. It also can be transformed into electricity in an electrochemical appliance named fuel-cell. A fuel-cell converts chemical energy provided by hydrogen into electricity. Batteries also turn chemical energy into electricity, but in contrast with fuel-cells, they need to be recharged. Fuel-cells can maintain electricity production as long as the hydrogen or the fuel inputs are being fed. Fuel-cells can also produce heat and water.

A distinct advantage of hydrogen is that it is complementary to renewables. One of the most important disadvantages and barriers in the way of renewables is intermittency. This intermittent nature of wind and solar energy raises the need to install more than base demand and consequently impacts upward on costs. But if there is practical storage for their output energy, extra capacity can be used for saving energy, and then in the peak-load or lower availability of the renewable source, the stored energy can be supplied to the grid. Based on this, there are development plans for application of batteries or other storage facilities. So far the cost for batteries is so high that they have failed to gain a considerable market share, but there is a consensus among some analysts that the hydrogen economy can take a very significant role to act as a storage system since it can be easily produced from the excess electricity through electrolysis and also can be used for power production through fuel-cells. Using renewable feedstock to produce hydrogen is very attractive in terms of environmental aspects, and this can play a great role in lowering the cost of renewables.

Hydrogen energy storage also offers some other benefits compared with the batteries. In batteries, the capacity of the cells and also the lifetime of the battery, as well as the proper time period for the charge and recharge, are important, and they impose some constraints in the way of their application. Hydrogen can be easily stored in a variety of ways, such as in containers or in underground storage (e.g. depleted hydrocarbon fields and salt caverns). It can also be stored over longer time periods in accordance with seasonal or long term demands. This also brings great benefits in terms of energy security.

Apart from being a good complement for renewable electricity, hydrogen also can be used as an electricity buffer for power plants. Conventional power systems conserve a reserve of around 20% more than projected demand in order to maintain more secure power supply. In the future, hydrogen can also work with power plants to provide the buffer needed.

Hydrogen can also promote more integration between energy sectors and connect the power system to non-electricity demand in the transport, commercial, and residential sectors. This also encourages investment in hydrogen research and development in order to better integrate energy systems and greatly reduce operating costs.

Off-grid and distributed generation is also important for the future of power generation. Decentralized power systems are a potential advancement that may help reduce energy costs, especially in remote areas. If this power generation can be coupled with hydrogen backups, the investment could be more secured.

The great advantage of using hydrogen in fuel cell electric vehicles (FCEVs) is being emission-free, which is promising even if hydrogen is not sourced from renewable energies. That is why most car manufacturers are considering FCEVs in their long-term production plans, not only as a substitute for gasoline in road transport but also for diesel operated heavy duty vehicles and maritime transport where electrification is currently doubtful.

Figure 1 delivers a highlighted version of the GECF RETM. The RETM aims to cover all technological subjects along all energy supply chains and it is used to map technologies in a pictorial way to provide a better understanding of what we are discussing. It can help readers understand the impacts, relations and other associated issues to the main topic.

Hydrogen related technologies are highlighted in blue. All technologies related to hydrogen will fall into this category, meaning this is a vital issue for the modelling process and the assumptions imposed or the results obtained. Fuel-cells, electrolysis, and technologies related to the production of syngas are also highlighted in blue. Other highlighted boxes are those which can be substantially affected by any change or advancement in blue boxes.

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## Box 2.
## Reference Energy System (RES) & Reference Energy Technology Map (RETM)

A Reference Energy System (RES) is a way to visualize all processes and interactions being undertaken within the energy system in its entirety. It can be presented as a network diagram depicting the energy demanding sectors and all available resources. Energy conversion technologies are also an inevitable part of any RES as the technologies take the main and vital role in the way of energy supply. Especially in mathematic modeling, a pictorial format of the network and flows can give a better understanding of system boundaries. It can help us to see in which part of the energy system we are digging into and clarify what aspects are taking into account and what parts are excluded from the analysis.

Within the framework of the GECF GGO and in order to have a pictorial reference of what we can discuss in the area of technologies and, to a wider extent, the whole energy sector can be affected by, a diagram was designed and presented in the GECF GGO 2018 to cover our boundaries of technology perception in the whole energy system. We call this pictorial presentation of the energy technology system, the Reference Energy Technology Map (RETM).

The RETM, just like a RES, aims to represent the components of an energy system just by more focus on the technologies compared with a classic RES. Under a certain and decided level of aggregation, the RETM covers all components, activities, and relationships of an energy system including energy demand sectors, energy extraction technologies, energy production technologies, treatment technologies, conversion technologies, transformation technologies, and storage technologies. In order to make it possible to depict almost all technologies in the energy system, the aggregation level is adjusted to a medium level. Therefore, a set of specific technologies can fall into the same



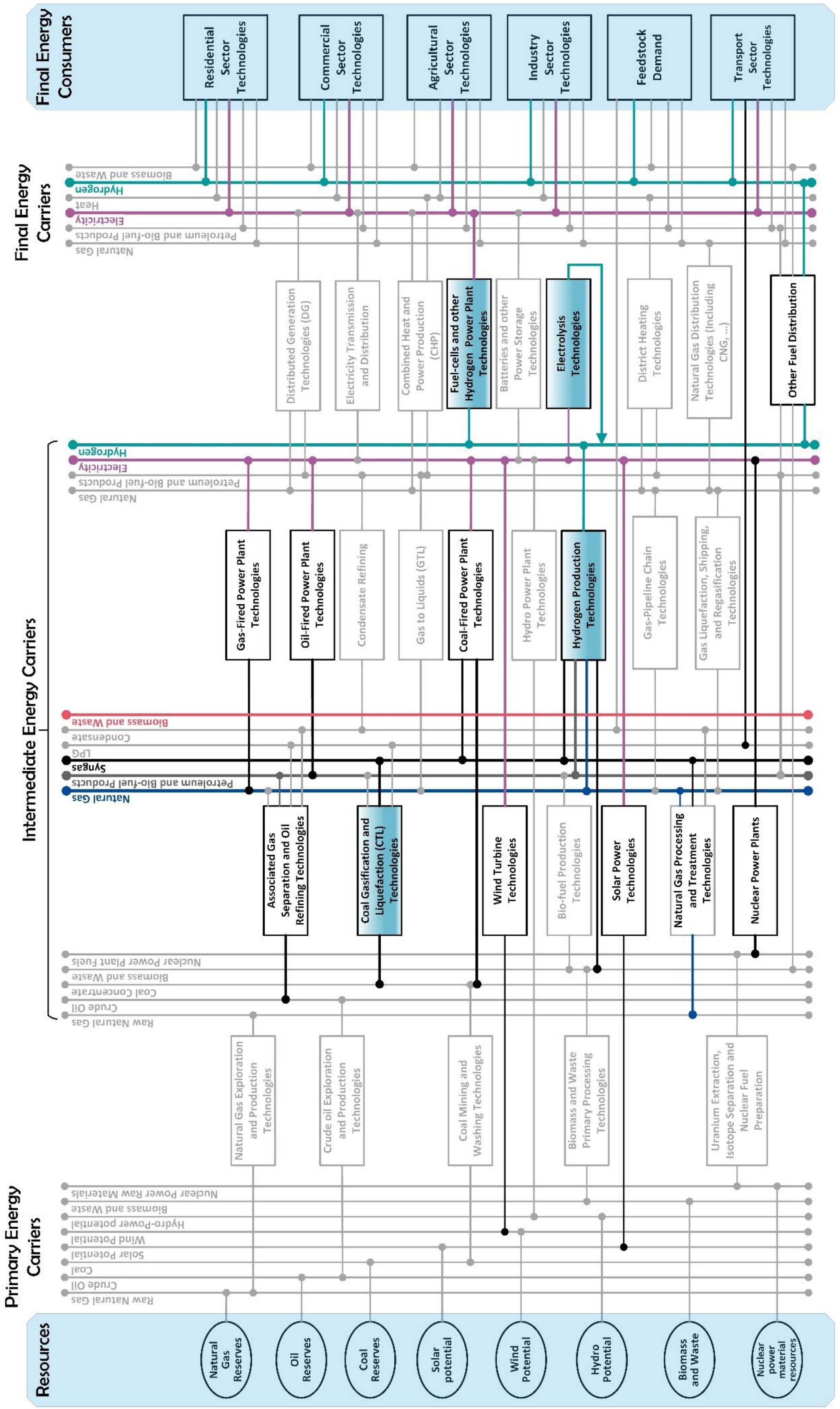
box illustrated in the diagram. For example, for all gas-fired power plant technologies such as different types of open cycles and combined cycle power plants, only one box is considered with the gas as the input and electricity as its output. As another example, all topping or cracking refineries as well as units to separate associated gas from crude fall into a single box with a related name. So in order to make an analysis in any of the subjects, there is a need to illustrate a more detailed diagram that shows all technological issues.

Apart from giving a schematic picture of the area in which we are leading our analysis, the RETM also helps us to attribute our assumption to any part and issue of the selected technology in order to impose to the Global Gas Model for the purpose of developing a new scenario or making a sensitivity analysis. In other words, it provides clear pictorial formation for the readers to have a better understanding of what issues and related parameters are subject to change in the new scenario or in the sensitivity analysis.

This analytical methodology has been applied in the development of the Technology Advancement Scenario since the first version of its results were published in the 2018 GECF GGO. This is also employed in this report that is dedicated to the advancement of the hydrogen economy. This is to illustrate the system boundaries used in our conceptual model, as well as the capabilities of the GGM (see Figure 1).

It is important to note that the pictorial representation of a RETM becomes more complex with the addition of more technologies and resources. Due to the intensive nature of energy systems modelling, several energy carriers featured in the RETM (as well as their associated technologies) were omitted from detailed consideration. Energy supply chains with higher granularity are provided for natural gas, coal, and renewables (wind and solar) in the following sections.

**Figure 1. GECF Reference Energy Technology Map (RETM)**





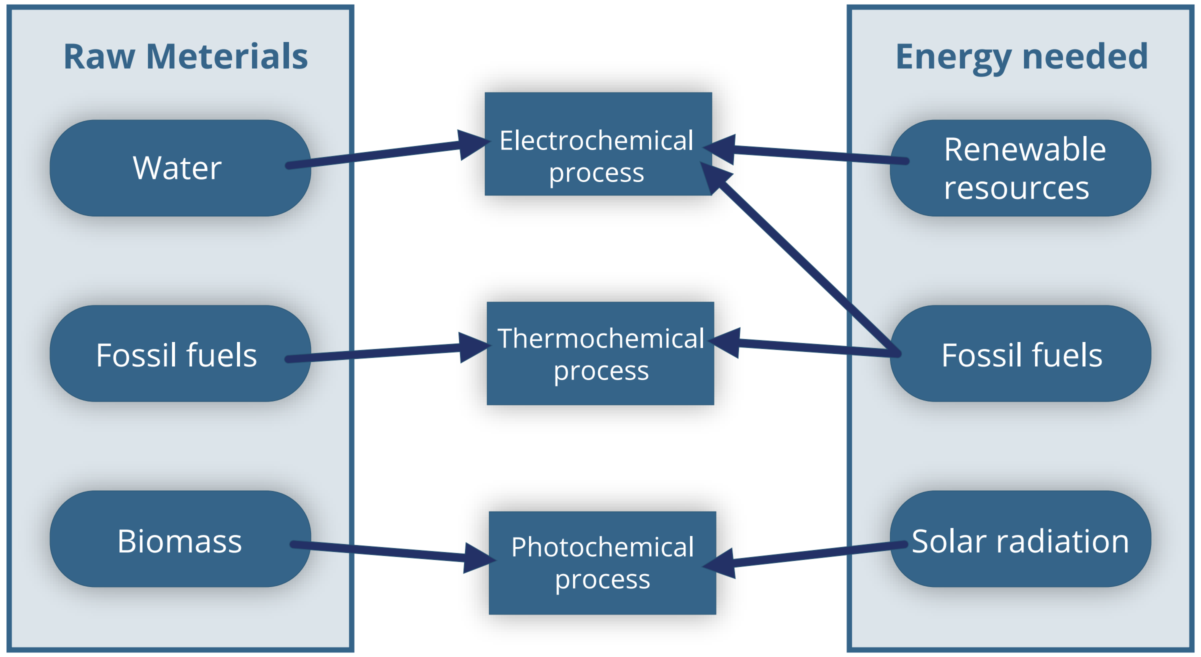

# Hydrogen Sources

Unlike oil and gas reserves, hydrogen cannot be found as a separate substance in nature. As a free element, hydrogen can only be found in volcanic gases like what is detected in some volcanic eruptions. Definitely, the extraction of hydrogen from volcanos will not be a practical way to produce hydrogen. Therefore the only way to produce hydrogen is by transforming other energy sources or materials. As previously mentioned, hydrogen can be produced from energy carriers and raw (non-energy) materials.

Some energy carriers, like natural gas and coal, are transformed into hydrogen through reforming and gasification. Water is not considered a fuel or energy carrier, but it can be split into hydrogen and oxygen through electrolysis. Electrolysis requires electric energy, which can be provided by any type of power production, including those which consume fossil fuels or those which produce electrical energy from renewable resources such as wind and solar.

Sources of hydrogen are depicted in Figure 2. The processes can be grouped into thermochemical, electrochemical, and photochemical.

**Figure 2. Hydrogen source map**



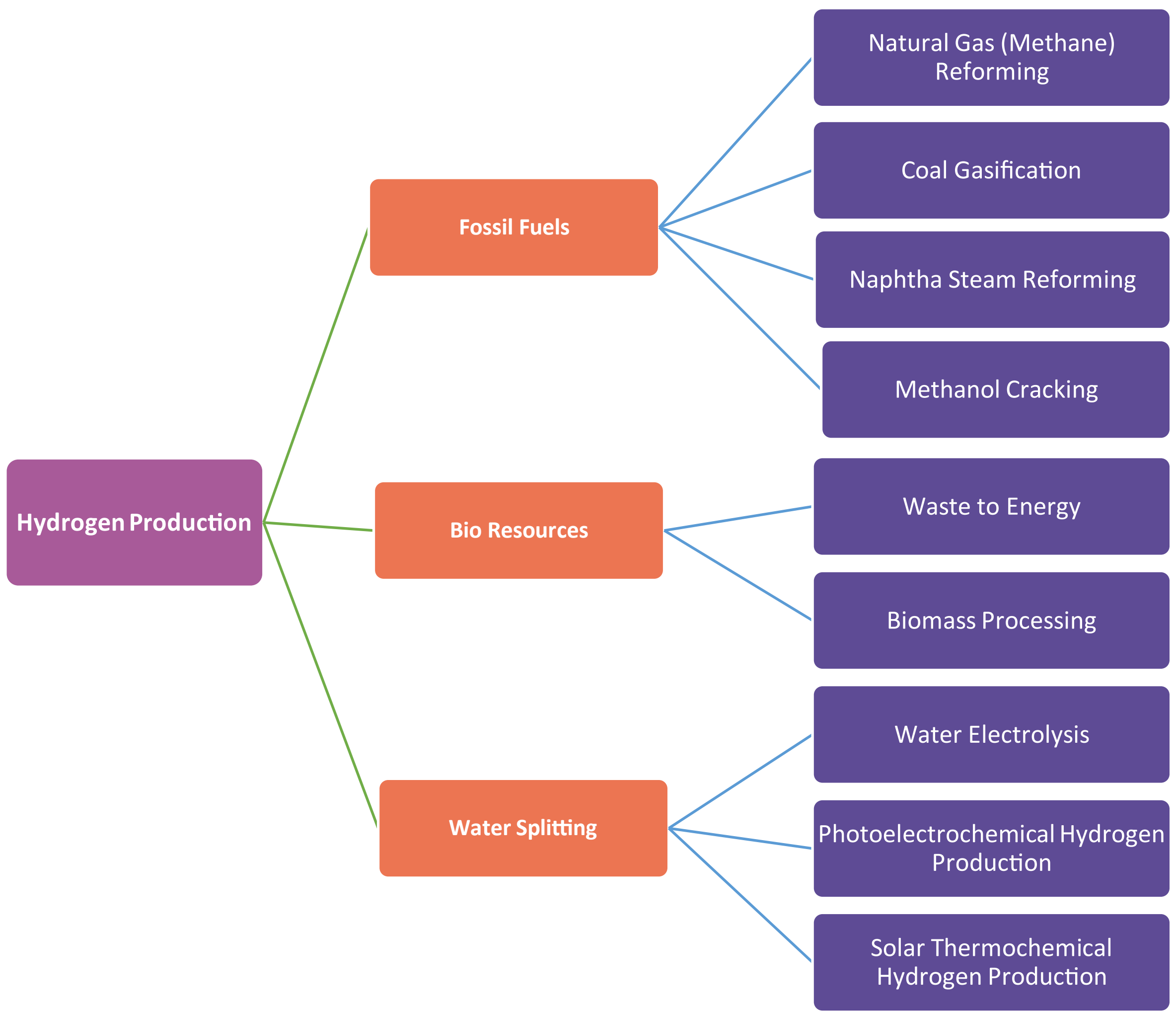

There are several ways of producing hydrogen depending on the scale of production and cost of available feedstocks. The most frequently implemented method is catalytic conversion or steam reforming of hydrocarbons followed by gasification of coal, tar sands, etc. Around 95% of current hydrogen production is from gasification or reforming.

Water electrolysis accounts for less than 5%. For large scale production, natural gas steam reforming is the preferred method. Gasification of heavy oil produced especially heavy fractions that are increasingly facing with falling demand may play an increasing role. Methods that implement aerobic or anaerobic digestion of waste and other bio-materials also are considered as a potential for production.

# Hydrogen Production technologies

Hydrogen can be produced from a variety of sources, including raw materials and energy carriers. Figure 3 shows some established technologies for hydrogen production. This figure is a very simplified depiction that we use to categorize hydrogen production technologies into three main groups based on the raw materials being used, not the energy needs. For example, electrolysis needs electricity that can be provided through fossil fuel-fired power plants. However, in this diagram, it is categorized under the water consuming categories.

**Figure 3. Hydrogen Production Technologies**

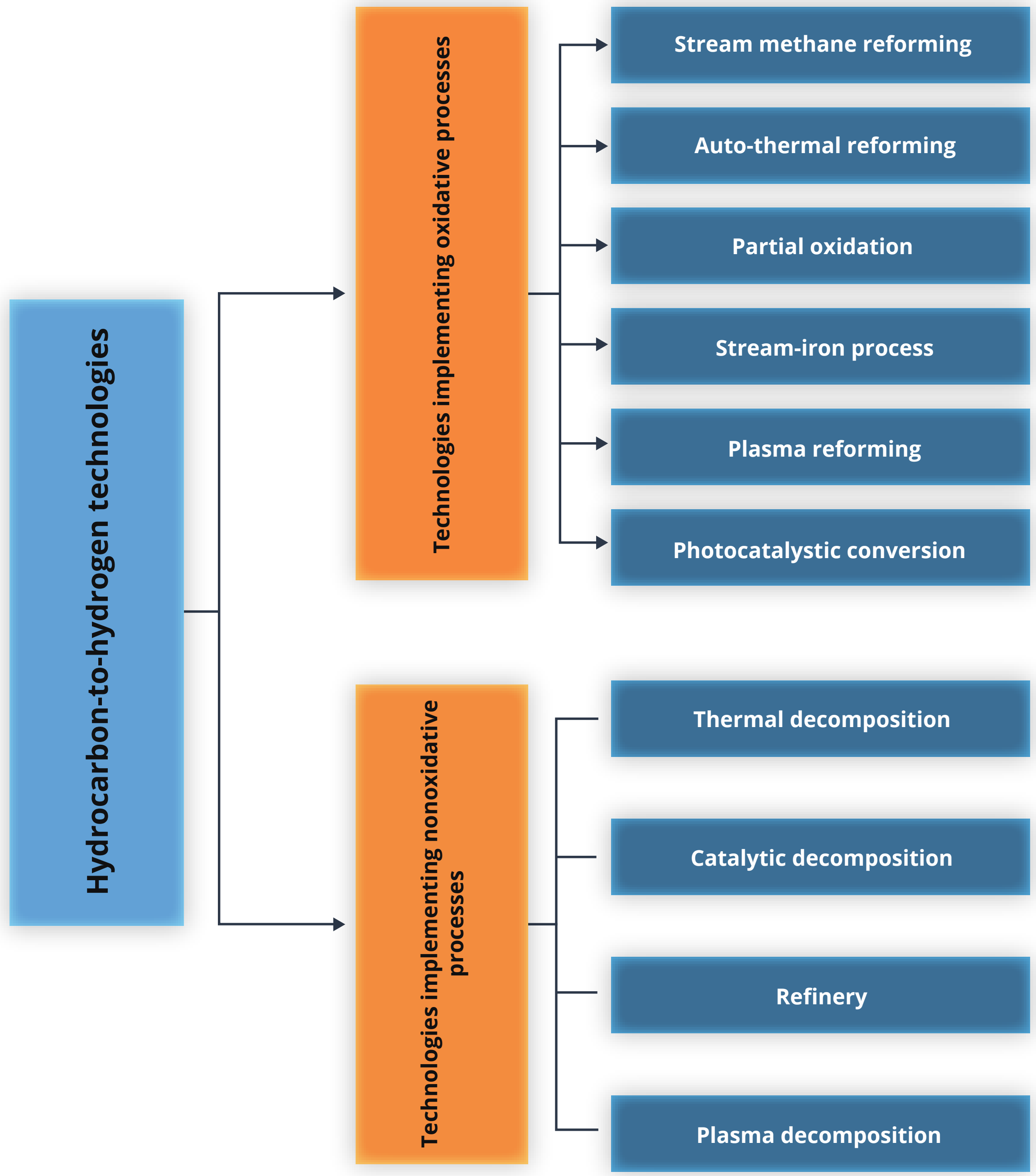





# Hydrocarbon to hydrogen technologies

The dominant technologies used to produce hydrogen are those which convert hydrocarbon materials to hydrogen. These technologies can also be categorized into two main groups: oxidative and non-oxidative processes. However, hydrocarbon to hydrogen technologies can be categorized in several different ways. From a thermodynamic viewpoint, they can be end othermic or exothermic. They can also be classified as catalytic or non-catalytic. From the viewpoint of technology, the first categorization is best to introduce the processes. Figure 4 shows a list of hydrocarbon to hydrogen technologies based on the categories of being oxidative or non-oxidative.

**Figure 4. Hydrogen production technologies from hydrocarbons**

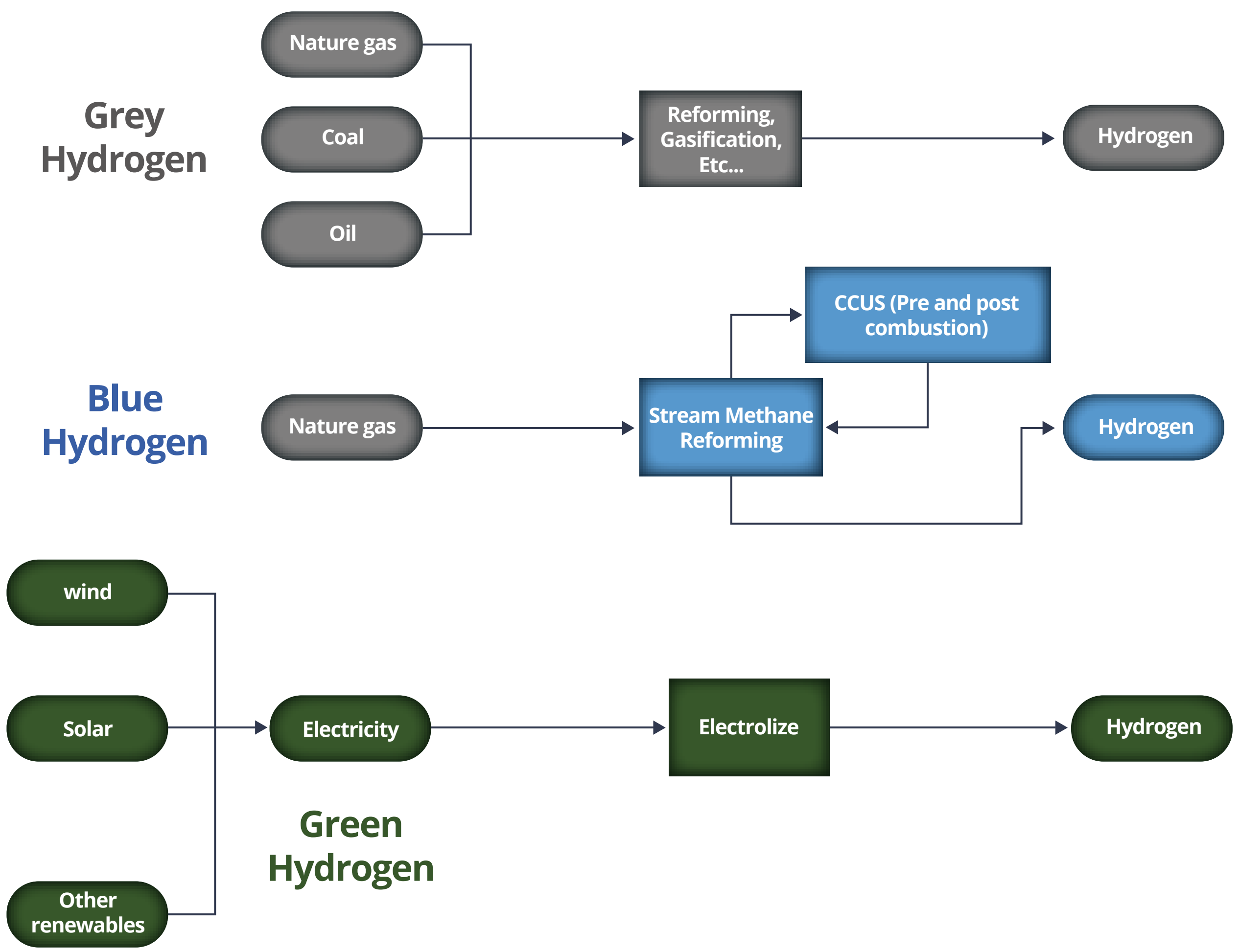


# Blue and green hydrogen and other initiative hydrogen economy trajectory

Blue hydrogen refers to hydrogen produced from natural gas by chemically fragmenting into the hydrogen and carbon dioxide while carbon capturing measures are employed. The captured carbon, mostly in the form of CO2, will be injected safely in depleted gas fields or used to enhance oil and gas fields' recovery or as feedstock for the chemical process in the industry. The latter processes are commonly translated into CCUS.

So blue hydrogen is not only the hydrogen produced from natural gas, but it is obtained from the natural gas on the condition that the CO2 produced along with the process is not released into the atmosphere and it is stored safely. Generally, the hydrogen produced through reforming without implementing carbon storage is called grey hydrogen (see Figure 5).

### Figure 5. Grey, blue and green hydrogen concept



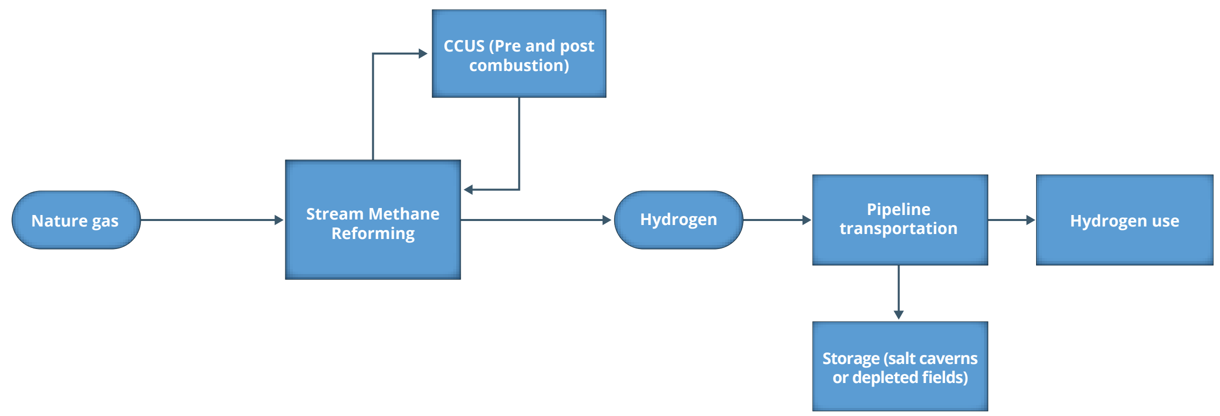

Blue hydrogen, by its definition, includes pre-combustion carbon capturing. So far, the carbon capturing process is categorized into three categories, each of which has its own characteristic and technical condition and therefore associated costs, common scales and availability: post-combustion, pre-combustion, and oxy-combustion.



The post-combustion capture process is the most mature CCS technology. CO2 is absorbed from the results of fossil fuel combustion that are flue gasses, mostly by using amine-based or aqueous ammonia solvents during a recoverable process. Pre-combustion is applied in modern technologies such as Integrated Gasification Combined Cycle (IGCC) systems, where the nature of the process is producing syngas that is a mixture comprising of carbon monoxide, carbon dioxide, and hydrogen. CO and CO2 are removed from a syngas that means the carbon content substances are removed from the process before combustion. Oxycombustion technology involves using extra oxygen for the combustion of fuel that results in water vapour and CO2.

Among these mentioned, carbon capturing technologies pre-combustion has gained more interest recently. This is also called smart CCS as carbon content materials are separated from the fuel before the combustion and make it possible to employ the technology in a smaller scale and yet economically viable compared with the post-combustion capturing that is not adequately economical in small scales.

### Figure 6. Blue hydrogen supply chain




Green hydrogen is also another term to call hydrogen produced from renewable resources like wind and solar. Wind and solar are among the most deployed renewable technologies and their produced electricity can be used through the electrolysis process to split water molecules into the hydrogen and oxygen. Electrolyze process needs pure water and electricity and it will not contribute to any carbon provided we don't consider the whole supply chain including the carbon footprint associated to the manufacturing of the solar cells and wind technology parts.

During the last years, there has been very widespread debates among energy analysts, decision makers, and government officials about which of these hydrogen technologies can make more contribution on the climate ambitious in the way of the energy transition. Most of the time those who sympathize with green hydrogen, compare the volume of carbon footprint with the grey hydrogen but if CCUS measures are taken into account, it is proved that the volume of the emission can be comparable to those form green hydrogen.

For instance, CE Delft performed a study on this issue and published the results of the study in July 2018. The study considered the feasibility and sustainability of the blue hydrogen. The results of the study showed that the carbon footprint of blue hydrogen is completely comparable with that of green hydrogen. They calculated the amount of CO2 per each kilogram of blue hydrogen to around 0.82 to 1.12 kg of CO2. That amount for green hydrogen based on which renewable technology is being used range between 0.92 to 1.13 kg CO2 eq per one kg of hydrogen. Other studies also in some GECF member countries showed the same results.

Furthermore, some other countries also considered developing blue hydrogen in their energy system. The Netherland gathered 16 partners to conduct studies on using blue hydrogen and assess how it could affect positively the application of blue hydrogen on the energy transition and to a larger view of carbon mitigation and sustainability. Most of these players are from the industrial Rotterdam port. The above-mentioned study conducted in CE Delft is also one of their results.

Therefore considering the cost for steam reforming and the economic benefits of pre-combustion carbon capturing, we believe that blue hydrogen can gain a promising position in the energy transition. The fact that is also admitted by the results of our newly developed Hydrogen Scenario.

## Hydro-methane or enriched methane: a game changer mix of hydrogen and natural gas

During the last decades, the industry has been consuming many types of hydrogen mixtures as fuels such as synthetic gas (syngas) or coal gas but a composition of hydrogen and natural gas (methane) to be consumed in varied sectors, has become a center of attention in recent years. The most important advantage of this fuel is that it can be easily used in the current natural gas infrastructures as well as in common ICEs without a significant need to be adjusted for the new fuel and heavy investment. This is also employed and testified in many companies such as Hythane in the United States or Gazprom in the Russian Federation as some examples.

Basically, the hydrogen economy for pure hydrogen employment and fuel-cell dominated system is not yet technologically mature. In fact, the costs for large scale fuel-cells are high, and scientific challenges are being sensed by the related communities. Apart from the fuel-cells technologically immaturity, using pure hydrogen in other infrastructures or current applications such as ICE is challenged. The energy density of gaseous hydrogen is low and cause low benefit such as the need for larger storage tanks when it is supposed to consume in a vehicle and consequently lower mileage. Moreover, having a higher flame temperature that fortunately increases the efficiency of the system but at the same time causes NOx pollutants.  These are some examples that illustrate the current deployment of technologies at least in the medium-term are not ready for an intensive pure hydrogen system. That is the main reason why the societies are well noticed of usage a mixed fuel composed of natural gas and hydrogen that is called hydro-methane.

When both natural gas and hydrogen are employed in a mix innovative fuel where the natural gas is the main component, and the mix contains a minimum portion of 5% to a maximum of around 30%, the advantages gained will also be a mix of both natural gas and hydrogen advantages. The density of hydro-methane is very close to that for natural gas compared with pure hydrogen. Hydro-methane can use mostly in all infrastructures, technologies, and appliances that are developed for natural gas. The most important advantage of hydro-methane compared with natural gas is its higher thermodynamic efficiency when it is used in internal combustion engines as well as emitting less volume of pollutants.

Most of the recent studies on the issue acknowledged that this limited share of hydrogen (around or less than 25%) would positively effect on the gas consumers appliances and technologies such as internal combustion engines by enhancing their thermodynamic efficiencies and to a considerable scale abatement of pollutants associated with the combustion. There is no need for fundamental technological enhancement in the consuming appliances so Hydro-methane can be easily employed in vehicles compared with the pure hydrogen. In this case, the mix of hydrogen and natural gas sometimes are being called as HCNG (hydrogen enriched compressed natural gas).

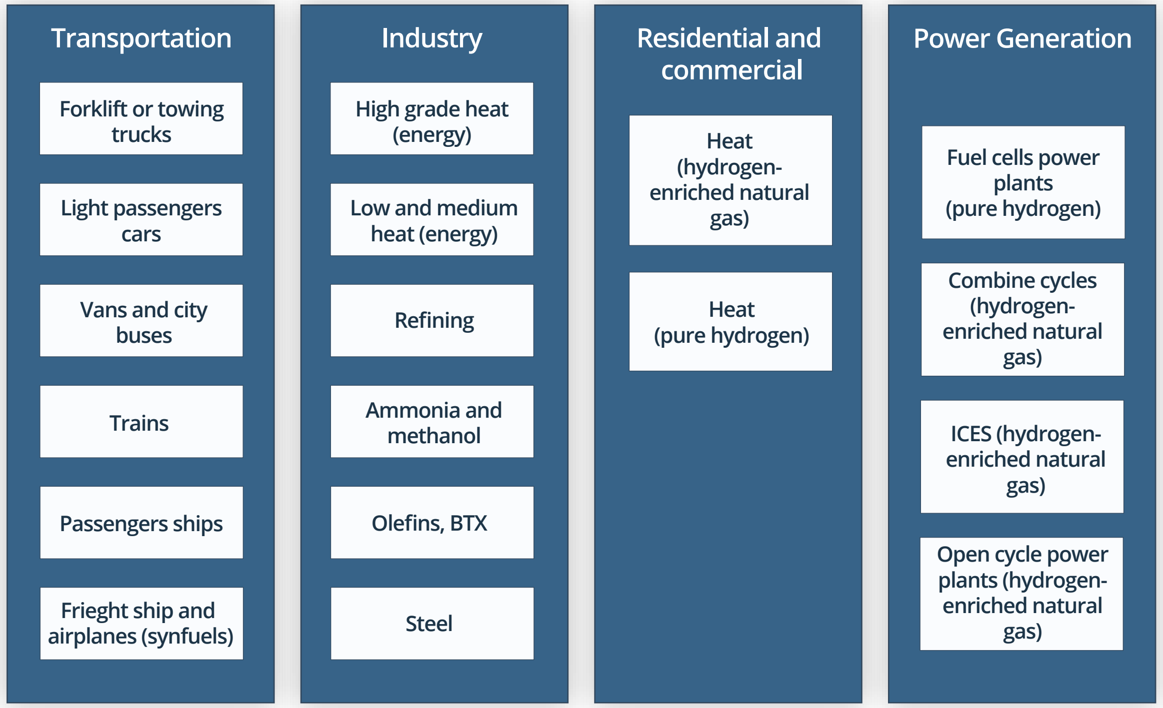


## Hydrogen distribution and consumer technologies

One of the great advantages of the hydrogen economy that makes it a distinguished energy vector among all others is its flexibility of consumption. Hydrogen as like other fuels can be transported through mature technologies like pipeline and tanks, but as mentioned it is easily can be reform to the electricity, and in this case, it also has the flexibility advantage of electricity. This unique characteristic makes this fuel to have the potential of being used in a variety of the consuming sector such as transportation, industry (as both energy and feedstock), and residential, commercial, and also power generation. However, currently, transportation and industry feedstocks are the only two sectors that are using hydrogen in their process. Hydrogen as a fuel currently is just being used in forklifts in transportation. Fuel cell forklifts or towing trucks have the advantages of being used indoor as they are zero pollutant emitter. Currently, more than 20000 hydrogen forklifts are being used in warehouses and factories in the US.

Figure 7 illustrates the sectors that potentially can be hydrogen consumers in the future as well as the technologies that can be implemented in the future to employ hydrogen as fuel or feedstock.

**Figure 7. Potential and existing hydrogen consumer sectors**



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CHAPTER

# Hydrogen Scenario assumptions and results

Introduction and aims of the scenario

# Chapter two:
# Hydrogen Scenario assumptions and results

## Introduction and aims of the scenario

In the previous chapter, hydrogen technologies across the whole energy supply chain were introduced. According to what was discussed, there are a variety of ways to produce and consume hydrogen. Currently, hydrogen is being used only in industries as feedstock for sectors such as refineries, ammonia, and methanol production and some in transport. But as for the huge advantages of using hydrogen for achieving the goals of sustainable development and the Paris Agreement, a lot of ongoing efforts and studies have been undertaken. In light of this, the GECF Secretariat has developed a dedicated scenario on the issue to assess how this effort can impact the energy market and specifically gas sectors. This scenario, which is named the “Hydrogen Scenario,” tries to investigate the role of the hydrogen economy on a wide scale on the supply chain of other energy vectors such as gas, oil, coal, and renewables.

Most scenarios developed for investigating the hydrogen economy make their forecast for the period until 2050, as a huge advancement in hydrogen technologies are assumed to materialize within the years after 2035 and market penetration is assumed to enhance significantly after 2040. We also extended the timeframe of the Hydrogen Scenario for the period until 2050. Therefore, in the scenario presented in this report, all assumptions are imposed through to 2050.

The modelling methodology is based on the GGM architecture and follows its formulation and dynamics. The transport sector is divided into road passenger transport, road freight transport, rail transport, aviation, and the marine sector. All of these sectors have the potential to develop hydrogen. In road passenger transport, the model considers three subsectors: automobiles, buses, and motorbikes. Only motorbikes are excluded from our scenario. Hydrogen is very promising in heavy freight, where electrification is complicated by long distance travel and the huge size requirements for electric batteries.

The industry also has significant potential for hydrogen consumption, especially the iron, steel, and chemical sectors. Hydrogen is currently being used in some industry sectors as a feedstock, but the use of hydrogen for industrial heat (especially high- and medium-grade industry heat) is very promising. Hydrogen will help decarbonizing industry sector in high-grade heat that is roughly 25% of the total heat needed for the sector. Decarbonizing from other ways like electrification and post combustion carbon capturing are entirely challenged. Decarbonization can be maintained by blending hydrogen with natural gas in the short-term. Most countries that demand a huge amount of high-grade industry heat also have an extensive gas network infrastructure that can be used for the blended fuel (enriched methane) or even pure hydrogen in longer-term.

Hydro-gas (enriched methane), or hydrogen blended with natural gas, can also be used in the building sector to meet heat demand. More than half of final energy demand in the building sector, both in commercial and residential, is used for space heating, warm water, and cooking. Using hydro-gas or pure hydrogen for residential heating is a vital assumption in the Hydrogen Scenario.

Power generation is also another pivotal sector for the hydrogen economy. As discussed, hydrogen can take a buffer role for existing power technologies. Storage can be promoted by enhancing storage technologies and transportation. It can also enhance energy distribution among regions and among energy sectors.



## Main assumptions

The main aim of developing the Hydrogen Scenario is to assess the impact of the hydrogen economy on the total energy system, specifically on the natural gas system. Hydrogen development is based on the advancement of related technologies, as well as market penetration of established technologies. The GECF Secretariat considers issues related purely to technology advancement in the Technology Advancement Scenario (TAS) that is presented in GECF Outlook 2018. In the Hydrogen Scenario, we also consider the penetration of technologies. For example, in transport, we impose assumptions indicating the use of more hydrogen fuel cell vehicles. In the power sector, we need to consider advancement in large-scale fuel cells to realize a penetration of hydrogen power plants into the system. Below, some of the assumptions of the scenario are presented. It is worth mentioning that we change the parameters in the econometrics time series by adjusting the factors that will have a direct effect on other parameters as our assumptions. Here we present the results of the functions to understand better what we really imposed into the model. That means these figures can also be introduced as results from the model, but those which are directly affected by our adjustments. Then when these functions work with all other functions across the whole model and modules, final results can be obtained.

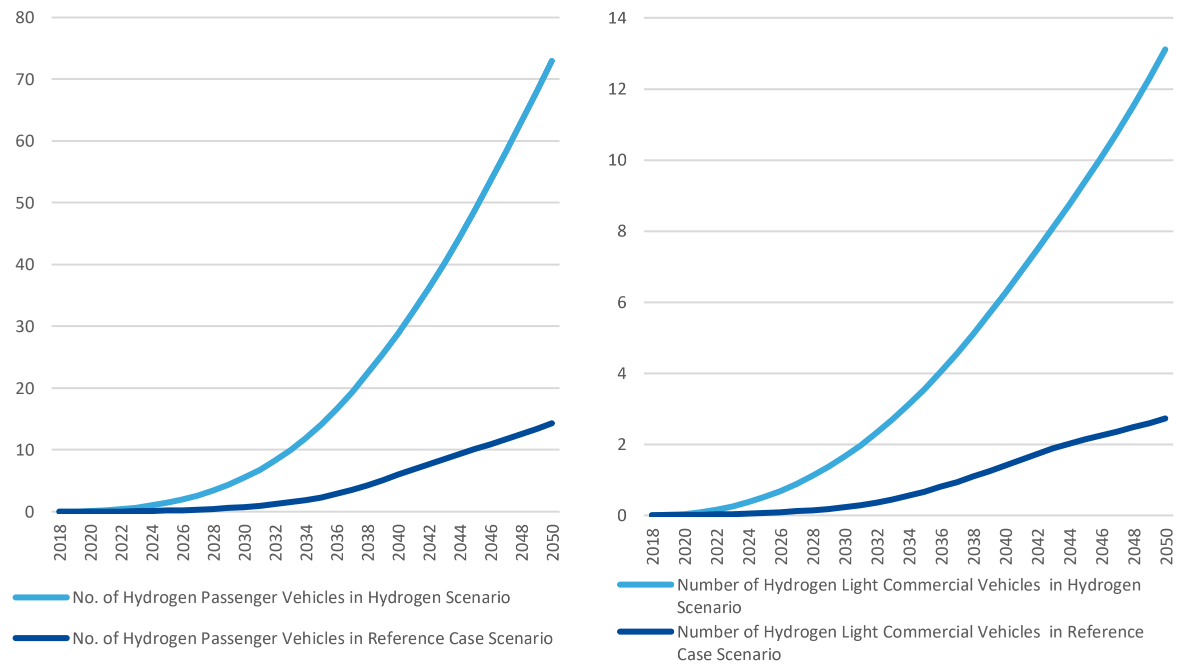
### Transport

In our scenario, we have set adjustment factors that resulted in an increased number of hydrogen vehicles in passenger and light commercial sector (LCVs). The total number of passengers and LCVs remained constant as we have not imposed any assumption on the passenger and LCV transportation demand drivers, such as population. For both scenarios, slightly over 2100 million is presumed for the year 2050. Imposing scenario adjustment factors in the Hydrogen Scenario resulted in 73 million hydrogen cars in the passenger sector by 2050. The number of hydrogen vehicles in the LCVs fleet was adjusted to slightly less than 13 million by 2050. A total of 86 million hydrogen cars is assumed to penetrate the market by 2050, equivalent to 4% of total passenger and LCVs (see Figure 8).

For heavy goods vehicles (HGVs), we assumed 22% of the total consumption in freight will be undertaken by hydrogen-fuelled heavy vehicles by 2050. The share is currently zero in the Reference Case Scenario. GGM in HGVs and train part employs methodology using the tons of freight transported per kilometer per year, which is determined by overall economic activities driven by GDP, fuel cost, and industrial output. While in the passenger sector model results are based on a stock model driven by the number of cars. The HGV sector needs to be adjusted for the penetration of hydrogen into the entire freight transportation market. Obviously, as the other income drivers are not subject to change, total freight in both scenarios is the same. However, the total energy consumed might be changed. As for our scenario, hydrogen vehicles were substituted for other types to consume 22% of the total energy demand in freight.

In rail, as well as marine bankers and aviation, hydrogen is assumed to penetrate. Hydrogen can be used to produce synthetic fuels to drive commercial aviation and marine bankers, but the amount of penetration in our scenario is not as huge as for LCVs and passenger vehicles.

**Figure 8. Number of passenger and light commercial hydrogen vehicles in both scenarios (million)**

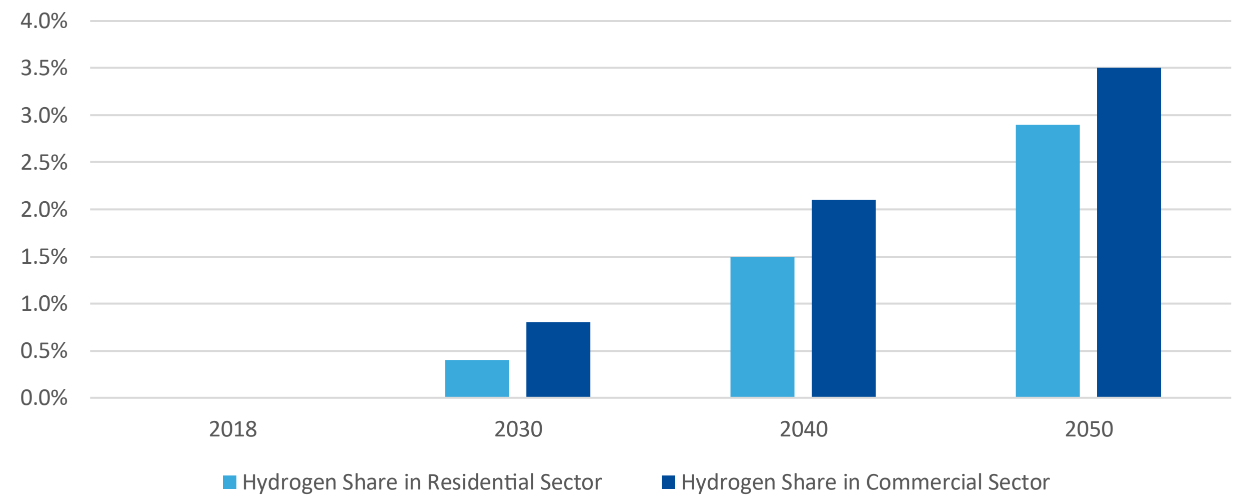



## Residential and commercial

In these sectors, we also imposed assumptions based on the use of hydrogen for heating. These assumptions are considered from a short-term perspective for blended hydrogen and a long-term perspective for pure hydrogen consumption. Using Hydrogen-enriched natural gas is now considered a practical way to increase fuel efficiency, as well as for decarbonization, in several sectors, including the building sector to produce heat. To model this progress, we imposed some adjustment related to hydrogen grid coverage and market shares. This implies that if we blend hydrogen with natural gas and inject it into natural gas pipeline infrastructure, we will dedicate a share of our pipeline network to hydrogen supply. We can see that even for a very small development in hydrogen network coverage, we can see considerable hydrogen penetration into the system. For those countries with the developed gas network, we assumed a hydrogen network coverage of less than 10% in the commercial sector and 5% in the residential sector. Improving hydrogen coverage for these countries alongside the increase in hydrogen market share can maintain the impactful assumption for the sectors. Overall, a global market share of around 2.9% by 2050 in the residential sector and 3.5% in the commercial sector is assumed in the Hydrogen Scenario (see Figure 9).



**Figure 9. Hydrogen's market share in the building sector in the Hydrogen Scenario**



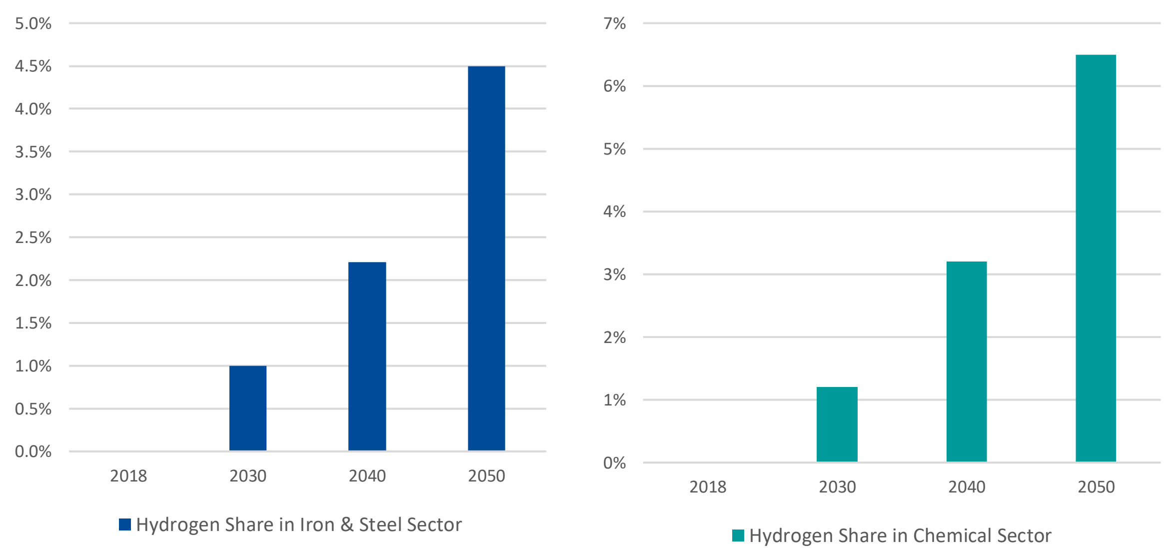

## Industry and feedstocks

Hydrogen can be promoted in the industry sector in iron and steel manufacturing, as well as chemical production (e.g. methanol, olefins, and other petrochemical products). The iron and steel sector is the largest consumer of energy and needs the largest volume of high-grade industrial heat compared with other industrial sectors. These two subsectors are considered the main drivers for hydrogen consumption in the Hydrogen Scenario, since using hydrogen can be an alternative to post-combustion carbon capture. The use of hydrogen in steel and chemicals production is assumed to be realized in Japan, Canada, the US, and European countries. According to the Hydrogen Council, around 10% of all chemical and steel plants in these countries will be driven by hydrogen heat by 2030.

High-grade heat is the most challenging issue for decarbonizing industry, as electric furnaces will fail to provide the adequate heat needed. Another issue associated with electrification for high-grade heat is that most of the fuels that are currently being used for this process provide not only the high-grade heat needed, but also result in some gaseous substances from the combustion that can help the chemical reaction to proceed. Therefore, these kinds of furnaces, such as blast furnaces in the iron industry, cannot be replaced by the electric furnace. In the Hydrogen Scenario, it is assumed that around 4.5% of the high-grade heat in the iron and steel sector would be driven by hydrogen furnaces by 2050. This development is mostly assumed to materialize after 2040, when only 2.2% of furnaces are assumed to be hydrogen-driven.

Similarly, in the chemicals sector, 3.2% in 2040 and 6.5% in 2050 of all chemical high-grade heat is assumed to use hydrogen worldwide. Figure 10 illustrates the assumption imposed for the Hydrogen Scenario. Other sectors are also considered for the development of the hydrogen economy, but they are not represented to the same extent as these two sectors.

**Figure 10. Assumptions for hydrogen shares in chemical, iron and steel industry heat in the Hydrogen Scenario**




Using hydrogen as feedstock in the industrial process is currently the only significant use of hydrogen. Hydrogen is being used in refineries for the cracking process. It is also vital in the production of ammonia for fertilizers. Methanol and other chemicals, such as polymers and fatty acids, are also minor users of hydrogen as a feedstock. It is assumed that hydrogen can be promoted much more in such industries for decarbonization. Most of the hydrogen currently being used as a feedstock is produced from natural gas, oil, and coal that enable this option to advance the system and produce hydrogen from cleaner ways such as blue and green hydrogen. This advancement can help these sectors to succeed in their contribution to decarbonization. Substituting and promoting blue hydrogen in these sectors can bring huge advantages, since blue hydrogen applies smart CCU/CCS (pre-combustion carbon capturing) and smart CCUS can be much more economical than post-combustion carbon capture. Other fossil feedstocks and carbon containing substances can be substituted for hydrogen and are also assumed to be clean hydrogen. This also brings considerable potential in decarbonizing the industrial sector.

In the Hydrogen Scenario, it is assumed that over 7% of feedstock for all industries except refineries will be sourced from hydrogen by 2050, compared with less than 5% in our Reference Case Scenario. Also for refineries, the hydrogen share is assumed to be promoted to 1.4% by 2050 in the Hydrogen Scenario compared with around 0.7% in the Reference Case Scenario (see Figure 11).

## Power sector

For the first time, the concept of using hydrogen in a practical scaled power plant was proposed by GE in 2006. These years this idea is being advocated by those who promote the role of hydrogen in energy storage for renewables, as well as its role to act as a buffer for existing power plants.

The idea is to feed a large amount of hydrogen into a large number of fuel cells in a power sector and transform hydrogen to electricity to send to the grid. The first aim is to use hydrogen as a storage system for electricity for renewables, like solar and wind. Hydrogen produced from electrolysis can be stored in tanks or underground and when needed, it can be transformed into electricity through hydrogen fuel cell power plants. Hydrogen power plants can also provide enough buffer to increase grid security of electricity supply, so hydrogen power plants can be used in this way alongside any type of conventional power plants.



In the Hydrogen Scenario, we assumed that the development of hydrogen power plants will gain pace after 2035. From the year 2035, the capacity addition is assumed to be significantly increased from around 2.2GW per year to around 29GW in 2050. Figure 12 illustrates the annual assumption for the global level on additional hydrogen power plant capacity.

**Figure 11. Assumptions for hydrogen share as feedstock in industry**

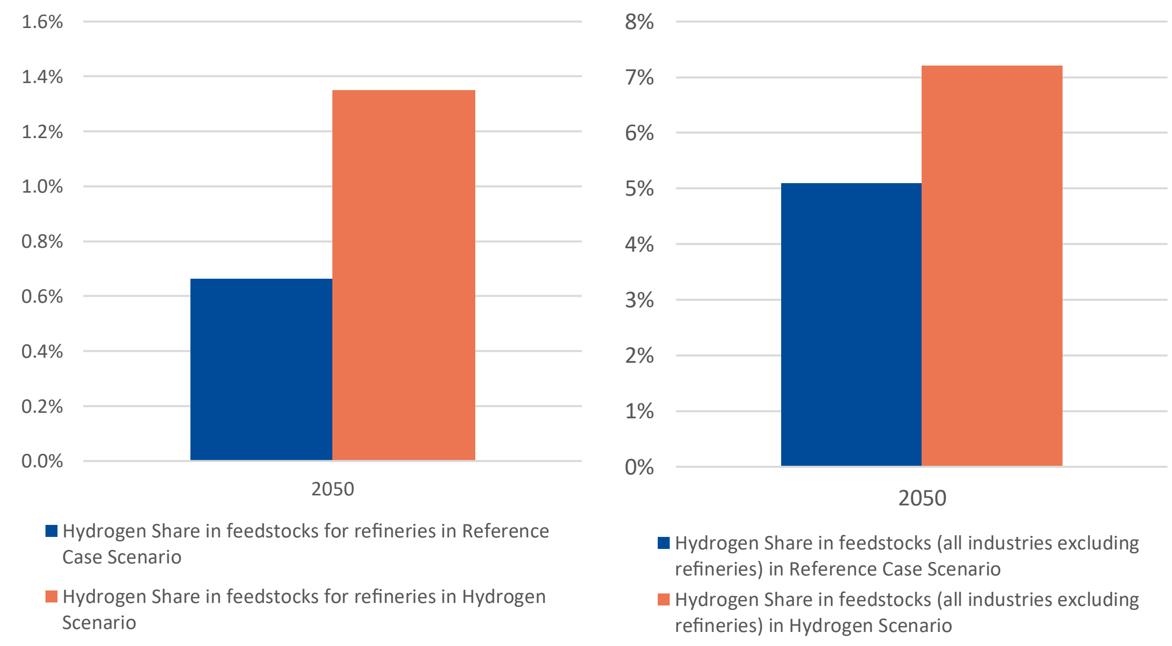
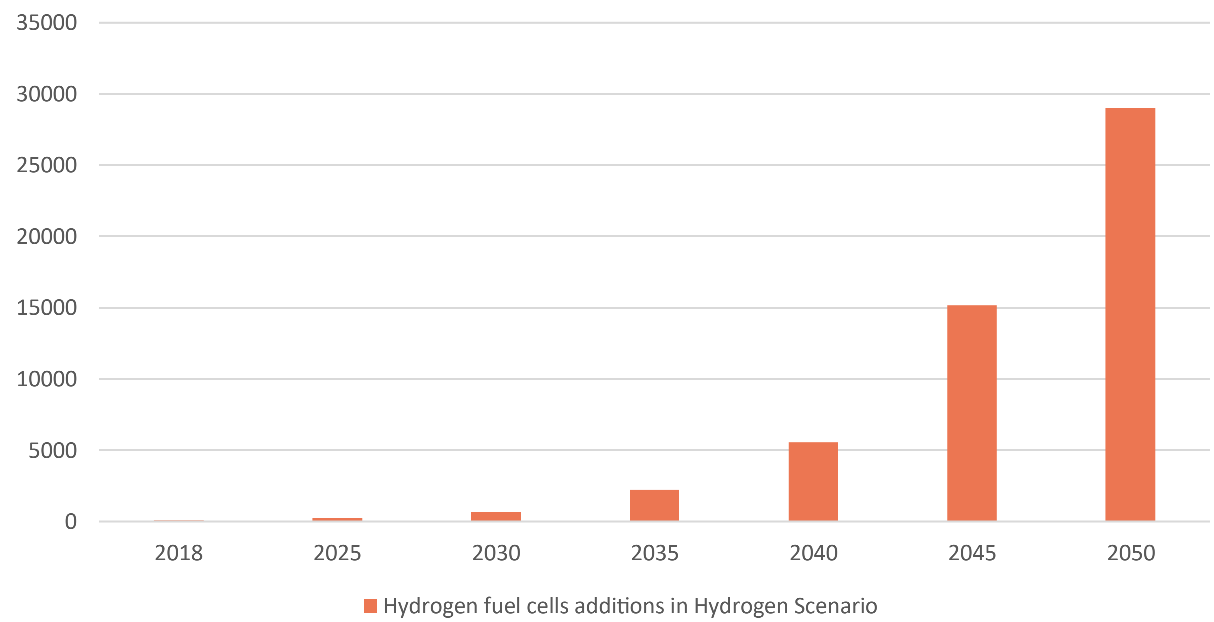



**Figure 12. Assumptions on hydrogen fuel cells, global annual power capacity addition (MW)**



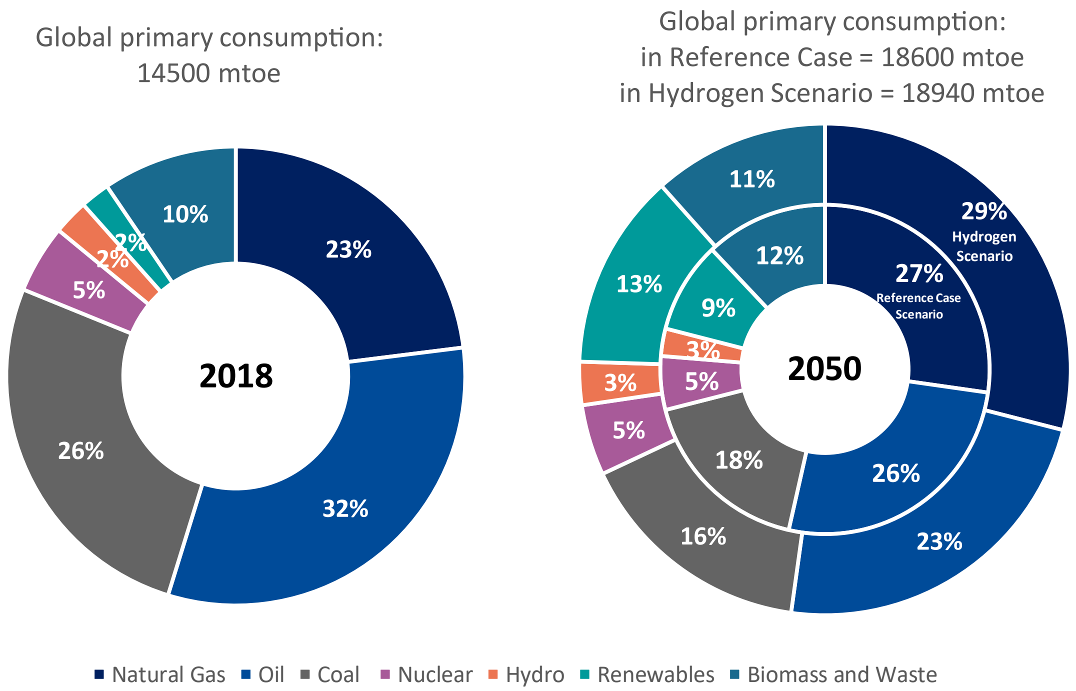
# Scenario results

In this subchapter, the results of the scenario are presented. Total primary energy consumption in the Hydrogen Scenario is forecasted around 340 mtoe more than what is forecasted in the Reference Case Scenario. In the Hydrogen Scenario, we considered very soft efficiency advancement only in the hydrogen supply chain and tried to promote the hydrogen technologies mostly based on the current situations, for example in industry and feedstock.

Figure 13 illustrates the combination of the fuel mix in total primary energy consumption in both scenarios. Unsurprisingly the share of natural gas in total primary consumption increased by more than 2%, since blue hydrogen can be a very reliable and affordable way to contribute to the production of total hydrogen needed in hydrogen economy development. Renewables are the second set of energy vectors that gain shares in the Hydrogen Scenario, from less than 9% in the Reference Case Scenario to more than 13% in the Hydrogen Scenario by 2050. That also acknowledges that the use of renewable energy in hydrogen production (green hydrogen) is an economical and viable way.

Other fossil fuels, including oil and coal, lose shares in the Hydrogen Scenario and nuclear remained constant in both scenarios.

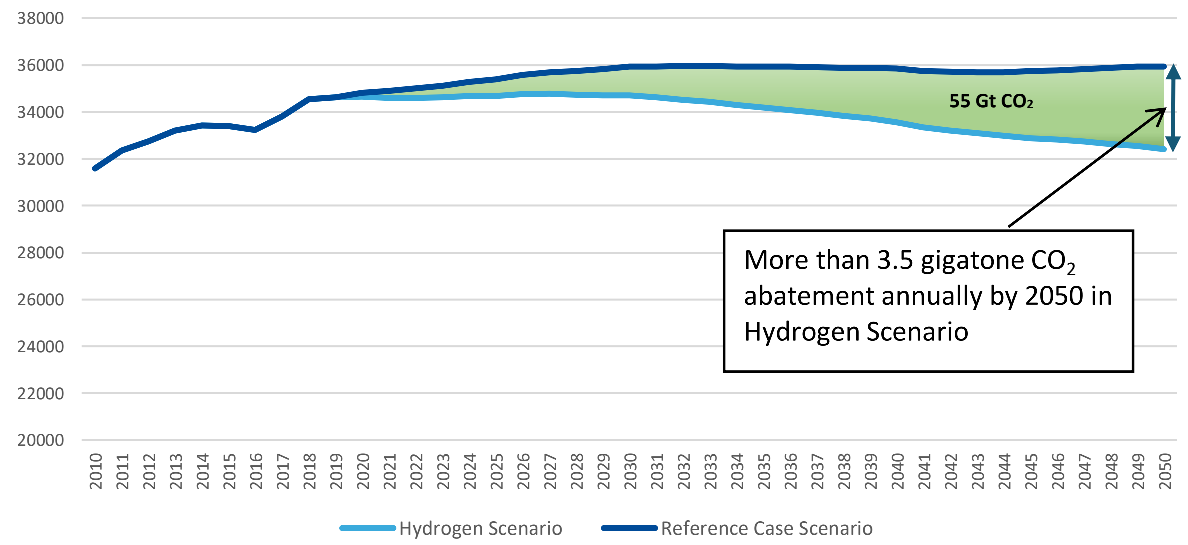
**Figure 13. Outlook for primary energy consumption mix, RCS and Hydrogen Scenarios**




Carbon emissions are considerably mitigated in the Hydrogen Scenario. Figures extracted for total CO2 emissions demonstrate that around 3.5 gigatone of CO2 can be abated on a yearly basis by 2050. This translates to a cumulative total of more than 55 gigatone of CO2 from 2019 to 2050. It is worth mentioning that in our scenario, carbon capturing measures are taken into account. Therefore, a share of this abatement is due to the captured CO2, but most of it is because of decreasing the share of coal in total energy consumption. That means that even when carbon capturing measures are considered, coal will lose shares in total primary energy and CCUS technologies enable natural gas to contribute significantly in hydrogen development, while overall emissions are being reduced.



**Figure 14. Outlook for CO2 emission in both scenarios (Mt CO2)**




The results also suggest that the volume of carbon emissions per unit of GDP will be less in comparison with the Reference Case Scenario. This indicates decoupling of economic growth and total emissions through the hydrogen economy. In the Hydrogen Scenario, around 170 tons of CO2 is forecasted to be emitted per each real million USD of GDP for the year 2050, compared with more than 180 tones per real million USD for the same year in the Reference Case Scenario.

Another advantage of hydrogen use is to reduce other greenhouse gas emissions, such as NOx and SOx. Both NOx and SOx emissions are forecasted to reduce compared with the Reference Case Scenario. NOx is forecasted to be emitted slightly less than 2 million tons compared with the Reference Case Scenario. As the same way, emission of SOx will also be abated by 3 million tons annually by 2050 compared with the Reference Case Scenario.

Among final consumer sectors, most of this abatement comes from the transport sector as well as the power sector in transformation sectors. Commercial, residential, and industry also make a contribution to greenhouse gas abatement.

In the Hydrogen Scenario, morethan 1200 mtoe of hydrogen is demanded by all mentioned sectors by 2050, much more than the value of 91 mtoe forecasted in the Reference Case Scenario. As can be seen in the pie chart on the right of Figure 15, transportation will be the main driver of this huge demand, followed by the power sector. Industry use of hydrogen, including as fuel or feedstock, Residential and commercial sectors also have an important role in hydrogen demand by 2050.

**Figure 15. Outlook for total hydrogen demand (mtoe, %)**

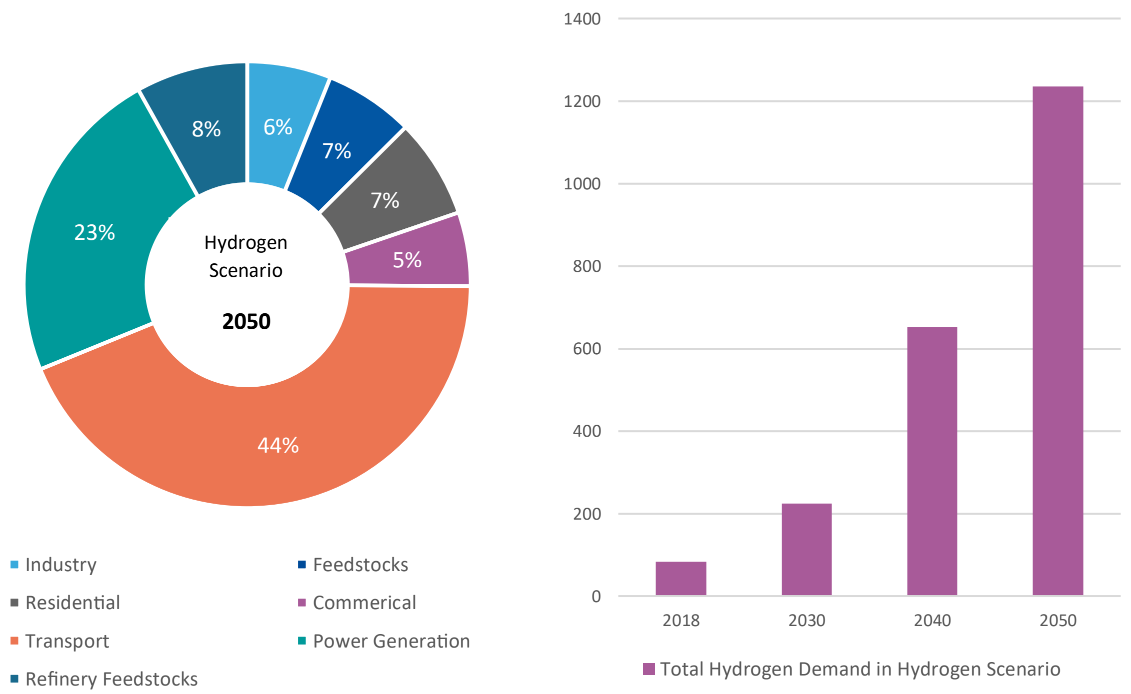
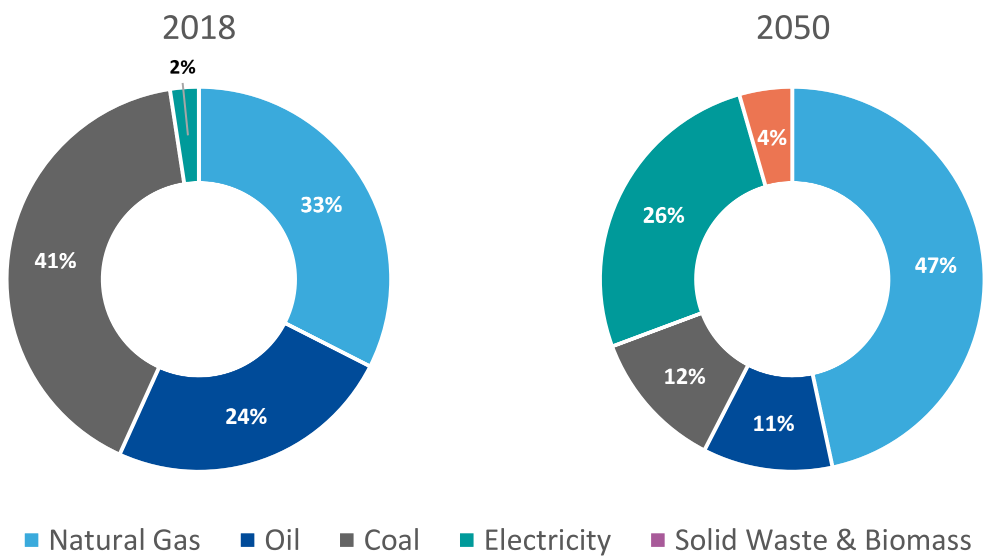



Figure 16 presents the share and volume of sources for the production of hydrogen in the Hydrogen Scenario in 2018 (current situation) and 2050 (outlook horizon). Currently, more than 98% of all energy sources used to produce hydrogen are from fossil fuels. This share will significantly reduce by 2050 in our Hydrogen Scenario. Also, the absolute volume considerably rises due to the huge increase in total hydrogen demand.

We can see that among fossil fuels, the only energy carrier that maintains its contribution is natural gas. Around 47% of the hydrogen process will be sourced from natural gas by 2050, mostly in the form of blue hydrogen. Electricity or electrolysis gain significant shares in total hydrogen production. This implies that renewable power will be used in hydrogen generation by 2050.

Bio fuels, waste, and biomass also appear in the list of sources used for hydrogen by 2050 to 4%.

**Figure 16. Outlook for hydrogen production by input fuel (mtoe, %)**






# Conclusion and recommendations

The results of the Hydrogen Scenario admits that natural gas can play a significant role in the hydrogen economy development. Natural gas, along with the CCUS technologies, provides a very economical, competitive, reliable, and practicable option to produce hydrogen consistent with the sustainable development goals. Most type of greenhouse gas emissions, including CO2 can be abated significantly through blue hydrogen production, while the costs will still be competitive.

CCUS is a very crucial technology not only for the natural gas development in hydrogen production but also in most of the other applications of natural gas use across its supply chain.

Considering the significant natural gas reserves as well as very extended upstream and pipeline infrastructure in GECF countries, they have a promising potential to benefit from hydrogen economy development by promoting technology advancement in natural gas reforming as well as other essential measures such as CCUS and methane emission-reduction technologies.

We recommend continuing the discussion by organizing workshops and meetings on the potential of the hydrogen production and export in the GECF Member Countries and coordinating hydrogen-related activities through these workshops.

This can lead us to develop a hydrogen pathway in GECF technology roadmap and give a better view of the potential of this development within the GECF Member Countries.

# Annex

## Abbreviations

| | |
|---|---|
| BEV | battery electric vehicles |
| bn | billion |
| CBM | coalbed methane |
| CCGT | combined cycle gas turbine |
| CCUS | carbon capture utilization or storage |
| CCS | carbon capture and storage |
| CH4 | methane |
| CHP | combined heat and power |
| CO2 | carbon dioxide |
| CPP | Clean Power Plan (US) |
| EOR | Enhanced Oi Recovery |
| FCEV | Fuel Cell Electric Vehicles |
| GTL | gas to liquids |
| HCNG | Hydrogen-enriched compressed natural gas |
| ICE | internal combustion engine |
| IGCC | Integrated Gasification Combined Cycle |
| LCV | light commercial vehicle |
| LNG | liquefied natural gas |
| LPG | liquefied petroleum gas |
| NGV | natural gas vehicles |
| NOX | nitrogen oxides |
| PHEV | Plug-in hybrid electric vehicles |
| PV | photovoltaic |
| RES | Reference Energy System |
| RETM | Reference Energy Technology Map |
| SMR | Steam Methane Reforming |
| SOX | sulfur oxides |

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## Comments and questions regarding this report should be addressed to:


Seyed Mohsen Razavi

Energy Technology Analyst

Energy Economics and Forecasting Department

Gas Exporting Countries Forum

Tornado Tower, 47th-48th Floors, West Bay, Doha-Qatar

P.O.Box 23753

Tel: +97444048438

Email: SeyedMohsen.Razavi@gecf.org


More information is available at www.gecf.org