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# Gas Turbine Modernization – Fuel Conversion and Special Fuel Applications for the Asian Market

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**Answers for energy.**

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## Abstract

Siemens has a wide range of experience with special fuel applications and provides solutions for most needs regarding fuel quality and fuel quality ranges. Siemens' experience with liquid fuels ranges from heavy fuel oil with large amounts of contaminants and crude oil to nearly gaseous liquids such as naphtha and condensates. In the case of gaseous fuels, the Siemens V-frame gas turbines can be converted to be usable with sour natural gases and further off range gases with decreased heating values and unconventional gases. In addition, the Siemens V-frame gas turbines can be integrated into coal-based power generation concepts: for example, by firing coal-based methanol or syngases as well as their admixtures into conventional fuels (for the Siemens SGT5-2000E in particular, good long-term operational references are available).

This addendum will further spotlight the special design features of our robust, mature gas turbine type SGTx-2000E and its excellent value with low fuel qualities. Also highlighted will be the spectrum of fuels appropriate for the Siemens SGTx-4000F, which uses lower-calorific fuels as well as liquefied natural gas (LNG).

# Requirements of the Asian market

Asia is one of the most dynamic and fastest-growing economic areas in the world. This economic growth also has a significant impact on energy consumption in general as well as locally available resources in particular. Forecasts from British Petroleum (BP), for example, predict an annual energy demand that almost doubles by 2030 in the non-Organization for Economic Co-operation and Development (non-OECD) countries. This increased demand will lead to technical innovations with increases in efficiency on the one hand, and also to a change in the mix of primary energy sources used on the other. It is also believed that the utilization of additional fossil energy resources will shift the qualities of fuel oil and gases from the so-called conventional fuels toward non-conventional fuels and fuel qualities. These forecasts further predict a relatively disproportionate increase in the use of renewables (renewable energy → henceforth called renewables) and coal. The renewables in figure 1 also include biofuels, which emphasizes a trend

toward biofuels and biofuel admixtures playing a more and more significant role as fuels in heavy-duty gas-turbine power plants.

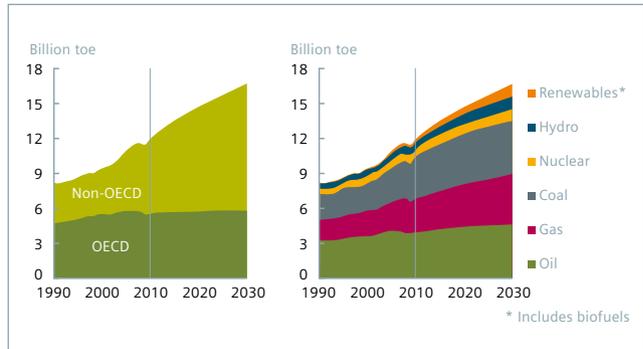


Fig. 1: Fuel consumption forecast worldwide; Energy Outlook 2030, BP 2012, toe: tons of oil equivalents

# Fuels for power plants with gas turbines

Siemens possesses a wide range of operational experience with different fuels, and also sees the feasibility for gas turbine modifications for enabling the usage of uncommon fuels as well as for the design of project-specific fuel solutions.

Figure 2 shows various gaseous, liquid, and solid fuels and the wide range of lower heating values (LHV) they cover. Gaseous fuels are shown as green triangles or yellow, orange, and green ellipses, and range from blast-furnace gas with the lowest LHV to methane with the highest LHV. The blue ellipses and solid blue dots indicate all of the common and less-common liquid fuels, including bio fuels and liquefied petroleum gas (LPG), butane, and propane, which are between the gaseous and the liquid phase. Solid fuels including lignite and hard coal and are indicated by black squares.

The hydrogen content shown on the vertical axis in Figure 2 is also a rough indication of two things: flame speed (ranging from 20 cm/s for pure carbon monoxide as the major component in low-calorific furnaces and syngases, to pure hydrogen at 360 cm/s) and the water content of the exhaust gas. Fuels essentially consist of hydrogen, carbon atoms, and/or (in the case of alcohols) oxygen atoms. This means that the low hydrogen content of fuel

oil and fuel gases also means a low content of water in the exhaust gas and a correspondingly higher amount of the greenhouse gas carbon dioxide emitted.

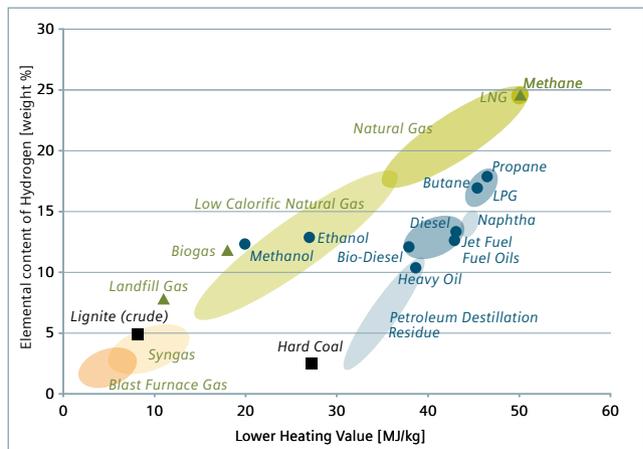


Fig. 2: Comparison of different fuels with respect to their lower heating value and hydrogen content

Due to the high number of possible fuel questionnaires and applications, in the following only some experience highlights will be offered.

## Natural gas and liquefied natural gas (LNG)

Natural gas and LNG are examples of the most commonly used gas turbine fuels. The difference between these two variants is the fact that LNG is natural gas that has been liquefied for transportation. As a result of this liquefaction process, it contains lower amounts of inert gases. In comparison, LNG typically has a slightly higher LHV and slightly higher Wobbe numbers than natural gas transported via pipelines. In actual gas turbine operation, this property

difference is a minor issue. In the case of LNG utilization for gas turbine power plants, it needs to be pointed out that LNG may originate from different sources and suppliers and always has unique characteristics. The utilization of LNG from different sources may result in increased requirements towards the applicable range of fuel gas qualities (fuel gas Wobbe range).

## Move and extension of fuel gas Wobbe range

Over the last few years, it has become more and more common to move the fuel gas Wobbe range toward new fuel gas qualities. The following scenarios are typical: a move toward lower as well as higher calorific values as well as questionnaires of dynamic changes in between. The move to lower calorific values is mainly driven by the increased utilization of new gas fields with low grades. The other extreme usually derives from the use of LNG with significantly reduced amounts of inert gases or hydrogen-enriched fuel gases. With several modifications of the combustion system, for example, a burner diagonal swirler

design (hole pattern, hole diameters, and diagonal swirler blade profile), the Wobbe range can be modified to site-specific requirements. In several cases, instead of one directional single quality changes, there is a requirement for frequent changes between fuel gas qualities. Siemens also provides solutions that allow operation with wide fuel gas Wobbe ranges or multiple fuel gas qualities.

The resulting required modification scope for most cases will be described in the next section.

## Performance with increased fuel gas quality ranges

Siemens' SGTx-2000E and SGTx-4000F gas turbines typically run on fuel gases that vary around the quality value specified on-site during commissioning, by a maximum of +/- five percent. This standard variation range can be extended by the implementation of the fuel gas analyzer upgrade package and the so called "Wobbe controller". The extension of the operation range above the standard often results in performance limitations for the deviating gas qualities. If the required emission values are very low, these performance limitations consist of a decrease in the turbine outlet temperature that primarily affects the gas turbine's base load power.

If a modification of fuel gas quality needs to be performed to further extend the modification of burner diagonal swirlers, the pattern and alignment of premix gas injection holes also needs to be considered.



Fig. 3: A closer look at required hardware design changes for the modification of fuel gas quality

In almost every case of fuel gas quality modifications, a unit- and fuel-specific tuning of the combustion system is required. The combustion tuning involves the determination of an optimized set of controller values. During combustion tuning, the optimized ratio between the premix and the pilot gas portion is determined as well as the ratios between air and fuel gas. Furthermore, this setup procedure adjusts the optimized ratio between air used for combustion and air that bypasses to the flame used for combustion-chamber cooling. The main tasks of the tuning procedure also include maximizing the performance during startup, shutdown, and base load operation and minimizing nitrogen oxide ( $\text{NO}_x$ ) emissions.

A secure and reliable operation with deviating fuel gas qualities can be insured by the Wobbe controller and the fuel gas analyzer. This analyzer unit measures the actual gas quality and delivers LHV as well as density to the power control system. The Wobbe controller, which comprises an instrumentation and control function, performs measurements in accordance with the given fuel quality to establish a reliable and secure operation through the reduction of the gas turbine's outlet temperature. In addition, this controller upgrade allows an interpolation between single optimized tuning setups for individual fuel gases.

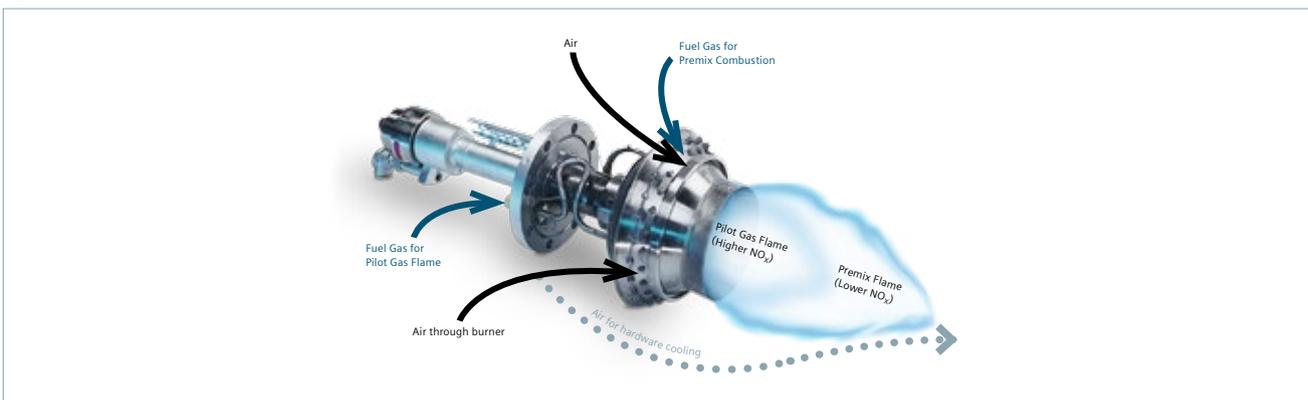


Fig. 4: Flows of the gas turbine's air and fuel around the burner, which need to be optimized by tuning. The resulting tuning values are site-specific depending on the working media used.

## Crude oils

Crude oil simply means the natural resource as it exists in its natural deposit, and the specific quality may vary enormously from case to case. Crude oil qualities may range from very clean fuels (like jet fuel, distillate No. 2, and diesel according to European standards) that are usable in film-cooled advanced-frame gas turbines, to the worst-case heavy fuel oil applications. The typically high amounts of very volatile short-chained hydrocarbons – which cause

low flash points – can be seen as normal characteristics of crude oils, and call for special safety measures.

As explained in the next section “Heavy fuel oils”, these oils are usually the residuals from crude oil processing: therefore, crude oils tend to have a relatively low content of chemical impurities and require a smaller technical effort.

## Heavy fuel oils

Heavy fuel oil is a class of liquid fuel that ranges from diesel fuel oils with slightly increased viscosity to bitumen like, highly viscous residuals from crude oil processing or other chemical processes. In addition to the fact that these substances are primarily composed of hydrocarbons, their individual chemical or physical properties vary in a wide range. Other typical characteristics of heavy fuel oils are the high amounts of impurities in significantly increased

concentrations. These two important characteristics require a significantly greater effort for fuel transportation, storage, and ignition. For improved transportation as well as for ignition, this fuel needs to be continuously preheated. Depending on the required preheating temperature and the fuel's flash point, additional measures regarding operational safety may need to be considered. Another significant source for this increased effort is the various chemical

components that accompany this fuel. Very typical are alkaline metals (sodium, potassium), alkaline earth metals (such as calcium and magnesium), halogens, and sulfur compounds as well as the technically very challenging vanadium. Depending on the specific composition of those chemical cocktails, different phenomenon within the power plant's hot-gas as well as exhaust-gas path may occur. The consequences can be high temperature corrosion as well as formation of deposits (reversible or irreversible). In addition, the separation of those impurities, for example, by fuel washing with water, is not a feasible scenario in every case. For example, vanadium is a very harmful component for hot gas-path hardware that cannot be washed out of the fuel in the same way that is possible with, for example,

sodium, potassium, or magnesium. To prevent the danger of vanadium and oxidized vanadium (vanadium pentoxide) releasing their harmful potential, magnesium or other chemicals need to be added.

Due to the fact that the heavy fuel oil combustion forms depositing liquid or solid particles, this fuel is usually not feasible for film-cooled advanced frame SGTx-4000F gas turbines; whereas the mature SGTx-2000E gas turbines can easily be modified for heavy fuel oil utilization. Another significant design advantage of this gas turbine type is the spacious design of the silo combustors, which allows for easy maintenance and removal of deposits.

## Sour gases

Natural gases from certain natural deposits contain high amounts of hydrogen sulfide, which is a very poisonous gas. In some natural gas deposits, hydrogen sulfide can even be the major component and may reach concentrations above 90 percent. The limiting factor for the use of sour gases for electricity generation is not the gas turbine: it is the major technical challenge posed by the fuel- and exhaust-gas impinging plant components. Hydrogen sulfide fuel reacts with metal components and forms metal sulfide particles that can settle within the fuel gas stream. This may block the flow path in small diameters, for example,

at burner nozzles, and also harms other components of the fuel system like the fuel valves. After combustion, the chemical compounds sulfur dioxide, sulfur trioxide, and water are formed. Sulfur dioxide and trioxide are poisonous gases that form sulfurous and sulfuric acids with water. The hardware-destructive potential occurs in particular below the water dew point of those exhaust gases. All of those fuel characteristics require enormous effort with respect to safety and the materials used. In addition, a clean second fuel is required for the plant shutdown as a purging agent.

## Power generation with gas turbines based on solid and alternative energy sources



Fig. 5: The dominant components in these power plants are their air-separation units and their syngas gasification units, which are located inside a main building in the center of each power plant. (Left: IGCC Power Plant, Buggenum, Netherlands; right: IGCC Power Plant, Puertollano, Spain)

The generation of electrical energy by gas turbines is also possible using alternative green resources as well as coal. Depending on the primary energy source, gas turbines can

be seen either as totally green, climate-friendly machines and also as machines with extremely high emissions of climate-harming carbon dioxide. As a result of the trans-

formation of biomass, waste, residuals, lignite, and coal into synthetic fuels, the range of primary energy sources can be extended from fossil fuels to renewable resources. Primarily from the view of process engineering, two pathways are available to convert these resources into fuels that are applicable for use in gas turbines. The first is based on the generation of gaseous synthetics, the so-called syngases, and the second on the generation of liquid fuels. Due to the enormous effort needed to modify existing power plants for syngas operation, the focus for the service business will be on liquids such as methanol, ethanol, and biodiesel as well as their admixtures into common fuel oils.

Biodiesel is intended as a supplement for fossil diesel, and has almost the same characteristics: but due to the absence of international standards regarding its specific quality, biodiesel may bring with it many impurities or high solidification points. Depending on project-specific

parameters and the specific composition of biodiesel or diesel-biodiesel mixtures, additional measures such as a required parallel liquid fuel system cleaning the fuel-oil armatures and piping needs to be considered.

Solutions for methanol deviate much further from standard diesel applications. The calorific value of methanol is about half of the value of diesel, and requires modifications that enlarge the fuel flow-path diameters and the parallel fuel-injection via premix and diffusion burner passages. Although the usefulness of pure methanol was tested in a test rig derived from a Siemens SGT5-2000E gas turbine, the merit of this fuel for advanced frame gas turbines (SGT5-4000F) is assumed to be adequate. In addition, for both gas turbine frames it is assumed that a methanol fuel with a water content of 12 percent (vol/vol) would be an appropriate fuel grade. The power generation of a combined cycle power plant would increase by about 13 percent using water-diluted methanol.

## Syngas applications for existing service power plants

A different class of widely used fuel gases is the so-called low-calorific synthetic fuel gas (syngas). These synthetic gases are common gases deriving from the gasification processes of coal, coal residuals, hydrocarbon residuals (bitumen), biomass, and other non-fluid components with high ratios of combustible components. These solids or high viscosity energy sources are not appropriate for gas turbines unless they can be transformed into a fluid fuel. In addition to the above-mentioned liquid methanol (which is a liquid synthetic fuel), syngas includes very low-calorific fuel gases. The syngases are rich in carbon monoxide, hydrogen, and inerts (water and carbon dioxide) and vary depending on their synthesis process. The modification of an existing fuel gas or fuel-oil fired gas turbine power plant into a syngas-fired power plant possible is in theory. But due to economic factors, a modification is usually not feasible because of the significant design differences that are not limited to the gas turbine itself. Syngas-fired gas

turbines are much more integrated into the power plant. Because of the heating value of syngas, which is about ten percent of natural gas, the required fuel flow path is much wider compared with natural gas. The compressor is also designed for significantly smaller air mass flows, or it is equipped with air extraction devices, which depends again on the plant design and manner of gas turbine plant integration.

The resulting effort required for the process and gas turbine control are much higher, and include additional measures with respect to explosion and fire protection, and safety measures in general.

Those classes of combined cycle power plants that are called integrated gasification combined cycle (IGCC) power plants are highly complex plants consisting of the syngas generation unit, syngas purification unit, and in the case of oxygen-based gasification, an air separation unit.

## Biodiesel

Biodiesel is also a biosynthetic fuel produced from vegetable oil or animal fat and methanol. The transesterification chemical reaction denotes the processing of vegetable oils or animal fat with an alcohol (usually methanol) into fatty acid methyl esters and glycerol. Those fatty acid methyl ester molecules are basically also long-chained hydrocarbon molecules with characteristics similar to those of fossil diesel. Biodiesel as a fuel for gas turbines is controversial for several reasons. Methanol itself is an excellent fuel for use in modified gas turbine power plants. The direct utilization of plant oils is also assumed to be appropriate for gas turbines. In terms of green renewable energy production, however, biodiesel is seen as controversial due to the fact

that it is limited to oily and fatty biomass, which makes it enormously expensive with respect to the agricultural area required, and the resulting ecological and economic impacts (such as negative influence on the global food market prices). In terms of fuel supply conservation economics, (bio-)synthetic fuels whose utilization is not limited to seeds or oils are preferred. As controversial as it might be, the modification of SGTx-2000E as well as SGTx-4000F for a biodiesel content of 20 percent (vol/vol) within standard diesel is possible after some minor modifications of the gas turbine. Operation with a 40 percent biodiesel admixture has been successfully tested, but this plant modification requires a greater effort.

## Biogas

A different approach to utilize biomass for energy production is the generation of biogas. Biogas is methane with a high content of carbon dioxide, and in general is appropriate for the operation of gas turbines. In practice, biogas is usually produced non-locally in small amounts and is typically not provided in useful amounts for the operation

of heavy-duty gas turbines. But biogas may be inserted into fuel gas networks and will influence the fuel gas Wobbe number. Depending on project-specific parameters, dynamic changes in the fuel gas Wobbe range may be a technical issue.

## Methanol

Methanol is primarily a synthetically produced fuel from various sources. The main chemical characteristics of this liquid fuel, which are its total miscibility with water, low heating value compared to fuel oil, absence of other chemical species, and its liquid state of aggregation, make this fuel an enormously interesting fuel for the not so distant future. The compression of this liquid to the pressure required by a gas turbine can be achieved much more energy efficiently than with gases. In addition to providing a beneficial increase in water content, the LHV also brings an enhanced potential to produce net power and efficiency increases in gas turbine power plants. With a LHV of a methanol-water mixture, the required fuel mass flow needs

to be higher to achieve a comparable base load performance. Another thermodynamic benefit of the LHV of methanol-water mixtures is the reduced temperature of the combustion process, which leads to extremely low  $\text{NO}_x$  emissions in the range of fuel gas premix operation.

As a consequence of the performance benefits of methanol-water mixtures, methanol-based electricity generation is almost economically competitive with natural gas and fuel oil, due to the possibility of saving the distillation process for water separation within the process of methanol synthesis.

## Ethanol

Regarding the thermodynamic performance potential, the required scope of modification, and modifications in plant operation, ethanol is almost comparable to methanol, but not to methanol's extent because of its calorific value, which is in between that of fuel oil and pure methanol. In spite of its value, ethanol as a regenerative green gas turbine fuel is also seen as controversial due to conventional ethanol production processes. Ethanol is usually

produced by the fermentation of starch or sugar containing biomass, and a subsequent distillation, which also makes it a competitor to food production.

Over the last few years, production processes have been developed that allow the fermentation of cellulose, and so finally a biomass that is not in competition with food production.

# Utilization of low-calorific liquid fuels

Gas turbine operation with liquid fuels of a lower calorific value than fuel oil require an increased diameter of the fuel flow path due to the higher fuel mass flows that need to be inserted into the combustion chamber. The typical combustion system of the SGTx-2000E as well as the SGTx-4000F gas turbine is equipped with two different burner passages for different operation modes: diffusion burners, which are characterized by a low grade of fuel atomization and a correspondingly low level of air mixture, and premix burners with a high grade of fuel atomization. In contrast to the standard fuel oil operation mode with an operation either in the premix mode or in diffusion mode, the combustion of high amounts of low-calorific fuels is generally possible with a fuel insertion through both burner systems in parallel, as shown in figure 6.

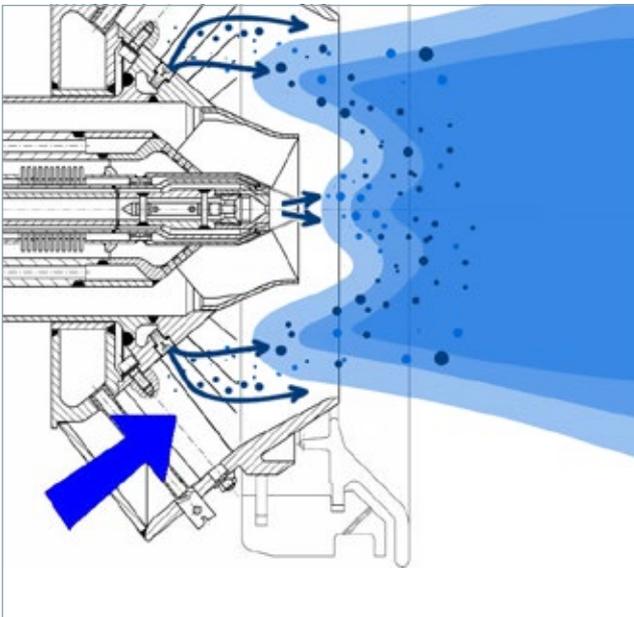


Fig. 6: Insertion of low-calorific liquid fuel (for example, methanol) via diffusion oil burners and premix oil nozzles in parallel

Although operation in the diffusion mode is usually characterized by a high rate of generated  $\text{NO}_x$  emissions, methanol combustion is expected to generate significantly lower  $\text{NO}_x$  emissions than typical of fuel oil. The reason for the projected low rate of  $\text{NO}_x$  generation is given in the chemical structure of methanol ( $\text{CH}_3\text{OH}$ ). During the combustion process, the OH group that is typical for alcohols will almost directly convert into water ( $\text{H}_2\text{O}$ ) due to the extremely high attraction forces between the oxygen in the OH group and other hydrogen atoms within the  $\text{CH}_3$ . This reaction to water releases a relatively low amount of thermal energy, with the effect that the newly formed water molecule stays close to the remaining  $\text{CH}_2$  residual from the former methanol molecule. During the subsequent reaction of  $\text{CH}_2$  with oxygen yielding carbon oxides and a second water molecule, the first  $\text{H}_2\text{O}$  molecule formed acts as a coolant for the  $\text{CH}_2$  combustion, with the result that the release of energy in the local area of the fuel molecule is much more homogeneous and lower than in the case of fuel oil combustion. In general, this combustion sequence leads to less extreme temperature values within the flame and a significantly reduced rate of  $\text{NO}_x$  formation.

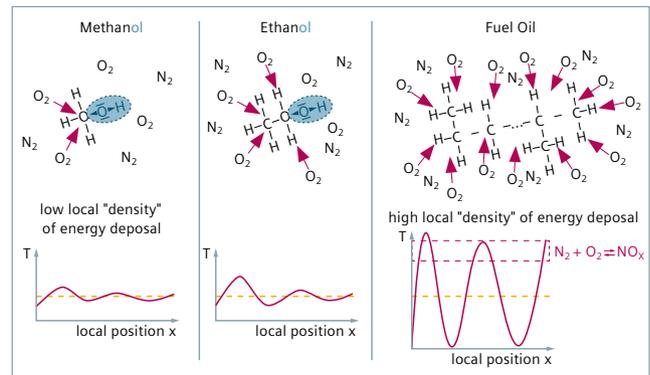


Fig. 7: A closer look into the molecular dimensions of combustion processes for methanol, ethanol, and common fuel oil

## Phase-change behavior/phase homogeneity

Many fuels like LPG, naphtha, condensates, and fuel gases with high amounts of long-chained hydrocarbons are characterized by their tendency to perform their phase change somewhere within the typical window of gas turbine operating pressure and fuel temperature. This leads to special safety requirements for storage and fuel handling as well as for the controlled homogeneous injection of fuel into the gas turbine combustion chamber. When there is a system design targeted for those requirements, almost all customer-specific needs can be fulfilled for new gas turbine power plants in advance and with optimized investment costs. In the case of the service business, the parameters are different. More customer-specific solutions need to be found, because existing power plants are usually optimized for a few specific tasks that may change significantly during the lifetime of the plant. Very common examples are changes in fuel composition and fuel quality.

Frequent operational issues originating in the existence of second-phase particles are very common. In the case of fuel gases, the formation of a second liquid phase that is formed directly in the gas flow is a common phenomenon. Fuel gases exhibit a behavior called retrograde condensation, which means that their evaporation or condensation curve is not the steady incline that is common for most substances, but is instead curved. This means that these fuels change between gaseous and liquid state within a certain range of temperature and pressure.

Outside this envelope, the fuel consists of one homogeneous phase. If both ranges (envelope and operation range) intersect, liquid particles form in the fuel gas and lead to a variety of technical problems. In addition to the fact that accumulated fuel condensates may block pipes and burner nozzles, the liquid particles also have the potential to become carbonized and form hard encrustations in the flow path. Unavoidable consequences can be performance-limiting combustion instabilities and even unscheduled outages.

If two phase flows occur in the pipes to the different burners, a distribution of the flames may appear. The hot zones that endanger the gas turbine's hardware are especially critical aspects of this heterogeneous distribution. With almost similar effects but due to a different root cause, solid particles may be formed by corrosion from water condensates or traces of hydrogen sulfide. In this case, the liquid particles can form in significant amounts and completely block the fuel flow. Another common phenomenon is the formation of particles in a pre-contaminated fuel system. These particles are carried through the system and can block burner nozzles or other equipment.

## Fuel gas preheating to avoid two-phase flows

When liquid condensates appear in the fuel gas system, the only reliable way to avoid problems for the gas turbine is to adjust the fuel gas properties to establish a significant difference between the dew point line and fuel gas operation range. A temperature difference of about 15 Kelvin between the highest temperature on the dew point line and the lowest fuel gas temperature is a reliable value for avoiding the formation of liquid particles downstream of

the turbine burner nozzle. In practice, the online observation of the dew point line is not feasible, which makes it difficult to reliably maintain the required 15 Kelvin difference. Therefore, two strategies are useful for avoiding condensation in gas turbine auxiliary systems and burners: fuel gas preheating by about 15 Kelvin, with a prior dew point adjustment, and fuel gas preheating to high values in the range around 100 Celsius and above.

# Future energy market for fossil and alternative primary energy sources

The energy demand forecast for the non-OECD countries as shown in Figure 1 leads to the consideration and utilization of all energy sources to a greater extent for the generation of electricity for the Asian market. It is a challenging but feasible task to establish a secure energy supply in a rapidly growing area with a parallel fulfillment of the obligation to minimize impacts on the climate. The minimization of climate change and a significant increase in the energy supply can be achieved with the help of innovative technologies. Gas turbine power plants will continue to play a major role in the future energy market: On the one hand, they are very flexible and available short term due to their rapid startup functionality, and on the other hand, they are potentially very flexible with different fuels. Both factors make them highly valuable for the compensation of fluctu-

ating energy generation by solar, wind, and other renewables. In the area of utilized fuels, there is an enormous potential to extend the use of renewables to secure the base load demand. Figure 8 shows a chart of a future and highly plausible energy/fuel economy, with storage and distribution of green energy using the existing infrastructures for fossil fuels. This exemplarily shown (partially) green energy economy is just a concept and actual future market development depends on several aspects, for example, the development of the global economy and related fuel consumption and prices, the future share of nuclear power generation, and local conditions. Regarding the optimized integration of gas turbine power plants in a green energy economy, theoretical as well as practical solutions are available.

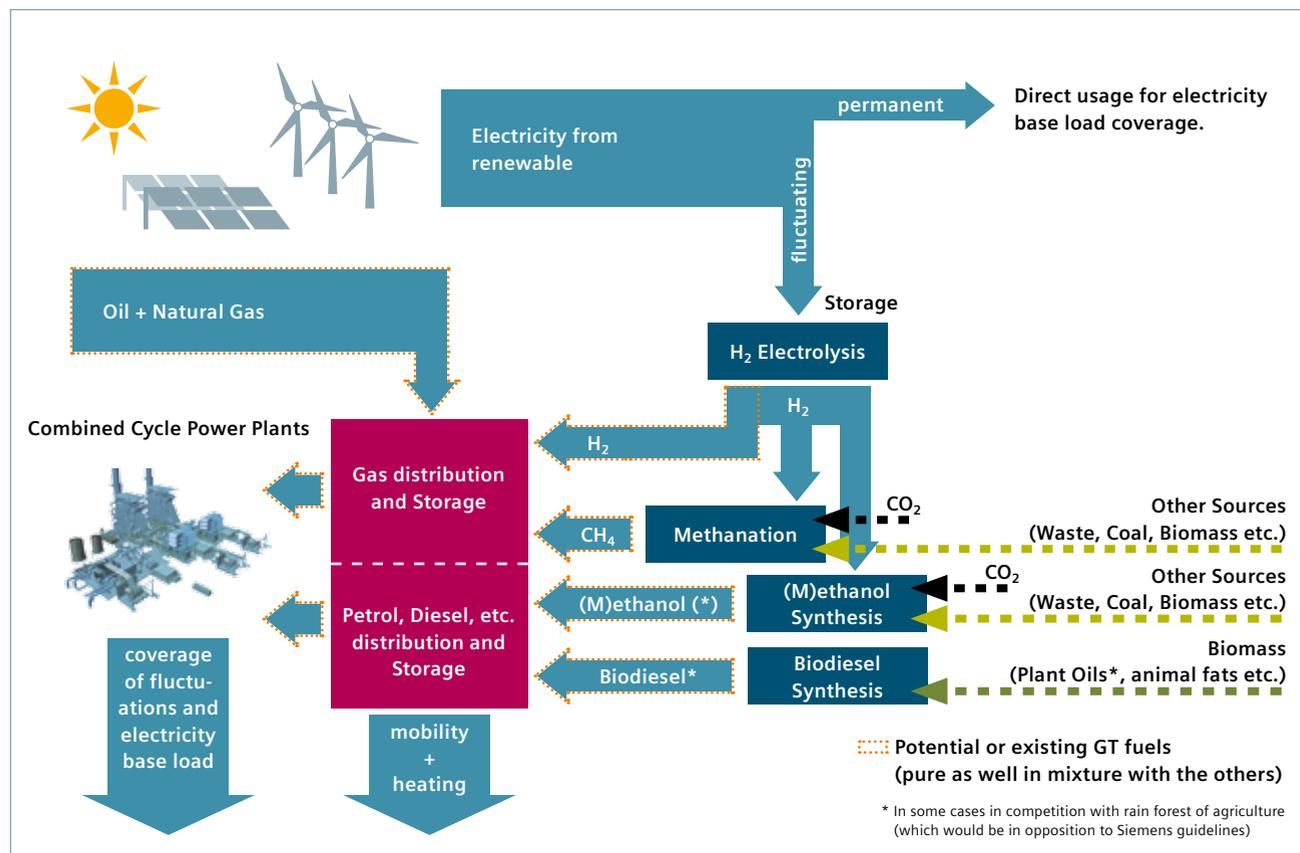


Fig. 8: If the renewable energy contribution increases significantly, its weather and seasonal fluctuations need to be leveled out. Gas turbine power plants are highly useful and can play a major role in balancing those fluctuations. The distribution as well as the long-term storage of local renewable energy excess can be realized by a fuel market that is based on synthetic fuels.

## Conclusion

The reliable coverage of base load energy can be achieved despite the limitations of conventional resources at increased power demand as well as the strong pressure to minimize the climate change. Siemens gas turbine power plants are available and/or can be modified for almost all possible future requirements and local conditions through the adaptation of fuels and increased operational flexibility.

With the increasing scarcity of fuel oils and fuel gases, alternative fossil fuels and their derivatives (synthetic fuels) will become more and more dominant. Synthetic fuels can be seen as a strong potential bridge technology that can allow the extended utilization of several primary energy sources with proven technologies and high performance. A wide range of different fuels and fuel qualities are anticipated for utilization in gas turbines, especially in the Asian market due to its rapid economic growth and the parallel increase in power demand.

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