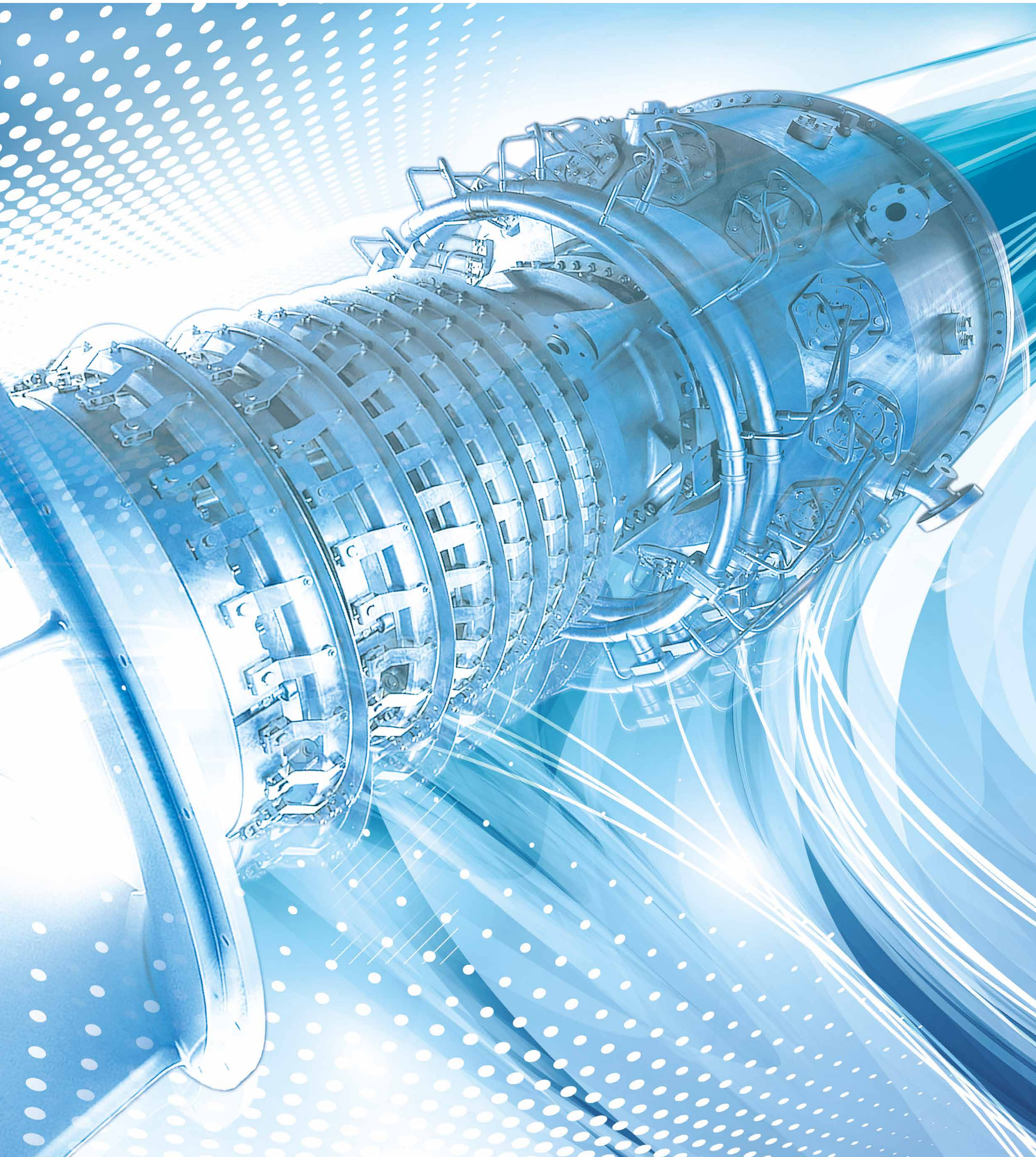
ETN
Global

ETN R&D RECOMMENDATION REPORT

OCTOBER 2018



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1. Introduction

Continuous Research and Development (R&D) efforts in the turbomachinery sector are of paramount importance to ensure the key role of turbomachinery technologies during the ongoing energy transition era & beyond. This includes the deployment of carbon neutral energy services and products. After having analysed the impact that turbomachinery can have in the future, the General Assembly assigned to ETN's Project Board the task to produce a Research & Development (R&D) Recommendation Report. The purpose of this report is to summarise recommendations for R&D topics based on the user community's needs and requirements as well as energy policy targets. The report is intended to be a living document revised on a biennial basis. The report lists topics in technical areas relevant to gas turbine systems being used in the two business segments ETN members are active in, namely "oil & gas" and "power generation". It considers topics related to: the integration of turbomachinery into new energy systems, the development of new system integration solutions, the improvement of the state of the art of component technologies, adaption to future emission regulations and other regulatory frameworks. ***The subjects suggested should trigger respective actions within the ETN community in various forms: R&D projects, feasibility studies, best practice guidelines, development of standards and technical briefing papers***.

The ETN Project Board is an ETN body nominated bi-yearly by the ETN Board. It provides a consultative forum and independent support to new initiatives or issues that are brought to its attention. Providing a sounding board for these ideas and initiatives that have originated from the entire body of ETN members, the Project Board advises on how to maximise the potential of new initiatives and gives recommendations for future actions.

Since the 2018 ETN Annual General Meeting, the ETN Project Board has additionally taken over the responsibility to lead and provide technical and strategic advices to the ETN Technical Committees (TCs), which cover the most crucial areas of future gas turbine technology development (see TC structure at the end of this document). The TCs serve as forums where the ETN members meet to share experiences and discuss ideas and initiatives during the ETN events.

The Project Board 2018-2020 consists of the following members who have all contributed to the various parts of this edition of the ETN R&D Recommendation Report:

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Gas Turbine performance, operation and condition monitoring;
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Gas Turbine Life Consumption Analysis; Combined Cycle Gas Turbines (CCGT);
Gas Turbine Performance Design and Tests; Combined Heat and Power (CHP);
Computational Fluid Dynamics (CFD)

2. Market Conditions & Policy Framework

Energy systems are undergoing fundamental changes across the world, driven by three key trends: Decarbonisation, Decentralisation and Digitalisation. Decentralised power generation, intelligent power grids, overall system integration, unconventional fuels and of course, renewable energy sources (RES) are at the top of the energy agenda. On a global scale the pressing needs to cut CO_2 emissions as well as local air pollution is resulting in an accelerated phase-out of coal-fired power plants and in increased investments in clean energy technologies. Digital solutions are being developed and become available on a widespread basis, transforming energy systems to make them smarter, more reliable, more interconnected, safer and, above all, more efficient.

Despite the renewable boom, it is foreseen (e.g. by the International Energy Agency (IEA)) that conventional gas-fired power generation, currently the largest gas-consuming sector worldwide, will continue to play a strategic role. Indeed, it will provide a reliable and cost effective, dispatchable power source to respond to peaks in demand and when intermittent renewable sources are not available, and its underlying technology can also provide carbon neutral solutions for power generation and mechanical drive in the longer term.

This chapter outlines topics which have a strong influence on gas turbine technology development, gas turbine sales and gas turbine deployment and use.

Economic environment for gas turbine markets (oil & gas, power generation)

After some years of depressed price levels for crude oil (at times as low as $28 per barrel in 2016), prices have recovered in 2017 to reach levels back up in the range of $70-80 per barrel. The ups-and-downs have had immediate effects on the exploration of shale (and other unconventional) gas resources and general investments in the oil & gas business. With the oil price recovery the situation has eased to some extent, even though the investment levels still remain significantly lower than in the pre-depression period (before 2014). The availability of shale gas (mostly in the USA) in huge quantities, combined with strongly enhanced worldwide distribution of LNG, and the general diversification of the energy mix have already changed the global energy landscape significantly, and this megatrend will definitely continue.

The unfavourable conditions of the European gas turbine market for power generation has also a certain influence on the gas turbine technology development for oil & gas applications as synergetic development effects vanish. This has shown already to have significant implications on the gas turbine manufacturing industry, leading to a wave of mergers & acquisitions, as well as major divestment decisions.

Decarbonisation of energy supply systems

The United Nations Framework Convention on Climate Change (UNFCCC) COP21 Agreement that entered into force on the 4 November 2016 has given new strength to policies on climate change and the energy transition to a low-carbon energy system. However, according to the IEA projections for Organisation for Economic Cooperation and Development (OECD) economies, the average CO_2 intensity of electricity needs to fall from 411 grams per kilowatt hour (g/kWh) in 2015 to 15 g/kWh by 2050 to achieve the goal of limiting the global increase in temperatures to 2°C. While many studies conclude that this is both technically and economically feasible, reaching this goal calls for new power market designs.

The roles of Carbon Capture and Storage (CCS) and low CO_2 emission technologies need to be considered in order to achieve CO_2 mitigation goals. However, for the moment, there is no market pull for the reduction of CO_2 emissions in Europe as the EU Emission Trading System (ETS) does not yet incentivise the investments needed in the sector.

The EU has clearly stated its objective of global leadership in the fight against climate change. With this in mind, the EU has set some of the most ambitious carbon emission reduction targets in the world with the agreement on the new 2030 framework for climate and energy – the Clean Energy for All Europeans Package – including EU-wide targets and policy objectives for 2030.

Targets for 2030

- At least 40% emissions reduction from 1990 levels;
- At least 32.5% energy efficiency increase;
- At least 32% renewable energy share;
- 15% increased energy interconnections between member states.

Policies for 2030

- A reformed EU emissions trading scheme (ETS)
- New indicators for the competitiveness and security of the energy system, such as price differences with major trading partners, diversification of supply, and interconnection capacity between EU countries
- First ideas on a new governance system based on national plans for competitive, secure, and sustainable energy. These

plans will follow a common EU approach. They will ensure stronger investor certainty, greater transparency, enhanced policy coherence and improved coordination across the EU.

These targets and policies aim to help the EU achieve a more competitive, secure and sustainable energy system and to meet its ambitious long-term 2050 greenhouse gas (GHG) reductions target: 80-95% reduction when compared to 1990 levels.

Operating conditions of gas turbine based power plants

Gas turbines are a viable and secure option both economically and environmentally for power and heat generation. In future energy scenarios, renewable energy resources (wind, solar) will play a much more significant role than in the past. As these resources do exhibit a weather dependent fluctuating non-controllable power source, it is indispensable to have additionally controllable electricity production technologies available which can compensate the variable electricity production from wind & solar, in order to keep the electricity network stable i.e. to maintain the balance between production and consumption of electricity. Even with large electric storage systems becoming economically viable in the future, flexible controllable electric power generation technologies, like gas turbine power plants, will be still required to provide sufficient generation capacity necessary to maintain grid stability and security of supply for electricity.

Flexible gas turbine based solutions

The increasing share of intermittent Renewable Energy Sources (RES) is changing the pattern of energy generation. GTs and Micro Gas Turbines (MGT) can help the integration of RES into the energy system by absorbing the fluctuations of the RES in the grid, as well as by using low CO_2 or CO_2 neutral fuels like natural gas, biogas, industry waste gas, or landfill gas. Hybrid GT and MGT applications that deliver high utilisation of RES and security of energy supply due to their fuel flexibility will provide significant contributions to the full deployment of RES in the grid and ultimately the decarbonisation of the energy system.

Rapid improvements in low-carbon, demand-response, and storage technologies can lead to a smarter, more efficient and

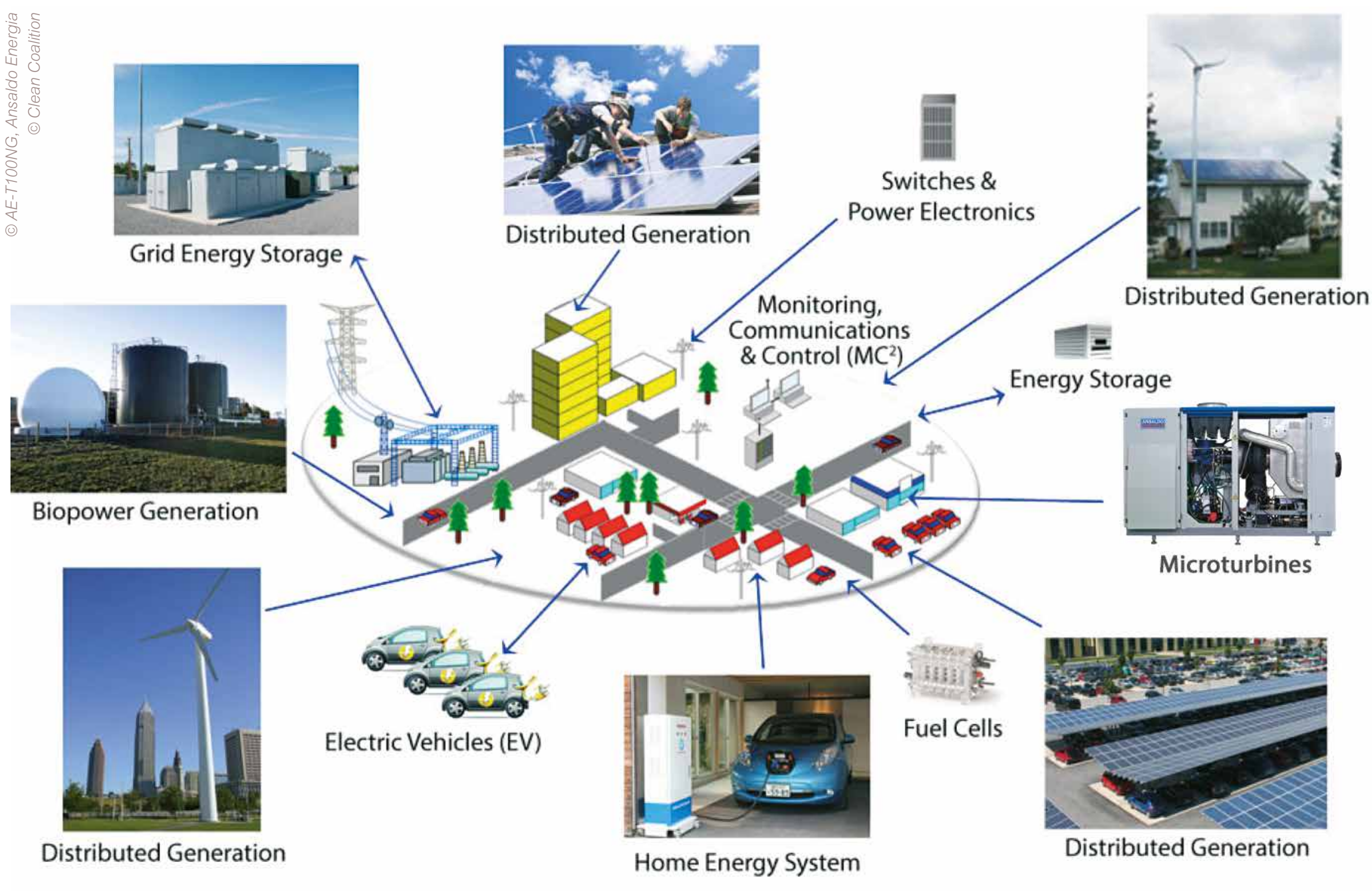


Figure 1: Decentralised generation

more secure system. However, achieving their full potential requires new approaches to policy and regulation. "Power-to-gas" technology could also provide significant amounts of hydrogen (H_2) and/or synthetic natural gas (SNG) making it necessary to adapt gas turbines for the future use.

Decentralised electricity production

We are currently moving from a highly-centralized to a more decentralized energy system relying on more distributed generation, energy storage and a more active involvement of consumers through demand response. If regulatory regimes, market design and system operation end up lagging behind technology deployment, the result may undermine electricity security and, ultimately, the low-carbon transition itself.

In this context, small scale power plants and MGT with micro combined heat and power (micro-CHP) can play a substantial role in supporting renewables and meeting the challenges of the modern electricity grid. MGT technology is able to support renewables at the system level in Europe and can realise multiple benefits in form of demand response solutions. They can operate as a stand-alone unit in off-grid operations or grouped in farm arrangement generating higher output and providing electrical power support to a local microgrid. As such, small turbines offer hybridization solutions with renewable energy sources, flexibility in operations, fuels and grid connection, resilience through modularity, as well as lower emissions than most alternative generation systems. All these features are honoured in the Vision 2050 of the European Technology and Innovation Platform for Smart Networks for Energy Transition (ETIP SNET) which outlines integrated smart network schemes for the ongoing energy system transition.

3. Operational Flexibility

The two main contributors to the increasing share of renewables in the power generation mix are solar and wind. Since both of them are non-dispatchable technologies, backup solutions are needed in order to assure grid stability. To bridge short term periods of low wind and solar power production, large-scale energy storage is expected to be used. In the medium to long term, commercially viable large-scale energy storage technologies are not available, with pumped hydro storage only possible in site-specific locations. In this scenario, conventional power plants will cover the backup needs for the next decades. For longer periods with one or two weeks of low wind and solar power generation, conventional (freely dispatchable) power plants are the only viable backup solution. Due to the significant time required to modulate, start up and shut down nuclear and coal power plants, they will continue to be mainly suitable for providing baseload electrical demand. The use of coal to provide backup has been driven mainly by short-term cost of generating electricity from coal in comparison to gas; this situation is expected to change in favour of gas; consequently, open cycle gas turbines or combined cycle power plants are considered the most suitable technologies to provide the major part of flexible back up to the intermittent renewables in the near future. For this to be commercially viable and reduce emissions, such plants should have higher operational flexibility than the current state-of-the-art. Increased operational flexibility is also prompted by the shift of combined cycle plants' operation mode from providing base load to load following due to changing gas prices, changing market conditions, and market deregulation. Current designs of combined cycle plants though were typically not optimised for the required shift from base load to intermediate or cycling requirements.

To enable plants to support flexible operation, they need to be designed for:

- Frequent start-up and shutdown;
- Fast load changes and load ramps capability, while keeping GT combustion stability and maintaining emissions within the permitted levels;
- High start-up reliability;
- Sufficient component life under the above mentioned operating modes;
- Suitable frequency control and ancillary services.

Historically, the risk drivers were addressed in the context of fluctuating fuel and electricity prices, among other factors, related to business opportunities. Thus, any research activity requires an extensive review of this fast changing subject to identify areas of future R&D. The following areas have been identified as active R&D topics:

Minimum environmental load

This is the minimum load at which the gas turbine is able to operate while meeting the environmental limits, in particular NO_X and CO emissions, taking into account that these limits will become more stringent in the coming years. This opens the need for further research into combustion technology.

Efficiency at partial and minimum load conditions

Combined cycles are operated at low load for an increasing number of hours. While the efficiency penalty for operation at medium load has been reduced for new plants, future plants should be designed to further reduce the efficiency penalty at part-load and minimum-load conditions.

High cycling capability

Recently built combined cycle plants are generally characterised by fast start-up (15-30 minutes hot start-up, 60 minutes warm start-up) and shut down, fast load change and load ramps (35-50 MW/minute max), moderate start-up emissions, and high start-up reliability. R&D is required on further reduction in start-up times and increasing load ramp rates, while ensuring minimum impact on the lifetime of critical components.

Operational flexibility at low operating costs

This means high part-load efficiency and short start-up time. R&D is also required to address the entire plant, including the bottoming cycle.

Reduction of investment costs

The operational hours of some of the flexible gas turbines will be limited to the hours with low wind and solar power. To enable a reasonable return on investment, the production costs of such gas turbines have to be reduced. R&D is required to develop new production technologies and different materials for cost reduction.

Energy storage solutions

Integration of energy storage solutions in thermal power plants is a field that needs to be further explored, in order to increase ramp capabilities and allow operation at nominal maximum and minimum loads while maintaining the possibility of providing ancillary services.

Renewable energy storage through hydrogen (implications on fuel composition)

A different path requiring further R&D is related to utilising excess energy from renewable sources or from conventional power plants during off-demand hours (e.g. night) for hydrogen production. There is a significant drive to use the gas grid to accommodate a higher hydrogen content, which helps maximise renewable energy storage. It is thus imperative to conduct research and development into increasing the tolerable level of hydrogen existing gas turbines or new designs (see chapter Extended Fuel Spectrum).

Reliability under fast cycling

To prevent increased outages due to fast cycling, the following topics need to be addressed:

- Key equipment design, materials and corrosion aspects;
- Component replacement, maintenance and operating costs;
- Strategies for optimising cyclic operation;
- Effect on thermal barrier coating;
- Effect on creep-fatigue of turbine blades, cracking and degradation of combustor.

CCS for flexible operations

Incorporation of Carbon Capture and Storage (CCS) solutions leads to restrictions on operational flexibility due to constraints in the part-load operation of CO_2 capture and compression, which is typically limited to 70% turndown. The impact of this is an increase of hot start-up to 1-2 hours and cold start-up to 3-4 hours. Strategies should be developed to reduce the impact of CCS on operational flexibility.

Computational tools (for modelling of instationary conditions)

There is a strong need for the development of high fidelity computational tools to model the power plant at non steady-state conditions (e.g. during power ramps), allowing for virtual simulations that lead to lower cost and system optimisation.

Technologies for improved control

An area of increasing interest for R&D is the use of more instrumentation and new sensor technologies to monitor and improve the control and operation of power plants (e.g. with higher time resolution during non steady-state operating conditions). This includes developments in the processing and visualisation of the large data sets produced by these sensor arrays, a field of research known as big data (see Sensors & Instrumentation chapter).

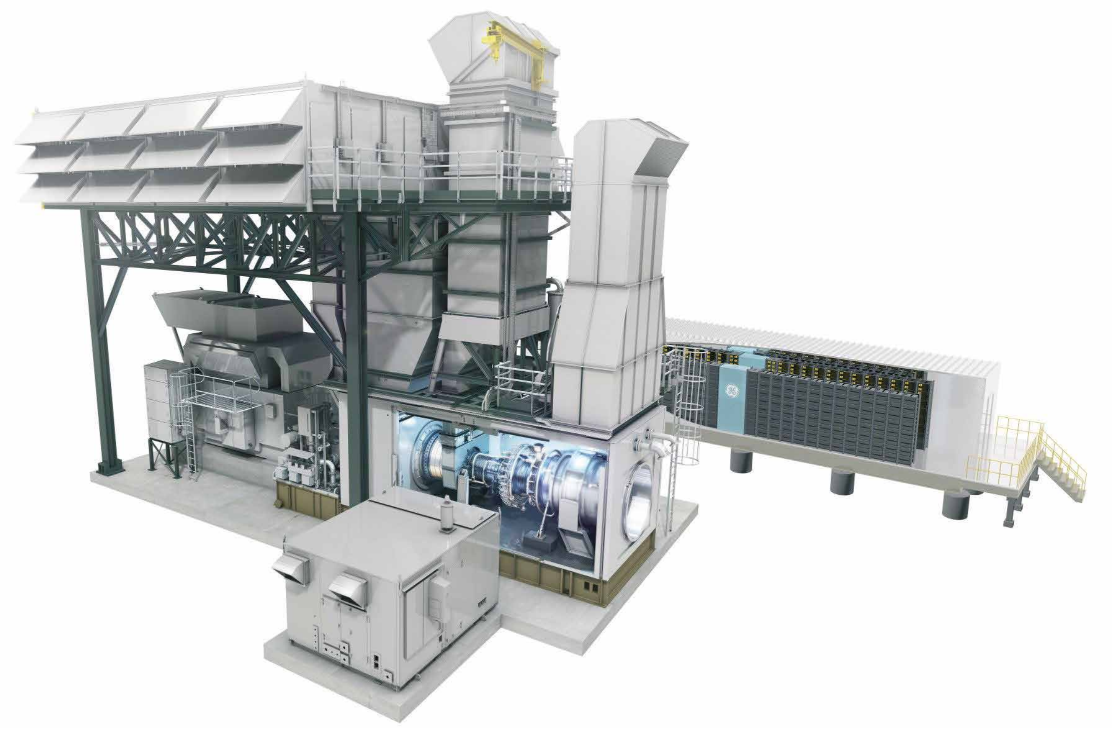


Figure 2: LM6000 gas turbine integrated with 10MW batteries

4. High Efficiency Power Generation

This chapter focusses on GT and GTCC cycles which are currently representing the bulk part of existing installations and those in planning. Concepts integrating other technologies and / or process will be covered in the chapter Advanced Cycles.

Energy efficiency is very important from the supply side as well as the demand side. The IEA estimates that of all efforts required to deliver a 50% reduction in global CO_2 emissions by 2050, 7% will need to come from power generation efficiency. Current European combined cycle gas turbine power plants operate at an average efficiency of 52%, while best available technology operates at above 60% efficiency. General measures to improve gas turbine efficiency are increasing Turbine Inlet Temperature (TIT) and compressor pressure ratio in parallel with cooling air reduction, more advanced aerodynamic concepts to improve component efficiencies and reduced leakages in addition to cycle innovations. Other measures also include other components of the plant such as the steam turbine, waste heat recovery heat exchanger as well as electrical equipment. The above measures imply the need for development of new materials for improved component life (especially if cyclic operation modes become more dominant).

One of the implications of future flexible operation in power generation is the requirement for high part-load efficiency. Conventional power plants designed for base load have high design point efficiency, while part-load efficiency is comparatively low. Flexibly operating power plants should be developed to have higher average efficiency over the operating cycle, with higher part-load efficiency possibly being achieved at the expense of some reduction in design point efficiency as shown in Figure 3 (unless some innovative concepts become commercially viable). Also with the future scenario of CO_2 neutral fuels, it would be still important to achieve high average efficiency to maintain commercial competitiveness of the plants.

To enable efficiency improvements to meet the required targets, research and development is needed in the following areas:

Thermodynamic cycles

Investigation of novel and/or variable thermodynamic cycles to achieve high power generation system efficiencies at both design and off-design operating conditions. Novel combined cycles should be investigated to achieve high global efficiency of power generation systems instead of gas turbines alone (See chapter Advanced Cycles).

Variable geometry

Variable geometry gas turbines and combined cycle power systems should be investigated to achieve high thermal efficiencies at high part-load operating conditions.

Flow paths design

Advancements in design both for the primary and secondary flow paths are needed. This requires adjusted axial and radial load distributions, new aerodynamic blade shape technologies, improved sealing and active tip gap control. It may also be possible to introduce end wall profiling or features that can disrupt secondary and leakage flows to improve efficiency particularly at part load.

Cooling system

Reduction in cooling air requirements through advanced cooling system concepts as well as adjustable cooling air mass flow. This requires advancement in both modelling and testing methodologies.

Design

Design optimisation to achieve high efficiency over a wide range of operating conditions. This requires advancement in modelling and design tools to reduce the lead time for new designs. Ultimately, it may also be possible to achieve higher design point and off-design efficiencies through more variable pitch blading and using further improvements in aerodynamic and mechanical designs.

Simulation tools

New thermodynamic performance simulation tools should be developed to assist the design and optimisation of gas turbine power generation systems to achieve high thermal efficiencies. Finite Element Modeling (FEM) for the evaluation of the mechanical load/integrity of given and new designs continues to be a helpful tool for the evaluation of new parts in order to qualify them for more frequent transient operating schemes.

Thermal barrier coating

Improvements in material technology and thermal barrier coatings to withstand the higher turbine thermal loads resulting from elevated turbine inlet temperatures and the increasing need for flexible operation (fast transients). This requires the development of tools to quantify material life under real operating conditions and improved material testing techniques.

Overall system efficiency

Optimisation of system efficiency should consider the combination of the gas turbine and the bottoming cycle at the same time, and thus R&D should take into account the performance of the heat recovery steam generator (HRSG) and the steam turbine. It should also consider the overall efficiency of the plant when used in CHP mode (including options for variable heat-to-power ratio and variable heat extraction).

Combustion

New combustor technologies are needed to enable low emissions and stable operation at part-load. This requires improvements in both modelling and experimental technologies in the field of combustion and issues of flame instability/lean blow-out and pressure pulsations.

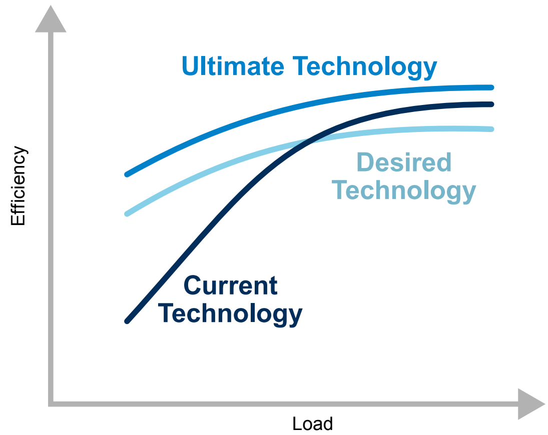


Figure 3: Efficiency versus load

5. Extended Fuel Spectrum

The need for gas turbines to be operated safely, with high efficiency and low emissions (long-term target: zero CO_2 emission, maintain low NO_x/CO), using a variety of gaseous & liquid fuels still remains to be an important issue for current and future gas turbine models.

Besides a wide variety of natural gas qualities, including gas compositions with higher content (> 1%vol.) of higher hydrocarbons (so-called C_2+, like ethane C_2H_6, propane C_3H_8 and butane C_4H_{10}) or with higher content (> 10%vol.) of inert species (N_2, CO_2), which cover a wide range of Wobbe Index values (35 - 55 MJ/Nm^3), additional fuel gas mixtures (syngas - CO/H_2, hydrogen - H_2) and diluents (CO_2, H_2O) come into the scene as new gas turbine based processes and new fuel resources (biofuel, shale gas, LNG) are being proposed for power generation and industrial applications. Additionally, liquid fuels remain to be of interest for mobile applications (aero engines, marine engines), oil & gas industries, island/off-grid operation and as back-up fuels. Meanwhile, their spectrum is increased by biomass and power derived liquid products (FAME, DME, Fischer-Tropsch products, pyrolysis oil, etc.).

The issue of wide fuel spectrum capability of gas turbines is strongly coupled with operational flexibility topics such as flame stability and emissions, and can be exacerbated if fuel switch-over procedures are to be considered.

Typically achieving ultra-high efficiency requires very narrow fuel specifications, whereas with widely variable fuels, one needs to accept slightly lower performance and possibly a redesign of key components in order to arrive at a fuel-flexible gas turbine set-up.

Specific issues, which need to be addressed in this respect, are:

Natural gas/H_2 mixtures (up to 100% hydrogen)

With large capacities of wind & solar PV installed, storage of intermittently produced surplus electricity has become an important challenge. Storage via H_2 production from water electrolysis and later re-electrification is one option being considered. This would require consumers to cope with an increasing H_2 content in natural gas (e.g. up to 20% vol. till 2022, up to 100% vol. till 2030), especially in decentralized small gas grids or dedicated hydrogen grids. This requires increasing hydrogen combustion capabilities of modern gas turbines (pure, premix or diffusion combustion with inert gas dilution). Issues to be addressed are safe combustion performance and control (flame stability, flashback, combustor cooling, thermo-acoustics) and NO_x emission behaviour.

Natural gas/biomass derived syngas mixtures

Biomass derived syngas (CO/H_2 mixtures from biomass/ wood gasification) is considered CO_2-neutral and thus has to play a role in future power generation scenarios. Co-firing of such syngas in large gas fired combined cycle plants offers high electricity conversion efficiency. With co-firing shares of up to 20% (by energy), the combustion performance is being influenced. Issues to be addressed are safe combustion performance (flame stability, flashback, combustor cooling, thermo-acoustics), emission behaviour (NO_X, CO) and material degradation due to fuel contaminants (particulates, corrosive species like sulphur, chlorine, sodium).

H_2-rich fuel gases (e.g. syngas or coke oven gas)

High hydrogen concentration (> 50%vol.) in fuel gas mixtures requires significant changes to the fuel-air mixing/burner/combustor design of gas turbine combustion systems. Beyond the findings of the EU funded project "H_2-IGCC" it is still important to find solutions and demonstrate the applicability (at full scale/full pressure) of potential low emission, reliable (safe ignition, stable flames) combustion technologies. Issues to be addressed are safe combustion performance (flame stability, flashback, combustor cooling, thermos-acoustics) and NO_X emission behaviour for process conditions relevant to gas turbines integrated with pre-combustion carbon capture schemes and/or solid fuel gasification (coal, biomass, process residues).

LNG/LPG

LNG (liquefied natural gas, LNG boil-off gas) and LPG (liquefied petroleum gas) have very peculiar composition when they are re-gasified and used as fuel gases for gas turbine operation. LNG consists of (mainly) CH_4 and thus reduces any impacts due to inert species (N_2, CO_2), but the low levels of higher hydrocarbons (e.g. C_2H_6/ C_2H_4) can cause operability issues due to the reduced reactivity of the fuel. LPG consists of propane (C_3H_8) and butane (C_4H_{10}) in various ratios and exhibits strongly different physical and chemical properties (i.e. combustion characteristics). Flame stability, flame speed and ignition delay times can be sufficiently different, such that a re-design of key combustor components could be required. Re-gasified LPG may be an attractive alternative to liquid fuels in locations where a natural gas supply is not available.

Unconventional natural gas

Unconventional natural gas (e.g. shale gas, coalbed methane) can show an even wider variation in composition than (conventional) natural gas qualities and expands the range towards even lower Wobbe Index values (below 35 MJ/Nm³) due to higher content of inert species (N_2, CO_2) which can also vary temporarily depending on the exploration conditions.

Liquid fuels (Biomass / Power)

Liquid products generated from syngas (of biomass gasification systems or power to gas processes), e.g. fatty acid methyl esters (FAME), alcohols, dimethyl ether (DME), Fischer-Tropsch products, …) or directly formed in pyrolysis processes of various types of biomass (i.e. pyrolysis oils of different origin) pose a significant challenge to the operation of gas turbine systems. Not only physical properties (viscosity, lubricity) bear certain difficulties, but also chemical properties (S/N/Cl content; acidity/corrosivity; combustion chemistry/ flame speed) vary significantly and are not yet fully characterized (operational limits such as lean blow out and flashback; NO_X/CO/SO_X emissions).

Non-carbon fuel (e.g. ammonia)

Ammonia has different combustion characteristics compared with conventional hydrocarbon and hydrogen fuels (e.g. significantly reduced fuel conversion rates). Ammonia is attractive for energy storage because it is carbon free and can be liquefied and stored at moderate temperatures and pressures. To convert the ammonia back into electrical power gas turbines can be used. There are basically two ways to use ammonia as gas turbine fuel: direct usage as fuel or to pre-process ammonia by reconverting it to nitrogen/hydrogen mixtures e.g. via thermal cracking. The main drawbacks of using ammonia for combustion is the production of NO_X due to the 'fuel-bound' nitrogen contained within NH_3: this issue is very severe if pure ammonia is burnt but is still present for the NH_3 crack gases because of any residual ammonia left over from the cracking process. Special low NO_X combustion processes needs to be explored to minimize fuel bound nitrogen conversion. For direct usage as fuel, ammonia has demonstrated to have a very slow reaction hence flame speed, thus one option is to dope the fuel with a more reactive molecule such as hydrogen, which conveniently can be obtained from cracking ammonia or from reforming of natural gas. Also ammonia or ammonia crack gases can be mixed with natural gas which could reduce the NO_X formation.

Special fuels incl. fuel pre-treatment

There are economic reasons to use also "poor quality" fuels for power generation. Despite the fact that fuel pre-treatment is necessary to avoid problems in gas turbines, such low-grade fuels are sufficient and cheap to provide.
With regard to natural gas, about 40% of the worldwide remaining reserves contain so called "sour gas", i.e. components like H_2S and CO_2 at a concentration, that these gas qualities cannot be utilised without further purification for turbine applications. This is also the case for associated gas which is a by-product of oil production. Currently (associated) sour gas is often flared, but such procedures will be illegal in the future.
If sour gas should be utilized in gas turbines, focus has to be laid on the treatment of toxic and/or corrosive elements, e.g. Sulphur. In addition to the aggressive properties of Sulphur, burning of H_2S can produce SO_X emissions at unacceptable levels.
It is desirable to have smaller, local and decentral pre-treatment processes to remove H_2S from the natural gas, so it can be used for the local energy demand. Such pre-treatment processes have to be much less complicated compared to the typical large scale gas processing, since it is usually not necessary to achieve the strict pipeline grade in order to utilise a treated raw gas in a gas turbine.
With regard to liquid fuels (e.g. crude oils), they are used in gas turbines as a cheap and reliably available fuel. Due to the content of alkali/heavy metal salts and sulphur the use of e.g. crude oils in gas turbine is also difficult. These components cause severe hot gas path corrosion and remarkable maintenance costs and/or efficiency losses can result from this.
The emission of certain components (e.g. heavy metals, sulphur, etc.) and their combustion products are typically controlled by legislation as they are harmful to the environment. A fuel pre-treatment that removes these undesired components would cause a significant reduction of the maintenance costs and would also improve the power plant efficiency and thus the harmful emissions (including the CO_2 footprint).

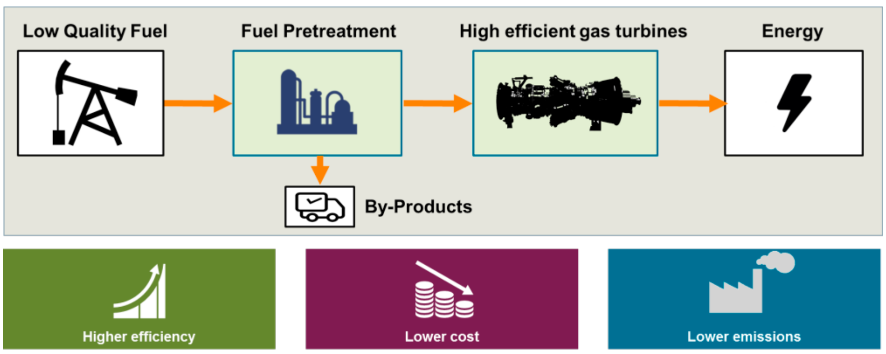


Figure 4: Fuel pre-treatment for economic and environmental friendly energy production

6. Emissions

The NO_X emission level of gas turbine engines has continuously been reduced over the last few decades. Even though 25ppm NO_X (corr. to 15%vol. O_2) is still accepted as industry standard (for gaseous fuel firing), more and more projects adopt 15ppm NO_X as an emission target, and even single digit ppm NO_X levels are being asked for in certain regions. For liquid fuel operation, 42ppm NO_X has long been accepted as the emission limit, but a new version of the Industrial Emission Directive (IED) of the EU now calls for 25ppm NO_X also for liquid fuels. Legislation for CO emissions has been less stringent (with new IED less than 100ppm CO is required), but in some cases CO emission limits (at base load) have been put as low as those for NO_x (e.g. 25ppm). Subsequent to the publication of the IED, the Best Available Techniques Reference document (BREF) has set an expectation for further reduction in NO_X levels for both existing and new plants.

Individual issues which should be addressed in the near future are:

Emission limits at part load

As gas turbines are much more often required to run at (low) part load and to cover a lot of cycling duties, including starts and stops, emission limits at part load are being given much more attention and emphasis. Maintaining low emission values (e.g. 25ppm) for NO_X (as well as for CO) down to very low part load and during transient load operation has become an important selling argument for gas turbine products. Issues to be addressed are safe combustion performance (flame stability, thermoacoustics) in combination with maintained low emission (NO_X, CO) characteristics over a wide load range (from below 50% up to 100% load).

Liquid fuels (emission of NO_X, CO and particulates)

Extremely low NO_X emission limits (less than 25ppm) for liquid fuel operation of gas turbines pose a significant technical challenge if they should be achieved by combustion measures alone (no additional flue gas treatment via selective catalytic reduction (SCR)). Issues to be addressed are liquid fuel atomization/evaporation and pre-mixing fuel with air for homogeneous combustion in the gas phase as a prerequisite for low NO_X formation. Combustion performance (flame stability) should not be compromised, either with or without addition of water/steam, and a combined minimum of emission species (NO_X, CO, particulates) has to be targeted. As particulate emissions are typically very low, the challenge of measuring such low levels in a reliable way is not yet fully resolved.

Exhaust gas recirculation

Exhaust gas recirculation can be applied with the intention of reducing or mitigating NO_X and CO_2 emissions (see chapter Advanced Cycles).

H_2-rich fuel gases / NG-H_2 mixtures

Combustion of fuel gas mixtures containing high hydrogen concentrations (> 50%vol.) tends to show higher NO_X emissions and require significant changes to the design of fuel-air mixing/burner/combustor systems in order to avoid this. If dilution with steam or nitrogen (N_2) is not an option, issues regarding safe combustion performance (flame stability, flashback, combustor cooling, thermoacoustics) need to be addressed while trying to keep NO_X emission low.

As H_2 will likely become available more abundantly (via water hydrolysis driven by surplus electricity from renewable energy sources (RES)) and be injected for energy storage reasons in larger amounts (> 2%vol.) into the natural gas grid, unambiguous data is required for such fuel mixtures (up to 20%vol. of H_2 in natural gas) concerning combustion properties and emission characteristics in order to define methods and designs which can mitigate the associated risks.

Dilute combustion / wet combustion / MILD combustion

As alternatives to conventional lean premix combustion for which heat release is localized in a distinct flame front, other combustion technologies which target spatially distributed heat release offer potential advantages such as low NO_X emission even if the premixing quality is imperfect. Volumetric heat release also provides more favourable conditions to avoid thermoacoustic feedback loops which can cause catastrophic pressure fluctuations. Possible means for achieving distributed heat release are strong dilution with steam (so-called wet combustion; e.g. related to Cheng cycle combustion conditions) or strong internal recirculation of exhaust gas leading to so-called MILD combustion conditions. Issues such as reduced burnout/increased CO emission and low load operating conditions need to be carefully addressed and managed.

7. Decarbonisation

There is a continuing pressure from policy and regulatory actions being taken to reduce CO_2 emissions while at the same time it is required to provide highly flexible generation solutions as backup power to compensate insufficient contribution from renewable energy sources (RES). This underpins the strategic importance for the gas turbine industry to maintain their commitment to continuing R&D into the development of low carbon options and cost-effective carbon capture and storage (CCS) for both new designs and for retrofit to existing units. However, there is currently little support and interest to develop such solutions (specifically for gas turbine based processes) via public funding.

Reducing CO_2 emissions from gas turbines can be achieved through the improvement in efficiency, process hybridisation, the use of low carbon fuels or by the integration of CO_2 capture technologies. The first two of these options are addressed in other sections of this document, while the third shares close linkage to the challenges from fuel flexibility. The application of CO_2 capture approaches may be post-combustion, with the capture unit located on the gas turbine exhaust; pre-combustion, where the carbon is largely removed early on in the process leaving a hydrogen-rich fuel gas; or by using oxy-combustion where the CO_2 is more readily separated from the steam in the exhaust gas stream. The following priorities reflect those not covered elsewhere.

Integration of post-combustion CO_2 capture technologies with gas turbines

The decarbonisation of gas turbine power generation, whether for existing natural gas-fired units or for new build schemes will have significant impacts on operating costs and levels of dispatchable power, due to the energy penalties arising when CO_2 capture is included. Selecting the most suitable capture technologies and optimising their integration (while maintaining plant flexibility) provide significant challenges. Among others, the following options are worthy of further research:

- Integration of 'conventional' post-combustion amine scrubbing, or competing liquid based technologies, to minimise costs and energy penalties.
- Investigation of alternative post-combustion capture technologies, such as Ca-looping cycles or solid sorbents using pressure or temperature swing concepts, which allow for improved heat integration, and hence lower operating costs. Also, the investigation of other post- combustion capture options, e.g. CO_2 separation membranes.
- Studies of the impact of exhaust gas recycling, including enhanced recycle options (e.g. using CO_2 separation membranes), to enhance exhaust gas CO_2 levels and so reduce the size and costs of the capture plant. This approach will lead to significant changes to combustion and hot gas path environments, and may also impact on operability, materials and component lives.

Of specific importance for the above mentioned technologies is the investigation and optimisation of the operational flexibility and performance of capture technology especially as GT based plants are seen as the most flexible solution to balance the grid and provide backup power for the incerasing share for fluctuating renewables.

Operation with hydrogen, biomass-derived and other low carbon gases

Such gases are often less clean than their fossil-derived counterparts and so can lead to combustion and hot gas path challenges. This links with research aimed at improved fuel flexibility and the use of H_2 used either in direct firing, or in dilution of natural gas distribution networks, such as reformed natural gas, H_2–rich syngas from gasification processes with pre-combustion capture, or from H_2 generated by electrolysis (from unused renewable electricity) or from biomass-derived sources.

Advanced, high-efficiency cycles using oxy-fired gas turbines

A range of advanced, high-efficiency cycles are under development to provide higher efficiency alternatives with inherent CO_2 separation to the application of post-combustion capture options. These use oxy-combustion to provide a low N_2 exhaust gas from which it is easier to separate the CO_2. In these cycles, the separated CO_2 is compressed for transport and storage, and some of either the CO_2 or the condensed steam may be recycled to the combustor to moderate combustion. Such cycles operate at very high pressures, up to 300bar, and present significant operational and component manufacturing challenges. Examples are supercritical CO_2 power cycles (e.g. the NetPower cycle), where the exhaust gas CO_2 is recycled, or the Clean Energy Systems cycle (which comprises natural gas/O_2 combustion) where steam is used to moderate the combustion conditions.

While offering significant potential for the generation of low cost, low carbon electricity, these cycles require major developments in combustion, hot gas path environments (due to the impact of high steam/CO_2 levels), materials, turbomachinery requirements, control strategies, etc., as these are very different to conventional systems and present many challenges and uncertainties which may limit the potential performance of the cycles and significantly hinder their development. Research into the impacts of these altered operating environments would help the identification of those cycles with most potential, and so provide a possible pathway for future turbine development.

8. Advanced Cycles

With the rapid rise of renewables (in the European Union they account for about 80% of the new capacity in a 2030 scenario), there is a need to provide backup power and grid stabilisation while increasing overall cycle efficiency and reducing CO_2 footprint.

An answer to those needs are advanced cycles, not only looking at them from a pure thermodynamic point of view but also looking at system integration opportunities of different technologies that can cater to those needs. Considering current installed capacity (traditional power plants) will continue to serve in a 2030 energy scenario and beyond, particular attention will need to be devoted to upgrade and conversion applicability.

Most advanced cycles gas turbines (GTs) are interconnected to other systems and components, or even processes such as for example high temperature fuel cells or solar air heaters. Their integration often requires a change in mass flow rates of compressor or turbine as well as different working fluids. Most GTs currently on the market are not designed for this type of process integration. Future R&D activities should therefore target the development of concepts for "easy-to-integrate" and flexible gas turbines, since otherwise each cycle would need its specific gas turbine adaptation.

Because of changes in the chemical composition of the working fluid and the operating conditions, the materials and coatings of the gas turbine have to be tested regarding their ability to withstand the new conditions. Most probably, new materials and coatings have to be developed for specific advanced cycle applications.

For efficient and meaningful cycle evaluation, reliable numerical simulation tools are indispensable:

- A tool or system of tools that allows the analysis of advanced integrated cycles without the need to manually iterate between power plant simulation and process modelling tools. This will avoid errors and should also result in a faster analysis and evaluation process.
- Tools well-suited for transient analysis of the process, as gas turbines are increasingly used to balance energy demand and the growing share of fluctuating renewables in the grid. Furthermore is it necessary to combine components with very different response characteristics in energy systems. Higher complexity and higher flexibility needs during start-ups and transients support this requirement.
- Tools for life cycle analysis in terms of costs as well as environmental impact (CO_2 and other emissions and impacts accumulated over the entire lifetime) as a base for standard evaluation of concepts.

The following promising advanced cycles, which have reached different Technology Readiness Levels (TRL), are worth considering for further R&D activity:

Wet cycles

Wet cycles are processes with extraordinary high water content in the working fluid. Water might be either added before the combustor (e.g. humid air turbine), in the combustor itself (e.g. Cheng Cycle) or after it (e.g. for power augmentation). Further R&D is needed to enable the stable operation of the combustor close to stoichiometric conditions and with high water content.

The materials and coatings of the gas turbine have to be tested regarding their ability to withstand the wet conditions. Most probably new materials and coatings have to be developed for this application.

Alternative fluids

The use of other working fluids than air, such as supercritical CO_2 or organic compounds such as cyclopentane, is an issue which requires additional R&D efforts. In this context, topics of interest might be:

- External heat source integration, either coming from external combustion allowing the use of various fuels and at the same time reducing the overall process complexity by avoiding extra efforts and components for fuel preparation/treatment, concentrated solar power (CSP) field or nuclear reactor.
- High efficiency, high temperature heat exchangers with optimized heat transfer and, depending on the fluids used, the possibility for easy cleaning to reduce the effect of degradation.
- The transient behavior and the sensitivity versus ambient conditions have to be investigated (e.g. for the trans-critical CO_2 cycles with a complex mass flow management or oxy-fuel processes with high complexity).

Another approach to enable better CO_2 capture and control and eliminate NO_X emission is the Allam cycle. The Allam Cycle is a so called oxy-fuel process, where the fuel is burnt with pure oxygen. It provides high CO_2 concentration flue gas from which the CO_2 can be separated by condensing its water content. Compressor and turbine working fluids are considerably different (from air), and require specific turbomachinery designs.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) applied to gas turbine engines can be a viable method to address a couple of issues: EGR can help to mitigate NO_X emission (via moderation of peak flame temperatures and a reduced oxygen level) or keep NO_X emission low even for increased turbine inlet temperatures (TIT). For example, EGR is already used by Mitsubishi Heavy Industries for NO_X control in their J-series GTs with a Turbine Inlet Temperature (TIT) of 1700°C. Additionally, post combustion CO_2 capture systems can be operated more effectively (lower specific energy consumption per ton of CO_2 removed) due to an increased concentration of CO_2 in the gas turbine exhaust. Critical issues with high EGR rates are combustion performance (flame stability) and potentially high CO emission.

Hybrid cycles

Hybrid cycles, combining different electricity production technologies (e.g. fuel-cell/gas turbine hybrids) or renewable based power generation with fossil fueled generation should also be developed further. Here plant integration and plant control (especially in transient operating modes) is a challenge. The combination of solar heat input to a natural gas fired GT is a particular technology which shows great promise.

Figure 5: Humid air turbine cycle

Figure 6: Picture of a Solid Oxide Fuel Cell/Gas Turbine hybrid system

Power plants with integration of storage

A way of solving the renewable energy source (RES) intermittence issue from a systemic approach consists in integrating existing power plants with storage capabilities. These could be either batteries (used e.g. for time shift, peak loads, load leveling, faster ramp rates or grid service support), high temperature heat storage (to be used during later discharge e.g. as second heat source for the combustor) or medium temperature heat storage (as a fuel saver by preheating the working fluid).

Low grade heat recovery with heat pumps

Another system approach can be to couple heat pumps to existing power generation systems and thermally upgrade the waste heat such that it can be used more effectively in a bottoming cycle.

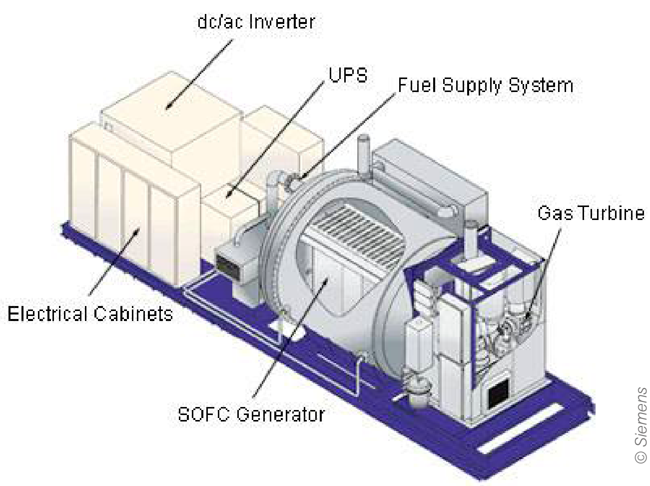


Figure 7: Schematic of a Solid Oxide Fuel Cell/Gas Turbine hybrid system

9. Decentralisation

While the increasing share of renewable energy has transformed the energy market from a centralised to a more decentralized power production infrastructure, the intermittent generation characteristics of wind and solar energy sources creates a need for fast, reliable, and dispatchable power generation to maintain grid stability. Besides large centralised combined cycle power plants, decentralised power production with smaller gas turbines is an increasingly attractive option, as they can stabilize the power grid on the low and mid voltage level while providing relief to the high voltage network. Decentral biomass and other renewable energy sources can be used at their origin without the need of transportation. Moreover, the high overall efficiency of such gas turbines can help to further reduce the energy consumption from the power production infrastructure if used in combined heat and power applications. And finally, if such decentralized units are connected to a “virtual power plant”, the reliability of the power supply can be further increased.

While small gas turbines in the range from 1 MW to 20 MW are well established in industrial applications, for smaller consumers, micro gas turbine (MGT) technology has the potential to provide effective distributed power generation systems with both fuel flexibility (e.g., biofuel stock) and compatibility with solar power generation. While small gas turbines are part of the portfolio of the large gas turbine manufactures, the R&D needs are similar to that of the larger gas turbines. MGTs are generally developed and produced in Europe by SMEs with limited research and development resources, with the major MGT production occurring in the USA (e.g., Capstone Turbine Corporation). Designs used by SMEs typically rely on off-the shelf components, such as those designed for automotive turbochargers, which are relatively cheap but are not optimised for MGT operation due to the different trade-off between high design point efficiency and system size and cost. Thus their performance characteristics are limited to what is achievable to balance research and development and production costs. Designs that are optimized for performance are used by some manufactures such as Capstone, however the relatively low production volumes translate into expensive component costs. With the growing demand for more efficient and cost effective energy systems to meet emission reduction targets, it is timely that research and development is conducted to take MGTs to a level that realises their theoretical potential in terms of cost, performance and reliability.

There is sufficient evidence that MGTs have the potential to become a fast growing industry in multiple applications with significant contributions to the energy efficient low carbon economy if a concerted research and development effort is accelerated to overcome the technological challenges that still hinder their progress.

Challenges

The research challenges are related to two categories. The first is mainly related to the general cycle efficiency resulting from the system configuration for given component characteristic which affect both design point and off design performance in addition to fuel flexibility. The second is related to the individual component performance which also affects cycle efficiency and fuel-flexibility, but also system operation, cost, reliability, operability and life.

Consequently, the following are the recommended areas for research and innovations in this field.

System Integration

While the typical layout for commercial micro gas turbines is based on the classical recuperated Brayton cycle, the integration of the micro gas turbine components in other systems can offer innovative solutions to improve overall performance. Such systems have been investigated by researchers and show high potential to significantly improve performance. Unfortunately, these systems are far from commercialisation with further R&D needed to solve technological and cost issues. Examples of such systems include the following:

- Hybrid Cycles – A unique cycle is integrated into the traditional MGT cycle, such as in high temperature fuel cells or with an external high temperature heat source (e.g. concentrated solar power (CSP));
- Integrated Cycles – The MGT cycle is connected to another cycle or technology, such as energy storage technologies or bottoming cycles;
- Non-Conventional Cycles – A new, non-MGT cycle that takes advantage of MGT technology like in wet cycles (e.g., micro humid air cycle (mHAT)) and inverted Brayton cycle.
- Higher efficiency Brayton cycles, such as high pressure ratio cycles and intercooled and recuperated cycles

In order to integrate MGT technology into in such systems, there is a need to adapt the design of the MGT towards:

- Higher electrical efficiency
- Higher flexibility for integration in or with other systems
- Increased flexibility towards the utilization of various sources of energy.

Component performance

Turbomachinery

The efficiency of small-scale compressors has been limited by the lack of detailed fundamental research into aerodynamics in comparison with their larger counterparts that benefited from investments for aviation applications. The effects of secondary and leakage flows, shock boundary layer interactions, surface finish, and relatively large geometric tolerances on aerodynamic performance require further research to determine when the payback from improved efficiency can counter the additional cost of design and manufacturing improvements. Newly emerging research into surface features that can provide passive control of secondary and leakage flows are worth considering.

Combustion

Combustion technology research typically aims to either improve combustion efficiency and stability while reducing NO_X emissions, or develop effective technologies for alternative fuel use. Alternative fuels of particular focus include biofuels and stranded/associated gas, both of which are of variable composition and quality (i.e., calorific value, impurities and potentially corrosive). MILD combustion is also emerging as important development area for MGTs.

Heat Exchangers

Used as recuperators or as the main heating unit in externally fired MGTs, heat exchangers are in principle a well-established technology with a large number of design options. However, challenges for heat exchangers still remain. In order to maintain high cycle efficiency, heat exchangers for MGT systems must achieve a reasonable service life with high effectiveness and low pressure losses while also keeping the weight and cost down. The main barrier to reducing the capital costs of MGTs is the difficulty in reducing the manufacturing cost of recuperators, even when mass production is possible. To overcome this barrier, technological advances are required in materials and manufacturing processes to improve performance and increase reliability while reducing production costs. Additive manufacturing has recently been used to produce compact heat exchangers, but typically at the expense of low effectiveness and high pressure losses. Thus, further research and development is still required in this area. Another area of research and development is in the use of metallic foam materials for producing compact heat exchangers.

Rotordynamics and bearings

Most of the current micro gas turbine designs rely on centrifugal compressor and radial turbine designs. An alternative approach is to use two-stage compressors and two-stage turbines in order to reduce the rotational speed and improve the dynamic behaviour. There are five options for MGT bearings: rolling angular contact ball bearings, oil film bearings/floating ring bearings, magnetic bearings and air/foil bearings. Rolling angular contact ball bearings are the most common bearing used in smaller MGTs. The technology is well known, but requires an oil system. The second type, oil film bearings, are most common in automotive turbochargers. This bearing type is robust, but has high friction losses making it unattractive for MGT applications. Magnetic bearing development has benefited significantly from research for larger engines; however, their development and implementation cost for MGTs has prevented them from being used despite their advantages of oil free operation and the inherent ability to control vibrations. Foil air bearings have made significant progress during the last 25 years in many applications due to their reliability and oil free operation. However, despite their potentially superior performance, they are not typically used in MGTs due to the high development costs, and thus, more research and development are required to capitalise on their advantages.

Power electronics and control systems

A key enabling technology for MGTs is the integrated high-speed electrical generators typically installed on the same shaft as the compressor and turbine, eliminating the need for mechanical gear-boxes. The result is a very compact, high efficiency system. High-speed permanent magnet (PM) generators are typically used due to their high power density and high efficiency characteristics. These generators operate as a motor during start up, but yield positive power production once combustion is stabilized and rotating speeds increase. The power flow to and from the generators is processed via power electronics with control systems regulating the overall process. Although power electronics and control technology are well-developed fields, the challenge is to provide a robust and cost effective design that also reliably incorporates non-traditional power sources outside of the MGT. One such area of research is in MGTs driven by concentrated solar power, where the fuel supply cannot be used as a control parameter as is typically the case. The challenge is to produce, control and optimize an inverter suitable for grid interconnection with the capability to support synchronous motor drives and variable solar radiation input.

Figure 8: C1000S

10. Materials

The materials and coatings used for the hot gas path components in gas turbines, and their behaviour in service, place limitations on turbine performance and reliability, and represent significant elements in the capital and operating costs of the system.

In recent years, changing operational requirements, such as the use of alternative fuels and plant cycling, and factors affecting components lives and costs, have focused attention on specific materials issues. These include:

- The need for improved alloys and coatings (bond-coats, corrosion resistant coatings, thermal barrier coatings (TBCs), etc.) for increased efficiency and/or reliability, including ceramics and ceramic matrix composites for uncooled parts, e.g. in micro gas turbines;
- Hot corrosion of blades and vanes arising from the use of H_2S-containing gas in offshore operations or biofuels in distributed power applications;
- The use of advanced and additive manufacturing methods for non-structural parts and component repair;
- Component materials inspection, condition assessment (see also Condition Monitoring and lifing and Sensors and Sensors & Instrumentation sections) and characterisation of service-aged materials for life prediction modelling and residual life assessment;
- Condition assessment and durability of TBCs;
- The impact of flexible operation and plant cycling on component lifetimes, monitoring requirements and repair costs;
- Reduced usage of strategic and environmentally-damaging elements (e.g. compliance with EU REACH legislation);
- 'Fit for purpose' materials selection (i.e. cost effective materials selection to match the design and operating requirements, and no more).

While increased efficiency with low emissions have long been priority drivers for gas turbine OEMs, end-user focus for current markets has broadened to embrace reliability, operating costs and the ability to handle cheap fuels. In these circumstances, the challenge for the materials used has become more important and more diverse, as indicated above. Operators are now demanding higher reliability of components combined with the capability to maximise service life, while minimising the risk of unforeseen failures and extending maintenance intervals.

Improved alloys, coatings and ceramics

The design of components for use in the hot gas paths of modern gas turbines of all sizes and for all applications, involves:

- the production of complex-shaped parts to meet performance needs;
- systems of compatible materials which can be manufactured to produce the required shapes, with the required mechanical and chemical properties;
- the need to allow for inspection and repair.

As a result, understanding the behaviour of these materials systems, comprising base alloys, bond-coats/corrosion resistant coatings and TBCs during component manufacture and during service is now of fundamental importance if required performance levels and manageable operating costs are to be maintained.

It is also necessary to develop knowledge of the materials suitable for advanced cycles, such as closed bottoming cycles using supercritical CO_2 or those using semi-closed oxy-firing where the turbine working fluid will be a mixture of CO_2 and steam. Changes in design of the required turbomachinery combined with the changed operating environments will mean that translating existing materials knowledge will require qualification.

The application of monolithic ceramics and ceramic matrix composites is also an important development area, in particular for micro gas turbines where uncooled parts are required. Improved understanding of their failure mechanisms and in-service behaviour are required to ensure reliable operation.

Hot corrosion behaviour

Hot corrosion is a major cause of damage, and service failures, which is seen in many operational environments when aggressive fuel contaminants (e.g. alkali metals, sulphurous species, etc.) and poor air quality (e.g. containing alkali metal chlorides) fail to be satisfactorily reduced or eliminated through filtration or other means and reach the turbine's hot gas path. The resulting formation of deposits and gaseous operating environments lead to very aggressive forms of 'hot' corrosion which can rapidly lead to failures. The successful elimination of such damage mechanisms must be tackled through a combination of approaches to ensure that the aggressive combinations of contaminants do not reach the gas path with the use of materials and coatings with maximum resistance to this form of attack. The multiple factors involved in hot corrosion mechanisms mean that no single approach can be wholly successful on its own.

The application of advanced and additive manufacturing

Advanced and additive manufacturing techniques are being explored by OEMs, third party suppliers and operators for the manufacture of new parts to reduce costs or provide new materials compositions/structures which cannot be achieved through conventional 'subtractive' methods. These methods can also be used as a repair option. However, these new or repaired parts, when used, must not compromise the mechanical performance, environmental resistance or the life of plant components.

Additive manufacturing (AM) processes allow production of components with geometries which are impossible to produce using conventional manufacturing through a layer-by-layer material addition process. This process opens up new design opportunities which could have significant advantages where intricate geometries may be beneficial, such as fuel injectors for gas turbine engines, heat exchangers, gas turbine blades or other aggressive environment applications found in energy technologies. In addition, when components have to be repaired, damaged regions of a component can be removed and replaced via an AM process. For the end user of the component which has been manufactured or repaired in this way, it is important that the materials behave in a predictable manner which is equivalent to those produced in a more conventional way.

Inspection and characterisation of ex-service parts for component life extension

There is an ongoing challenge to develop understanding of how on-line or off-line component monitoring or inspection techniques can be used to determine the condition of the materials used in the components, and hence inform an assessment of the component's condition with respect to it continuing in service. Stretching routine maintenance intervals to reduce operating costs has been a continuing aim, although the growing use of gas turbines for flexible generation or with low quality fuels have required more regular inspections to help avoiding problems. Relating ex-service component micro- structures to monitoring/inspection data, and its application in predicting the remnant life of the component remains an important area of research.

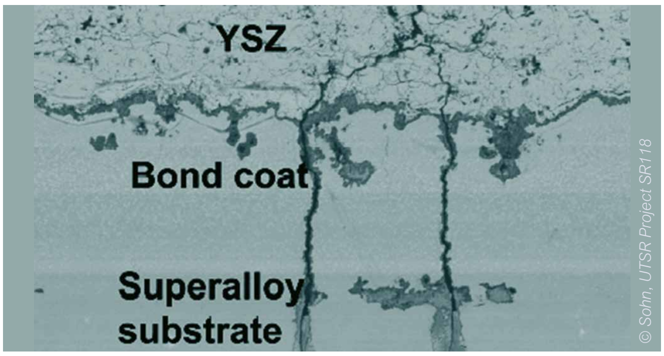


Figure 9: Scanning electron micrograph of cross-section of coated blade material expose in a combusted syngas environment showing deposit penetration

Condition assessment and durability of TBCs

TBC systems are based on yttria-stabilised zirconia or other formulations. Flexible plant operation to meet cyclic demands leads to additional thermal cycles which impacts directly on the risk of spallation of TBCs. Premature spalling of TBCs is also observed in sulphur containing gasses. TBC spallation reduces component life and increases costs through increased need for blade refurbishment. Improved on-line and off-line monitoring and inspection techniques are required to ensure costs are managed to avoid unforeseen failures and excessive maintenance/refurbishment costs.

Impact of flexible operation

The increased cycling of gas turbines in power generation applications has led to increasing incidences of unforeseen failures through fatigue and related mechanisms, as well as the premature spallation of protective coating systems. The current practice of applying the highest temperature performing base alloys with protective coatings may not provide an optimum approach where plants are designed for flexibility, rather than efficiency and low-NO_X performance. Research into the costs of different approaches across the full materials life cycle may lead to alternative strategies which have potential to reduce operating costs.

Reduced usage of strategic and environmentally-damaging elements

European legislation requiring the registration, evaluation and authorisation of specific chemicals that can be considered injurious to health (REACH) came into force in 2007. This has implications in many aspects of gas turbine component manufacture and use, as both chromium (hexavalent chrome) and nickel (notably fine nickel oxide particles) are on this list of SVHC (substances of very high concern) – those that are considered carcinogenic or offer risks to health – along with some 26 other base materials or alloying additions found in our structural materials and coating systems. Many alloys and coatings in common gas turbine use will need to be registered and the implications for component manufacture, performance and repair need to be considered. For example, corrosion by-products that give rise to chromium-6 release is an area of concern.

Figure 10: Image of Siemens V64.3 gas turbine blade being used for coating demonstration trials in the EC FP7 H_2-IGCC Project

11. Advanced Repair

Gas turbine maintenance costs substantially have been decreased by hot gas component repairs, limited repair fall out and life time extension of parts. In addition, economics have driven repair prices down significantly. The price pressure resulted in lean work scopes and functional repairs securing the part integrity for the full Time Between Overhaul (TBO).

To reduce the costs of ownership even further, overhaul intervals have been extended considerably. This has been achieved by design and/or service upgrades. In the design upgrades, the parts have been significantly modified while in the service upgrades, small geometrical improvements and better coatings led to significant life time and overhaul interval extensions. Needless to mention that longer intervals have reduced the design safety margin of the parts and therefore require more sophisticated repair scopes with stringent quality procedures to assure the extended overhaul interval is achieved.

A similar development has been seen for the repair of advanced technology gas turbines. Rejuvenation heat treatment of single crystal (SX) and directionally solidified (DS) materials require additional attention. Reapplication of MCrAlY overlay and or thermal barrier coatings (TBC), might reduce the cooling efficiency of cooling holes. Smart masking techniques or reopening through laser ablation might be required.

Given the extended TBO and life time expectations of the mature fleet and the improved gas turbine technology of the advanced fleet, repair technology needs to develop and stringent requirements must be set to achieve the expectations required.

In this position paper we will chronologically describe the status and repair technology developments.

Inspection

Advanced repairs start with an extended inspection, dedicated for the component examined. The inspection needs to focus on the geometry of the part, the material condition and the damages observed. Full assessment of the material is only achievable in the case that one part of the set is destructively tested and the high loaded areas examined by applicable techniques such as light and scanning electron microscopy (SEM). A relation between the material condition and remote monitoring, such as in flight engines is still not established. Local material sampling of highly loaded areas is still not established.

More and more, geometrical inspections are carried out by 3D scanning techniques. Compared to the standards set, such measurements provide a full map of the geometrical deviations. Interpretation of the results requires additional competency, since parts are distorted due to gas turbine exposure. Dedicated software is required to prioritise the load of data provided.

Wall thickness measurements of cooled parts are essential for the life time. Eddy current, ultrasound or Hall thickness gauges are used to assess the wall thickness. Evidently, removal of the coating is a very critical process since reduction of the wall thickness might influence the remaining lifetime of the subject parts. Both mechanical (blasting, grinding) and chemical stripping are applied. Depending on the chemical selectiveness, low chrominium contaning superalloys might be attacked by the chemical agent. For these materials mechanical stripping is preferred. In the case of chemical stripping, internal surfaces need to be protected, since aluminium diffusion coatings are attacked by the chemical agent. Robotic grinding in combination with 3D scanning might be helpful however has to be developed more accurately.

Surface damages are mainly detected by visual inspection, enhanced by red dye or fluorescent penetrants. Essential is that the cracks are clean and open. Solution heat treatment in a protective atmosphere of HF cleaning have a positive effect. Enhanced non-destructive techniques (NDT) such as eddy current or ultrasound provide dedicated solutions. Automatization of these techniques makes inspections more economical.

The internals of cooled GT components have to be examined by endoscope or X-rays. Both techniques have their limitations. Thermography has been developed as an alternative.

Repair

Repair technologies have been developed to remove and restore the damages observed and reported during the incoming inspection. Mainly welding and brazing is applied to restore cracks. The cracks have to be cleaned sufficiently beforehand. It should be noted that the repair of rotating blades is subject to welding limits due to strength of the welding material and braze material. Boron in the braze could even lead to a reduction of the ductility of the base material. The mechanical properties of thin walled products is subject for further examination.

Weldability of superalloys has improved significantly due to the use of low energy techniques such as microplasma or laser welding. A small heat affected zone lead to lower stresses and smaller cracks, if any. High gamma prime containing materials are able to be deposited defect free, however have a reduced strength compared to the base material due to their small grains. More research is required to optimise these weldments.

Removal of defective material replaced by coupons is well established. Laser added manufacturing might play a role in the manufacturing of these coupons. Mechanical strength of these materials is subject for further optimisation.

Service upgrades have significantly improved life time and increased maintenance intervals. Especially cooling improvements through modification of cooling tubes/inserts or additional external cooling holes show excellent results. Improved hard facings applied by welding or overlay are very effective for knife edges or other subjected surfaces.

Wall thickness restorations is feasible by means of overlay brazing, however shows poor results for SX materials. New technologies such as strong overlay materials applied by coating have to be examined

Coating

Perfect reapplication of coatings is very essential for the lifetime of advanced parts. High-quality MCrAlY overlay coatings, mainly applied by high-velocity oxygen fuel (HVOF) and good adhering TBC coatings are a functional part of the component. Quality control and inspection technologies are essential. Prevention of blocking of the cooling holes by means of masking remains difficult. New technologies such as laser ablation show promising results by reopening of the holes.

12. Reliability, Availability and Maintenance

Gas turbine operators are constantly focused on delivering their production to customers. A high rate of reliability allows ambitious forecasts to be reached without disruptions that would otherwise generate time loss, team and organisation efforts and obviously loss of revenue. High availability is a key driver to maintain and potentially increase production (electricity, oil and gas) with a given asset. A ten percent availability increase results directly in a ten percent rise in production, and highly increases profits. The ultimate goal for gas turbine operators would be a maintenance-free gas turbine, knowing that this expectation increases the asset availability and decreases operation expenditures, directly linked to profit improvements.

High reliability, availability and maintenance (RAM) values is paramount of importance to the user communities because it impacts their day-to-day results and, eventually, yearly profits.

In consequence, a constant effort from Universities, Equipment Manufacturers, Services Providers and OEM is necessary to improve gas turbine RAM. The following technologies and developments should be considered:

Reliability

- Tools such as sensors, data evaluation algorithm and/or procedure for early warning of incipient failures, in order to detect deviation from expected operational conditions before damage is done or to prevent severe subsequent damage. These should be directly usable by Operators or pool of Operators;
- More robust instrumentation (longer service life, reduced requirements for redundancy);
- Instrumentation for severe environments (e.g. in the hot gas path);
- Equipment and sub-equipment developed with higher quality standards at lower price;
- Condition monitoring such as online monitoring of roller bearings, hot components, lubrication oil, etc.

Availability

- Increased time between overhaul (TBO);
- Improved capability of engine and its associated systems to sustain harsh environment (i.e. gas and liquid fuels with high sulphur content, offshore and coastal in wet and salty conditions);
- Filtration system addressing industrial conditions like hydrocarbon vapours or soot in order to improve air intake filter performances and enable longer service time between maintenance at high efficiency;
- Slippery coating on compressor airfoils, in order to reduce fouling and the need for operational interruptions, such as shut-down for a compressor wash;
- Monitoring and prediction of degradation processes to better plan for required shut-downs;
- Auto-run calibration for low emission systems;
- Systems and algorithm eliminating rotor lock-in.

Maintenance

- Development of repair standards lowering costs;
- New component design leading to 100% components reparable and re-usable for cost reduction;
- Improved tools for Condition Monitoring, also through the integration of different tools available, enabling the adoption of Condition Based Maintenance;
- Risk-Based maintenance approach, taking into account for the probability and the economic consequences of the potential failure modes;
- Algorithms for predictive analysis (e.g. thermal engine performances, sub-system performances, etc.);
- Engine sub-system life extension depending on operating conditions;
- Optimisation of spare part management;
- Online transfer of data from remote locations and communication with centralized experts;
- Smarter contract models sharing cost benefits with maintenance service suppliers;
- Technology and methodology transfer from other industries considered to be best in class (nuclear, aviation, etc.).

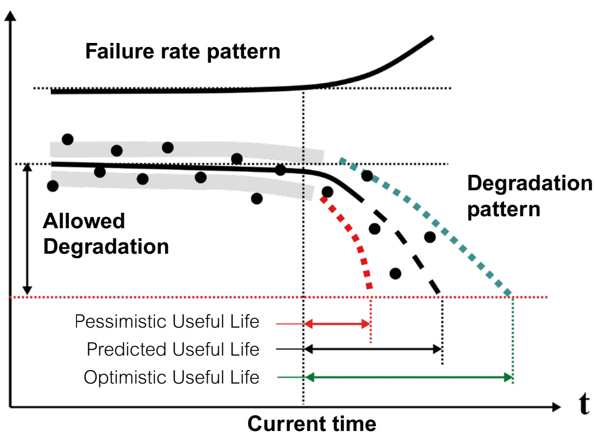


Figure 11: Degradation and prognostic model

13. Condition Monitoring and Lifing

As the share of renewable energy sources in electrical power generation increases, there is a need for more flexibly operating plants to maintain grid stability as well as meeting peaks in demand and providing dispatchable power.

This plant cycling together with quick start-ups and rapid load changes, results in less predictable effects of aging and degradation than in continuous operating conditions. Significantly changed operational profiles affect also reliability, availability and maintenance of plants. At the same time service and maintenance costs are a main focus area for many operators of grids and power plants. While grid operators mainly require information on the status of the plant (operational state and possible ramp rates for starts, stops and load changes) plant operators require detailed informaion from conditon monitoring. For them condition monitoring is a central tool and base to estimate operating hours to next service, remaining lifetime as well as required service activities and spare parts. It contributes to avoiding unexpected outages and reducing outage durations by allowing in advance detailed resource planning and identification of required spare parts. For the use of advanced alloys and coatings, for gas turbines (GTs) and heat recovery steam generators (HRSGs), condition monitoring supports the early detection of thermal barrier coating (TBC) spalling/blade hot-spots and the need for repair/refurbishment. Condition monitoring is therefore a necessary tool to ensure and support increased reliability, availability and maintenance planning of GT plants.

For the Oil and Gas industry, market challenges over the last few years also means that reliability and operational costs are more critical than ever. Condition monitoring linked to condition based maintenance is important to new and aging assets particularly as the GTs are operated in varying and often hostile environments.

The following list of proposed research and development activities represents a collection of ideas which might result in further / future projects.

Processing of measured signals from sensors and data storage

Signals from sensors, which are the base for condition monitoring activities (combined with routine process operating data), need to be processed and often stored before any further activity. This time consuming process is usually done by the operator and often based on manual interactions. An R&D activity could therefore target to automate the process, for example removal of bad data while, at the same time, avoiding loss of information. Additionally, the storage of important data and information is a critical topic; it is important not to lose information, which could be relevant for later usage in the frame of long term monitoring, and diagnostics often requiring multiple years of data. A project could therefore focus on identifying the needs of long term condition monitoring and develop the necessary methodologies for data storage and handling (e.g. event driven data collection, data compression and averaging etc.).

Sensor validation

Another interesting R&D topic to focus on is sensor validation, including differentiating between a failed sensor and a real event. This has the potential to avoid spurious gas turbine trips. Models can be developed and then tested in a first stage with physical networks which simulate operating and fault conditions, and so can help understand sensor responses. Micro gas turbines could also be used as test beds, with sensor fault applied manually. This approach enables partial validation of approaches before testing on commercially operational plants, limiting the risk and allowing evaluation of different scenarios, e.g. the need for redundant sensors to back up a failed one.

Monitoring systems with limited data available

These systems are used to evaluate the condition of components and plants for which not all characteristics are available to the required detail, thus data driven models are used such as artificial neural networks. The data needed for generating such a model are the results of real measurements on the individual plant and need to cover a relatively long period of operation to achieve a sufficient level of accuracy. This disadvantage could possibly be overcome by the development of so called “grey box” models, based on general available characteristics which are derived from physical laws and further improved by combining these characteristics with a data driven/black box model. The application of the resulting model should result in a significantly shorter period for data collection while still achieving a high level of accuracy for the specific plant/component of interest. A possible R&D activity could target building and implementing such a method for a gas turbine or e.g. a small scale combined heat and power (CHP) as a base for further development steps.

Inclusion of non-sensor based information

The inclusion of non-sensor based information (e.g. from inspections etc.) and off-line monitoring (may be sensors or other measurement devices, e.g. to measure material condition) might significantly improve the interpretation of data from condition monitoring systems. However this information is usually not systematically implemented. A project might target development of routines and tools to close this gap to sharpen the picture resulting from condition monitoring systems and result in the improvement of the connection to asset management. This information could ideally be assigned to individual components and parts. This way, it would follow case components or parts that are exchanged, and even those that are repaired and then implemented on a different machine/part.

Condition monitoring for transient operation

Condition monitoring during transient operation of the plant/component is another area, which requires further R&D activities. It is also closely connected to advanced data analysis tools due to large amounts of data (high sampling rate) and the associated fast processing requirements. Currently many maintenance systems rely on data from steady state operation as a base for analysis. Given the growing share of renewable energy sources, requiring balancing by conventional power generation technologies, the transient operation of GTs will increase. An R&D project may focus on developing improved condition monitoring tools for transient operating conditions. This should also include defining required sampling rates of measured data and their processing (e.g. to distinguish transients from normal fluctuations of measured values) to achieve accurate and reliable results. Results of such a project could also be used to refine the determination of consumed & remaining lifetime of the plant and/or components. A target would be, for example, to replace standard penalties for a start up or shut down with algorithms using measured values. Transients of load change during operation might be also covered based on the magnitude of the change as well as of the gradient of the change.

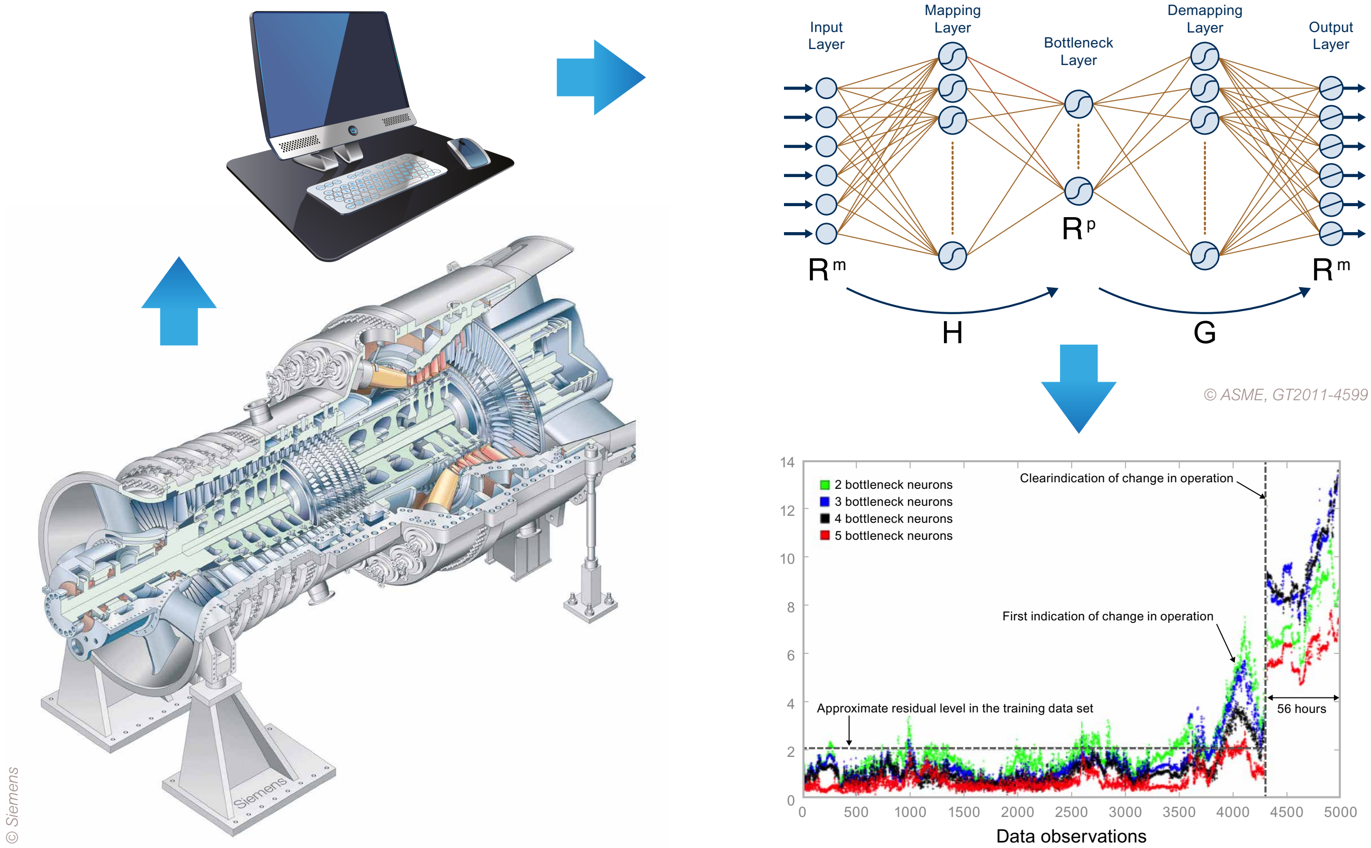


Figure 12: Collecting data and using a neural network for condition monitoring and early detection of upcoming faults

14. Sensors & Instrumentation

With the increasing share of non-predictable energy sources in the grid, gas turbines are required to operate in a very flexible mode. In order to maintain safe and reliable operation, a large number of machine parameters have to be continuously monitored.

Furthermore, the availability of a larger number of measures will enhance the benefits achievable with the adoption of data analytics techniques ("Big Data"), which will include the development of more accurate failure prediction models as well as the optimisation of the operation either for a generating unit or for a whole fleet.

Better sensing techniques could facilitate large fuel savings, with consequent CO_2 emissions reduction and economic benefits.

Sensors and instrumentation for the following purposes should be further developed:

Instrumentation for operation optimisation

The main control parameter of gas turbine operation, turbine inlet temperature (TIT), is currently indirectly evaluated from exhaust gas temperature measurement and other parameters. Direct TIT measurement would allow for a better control of the machine; enabling operation closer to its design values with benefits on efficiency. Measurement of the uniformity of turbine inlet conditions could also prompt combustion system design improvements, with consequent reduction of NO_X and CO emissions and increased hot gas path components life, enabling longer maintenance intervals.

Instrumentation for maintenance optimisation and failure prediction models

Power plants cycling results in additional accumulation of fatigue and creep damage in thick components, such as gas turbine (GT) and steam turbine (ST) rotor and heat recovery steam generator (HRSG) headers. The ability to accurately measure component strain with semiconductor strain gauges enables the online monitoring of high temperature component integrity, including welds. On-line monitoring of elastoplastic strains and dynamic rotor dissymmetry of GT and ST rotors during operation would provide information for the implementation of failure prediction models and would give the possibility to plan corrective actions and reduce the cost and time for repairs. Real time monitoring of rotating component temperature with infrared systems and telemetry would also provide information for the implementation of failure prediction models, enabling the adoption of a condition based maintenance approach, as described in the Reliability, Availability and Maintenance chapter.

Fiber Optic sensors offer an opportunity for the distributed measurement of temperature or strain. Solutions based on Fiber Bragg grating technology need a validation for high-temperature (i.e. 700°C) applications in industrial environments. Brillouin-based solutions, which offer a higher flexibility in the position of measurement points, need further development in order to make this solution available for industrial use.

The availability of mini-invasive sensors, together with the adoption of additive manufacturing technologies, enable sensor integration into plant components. Embedded sensors will provide valuable data for the continuous monitoring and diagnostics of component's health and life consumption.

Instrumentation for flexible operation (fast ramps/high gradients)

Gas turbines are required to rapidly change their operating conditions in order to maintain grid stability, especially when non-dispatchable plants cover a large proportion of the total generation.

Turbine blade tip clearance has a relevant impact on efficiency. With the fast load changes differential thermal expansion of rotor and casing could be a limiting factor for maintaining low clearance values. A reliable measurement of tip clearance with micro-wave, optical fibre or capacitance sensors is crucial for keeping high efficiencies while preventing rubs between gas turbine blades and engine casings and avoiding the risk of failures.

Figure 13: Microwave blade tip sensor

Instrumentation for machine protection

With the continuous reduction of NO_X emission limits, combustion stability remains a critical issue for GTs. Ultra high temperature dynamic pressure sensors, based on piezoelectric or optical probes, allow for a more precise measurement, and potential control of pressure fluctuations inside the combustion chamber.

Optical sensors for early detection of heat release fluctuations related to combustion instabilities would also enable protection of the machine against the damages caused by very high intensity instabilities. Real time monitoring of dynamic response of both compressor and turbine blades during GT operation with blade tip vibration monitoring systems could prevent blade cyclic damage due to flutter or blade stalling.

Figure 14: Piezoelectric Pressure Transducer

Figure 15: Optical Dynamic Pressure Transducer

Instrumentation to prevent shutdown or to reduce inspection time

When a potential risk is detected, an inspection of the machine is frequently required to assess the status of the components. Currently adopted inspection techniques demand a prolonged stop, with an unavailability penalty, mainly due to the need to cool down the machine before the inspection. Robotic and automated solutions, such as high temperature cameras and borescopes, would enable inspection during short stops.

Instrumentation for GT development

High temperature thin film strain gauges could be used for the study of crack development and propagation, residual stress, stress and strain distribution, thermal expansion coefficient of materials at very high temperatures as well as for blade vibration measurements. These sensors would be extremely useful in the design and development of advanced gas turbine engines.

Video cameras for real time flame visualisation in various wavelength intervals would allow monitoring of the dynamic behaviour of the flame, supporting the development of stable combustors, with higher fuel flexibility and larger operability ranges.

Entropy probes can be used to measure the time-dependent relative entropy field, which is related to the aerothermal losses. Entropy can be inferred from pressure and temperature measurements. The development of small-dimension fast-response entropy probes will help the design of turbomachinery with higher efficiencies and wider operating ranges.

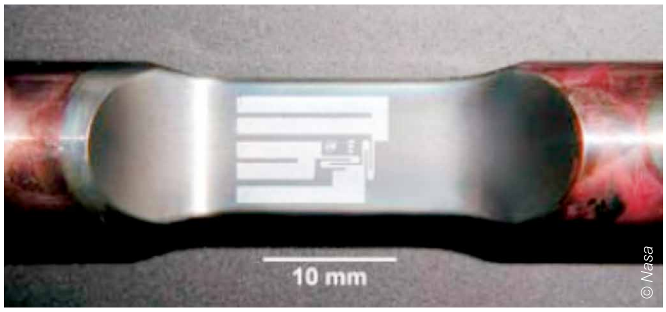


Figure 16: PdCr thin-film strain gauge on a turbine engine alloy test specimen

Wireless sensor networks

The advent of low-power processors, intelligent wireless net- works, and low-power sensors coupled with "Big Data" analytics has led to what has become a booming interest in the Industrial Internet of Things (IIoT). In this context, the application of Wireless Sensor Network (WSN) technology in process monitoring and control of gas turbines has demonstrated great potential.

WSNs bring several advantages over traditional wired industrial monitoring and control systems:

- No wiring and conduit, reducing installation cost;
- Low maintenance efforts (only the battery change is necessary after years of operation);
- High flexibility to relocate devices or to deploy additional ones.

The installation of wireless sensors on critical equipment which is not convenient to monitor with traditional sensors will favour the adoption of predictive maintenance, thereby helping to avoid unplanned downtime and critical, unexpected fault events.

15. Digitalisation

The development of digital technology over the last decade has led to Industry 4.0, the 4th industrial revolution, which is enabled by the Industrial Internet of Things (IIoT). However, oil and gas, and power generation industries have been cautious to adopt digitalisation. Indeed, remote monitoring and online machine monitoring are not new concepts, and the advantages of IIoT are not immediately obvious. Then, there are also concerns over cyber security and ownership of data. Business IT networks and business procedures need to be evolved to take advantage of digitalisation, but for this to happen, the benefits of digitalizsation must be examined and understood. Since it is not fully clear what these benefits are, the following suggested topics are aimed at answering the concerns of end users, and highlighting the benefits of digital technology.

Development of Digital Twins

A digital twin refers to a digital replica of a corresponding physical system. It represents numerically the detailed elements of the physical system, as well as its dymanic behaviour, operation, and degradation throughout its life cycle. This section should look at advanced computer modelling technologies to develop digital twins for gas turbine driven systems. This involves using field data and domain knowledge to adapt the computer models to the physical systems, and integration of the computer modelling, artificial intellence, machine learning, and software analytics with data to create digital simulation models that update and change as their physical counterparts change.

Data Management

Gas turbine driven systems may produce large amounts of data from their operations. It is important to manage the large data and extract useful information from the data for efficient, reliable and safe operation of the power systems. This section should develop and evaluate the technologies for data storage, data transfer via internet, data receiving, data security, and information extraction and processing.

Cyber Security

This section should consider remote connectivity, hardware firewalls, business risks, cloud solutions vs client-side networks, ownership and location of data, implementation of applications, and Quality Assurance, adoption of cyber security standards (ISO 27001, IEC 62443).

Life Cycle Management

With the support of digital twins, this section should look at the development and evaluation of the technologies for optimal control, operation, condition monitoring, condition-based maintenance and life management of gas turbine power-generation systems.

Review Potential Architectures

Not all digital solutions will be suitable to industries involved with ETN, such as remote locations, offshore installations, FPSO ships, etc. Some solutions will work better than others, and this section will review the connectivity opportunities that digitalization/cloud access technologies can bring to end users.

Benefits

When machine data plus asset and business data come together, the opportunities of analysis increase dramatically. The effect of machine performance on an entire business and network can be analysed, and reliability and production forecasting can be performed quickly with greater accuracy. Further benefits may be revealed in the process. ETN should look into the ways digital solutions can help its end users.

Software as a Service

Having data in one place means that analysis tools and services can be deployed differently. The process of buying and installing software on a PC has evolved into a delivery of service business model that provides benefits with a monthly fee or charge per use. This section should look at what these options are for ETN members and what business KPI's these can solve.

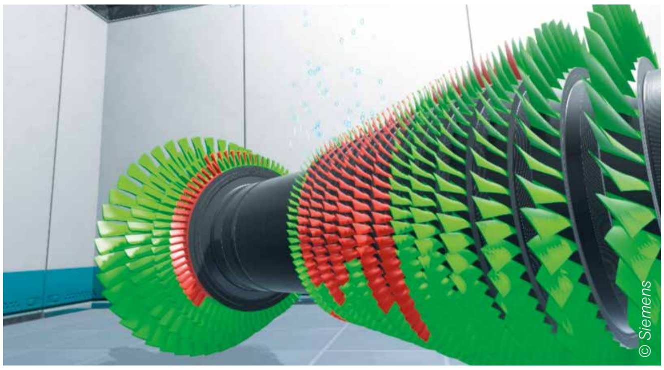


Figure 17: In a virtual reality representation of a gas turbine, complex sensor data is translated into colors to make the meaning of information in this case temperature differences easy to understand

16. ETN Support Schemes for Projects

ETN facilitates and assists in the development and progress of project initiatives that are brought by members to the ETN platform. In this respect, the ETN Project Board will give a recommendation on which type of project is deemed most appropriate and will offer to provide support during the start-up phase of the collaboration. In parallel, the ETN Office will support the project and will help developing a synergy between the participating actors. The partners initially involved will evaluate and define the project starting point (level of knowledge, maturity level, Technology Readiness Level (TRL)) and the project's needs with regards to academia and/or industry. A wide range of goals can be pursued, as for example, an increased level of knowledge; general dissemination of information; the development of tools; a demonstration/proof of concept.

R&D Projects

This kind of collaboration will likely be the most common type of project and can span a wide range in terms of number of partners involved, budget volume and source of funding. This type of cooperation would be best suited for the following activities:

- System and process development;
- Design of hardware components and (experimental) testing of new technologies;
- Development of (software, modelling) tools & procedures.

NEXTOWER (2017-2020)

The objective of NEXTOWER is to introduce a set of innovative materials to boost the performance of atmospheric air-based concentrated solar power (CSP) systems to make them commercially viable.

www.h2020-nextower.eu

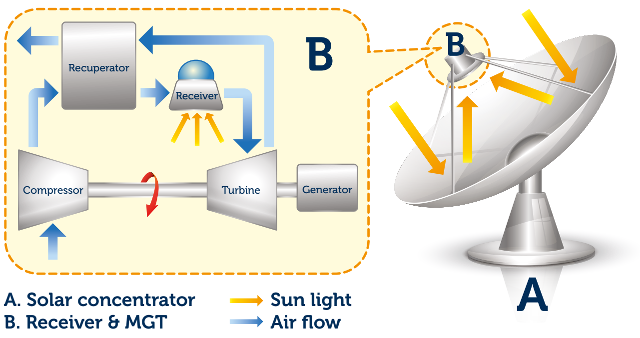
PUMP-HEAT (2017-2020)

The EU funded PUMP-HEAT project (Performance Untapped Modulation for Power and Heat via Energy Accumulation Technologies) was kicked off in September 2017. The objective of the project is to increase the flexibility of the Combined Cycle power plants and the operation of gas turbines.

www.pumpheat.eu

OMSoP (2013-2017)

Co-funded by the EU's 7th Framework Programme for Research and Development, the OMSoP project provided and demonstrated technical solutions for the use of state-of-the-art concentrated solar power systems (CSP) coupled to micro turbines to produce electricity.



www.omsop.eu

Thermal Barrier Coatings (2012-2015)

This project focused on performing an in-depth literature survey into thermal barrier coatings and provides, based upon operator's feedback, an overview of TBC related topics of interest to them.

H_2-IGCC (2009-2014)

Co-funded project under the EU's 7th Framework Programme, the H_2-IGCC project provided and demonstrated technical solutions which will allow the use of state-of-the-art highly efficient, reliable gas turbines (GTs) in the next generation of Integrated Gasification Combined Cycle (IGCC) plants.

www.h2-igcc.eu

Pre-study / Feasibility Study

If a certain topic bears high risk and/or knowledge is very limited, it might be warranted to deal with it at first in a well-defined, short duration type of work (max. 12 months). Usually, such studies will be performed by only a few partners (1-3), while parties interested in a follow-up project (in case of a promising outcome of the study work), would provide funding and serve as review body. Depending on the complexity of work required such studies might be linked with student thesis.

Best Practice Guidelines

Open issues about tasks which are performed repetitively and by a large number of parties for different business segments and applications, may warrant the documentation of best practice guidelines. These guidelines help the knowledge transfer across different businesses and speed up the learning curve for new entrants into existing markets or for established companies venturing into new business models. This domain of cooperative work is best covered by suppliers and service providers which aim to broaden their customer basis and are willing to promote their business by showcasing their accumulated experience.

Development of Standards

For quality assurance, certain business segments might want to define binding rules for how to perform certain tasks, design certain components or execute certain services. Definition of such standards goes beyond the documentation of best practices and must adhere to a formalised approach which requires the cooperation with a standardisation institution. This usually long-term, meticulous process is most likely initiated by customers (users of a certain service or a certain component of a plant), but suppliers will benefit from the well-defined procedures as guarantee issues and liability questions will reduce.

Position papers

When it comes to topics that are being discussed more widely in the public and/or in political institutions and for which their future perception will have a major influence on the business model of ETN members, the formulation of position papers is advised. Such documents are suited to describe the status/ state-of-art, to express the opinion of a group of parties, and to recommend future actions. Position papers must be balanced, but still address issues to the point. In order to be used for lobbying purposes, position papers should express the standpoint of a majority of parties whose business is directly affected by the public perception of the subject matter covered by the document.

- Gas Turbine Fuel Flexibility for Zero Emission Power Plants
- The Impact of Natural Gas Quality on Gas Turbine Performance
- Enabling the Increasing Share of Renewable Energy in the Grid
- The Importance of Flexible and Efficient Power Generation in Horizon 2020
- Industrial Internet: the next age of productivity for European GT based plants

Working Groups

ETN Working Groups are created when individual projects can be developed. They connect the key stakeholders in the gas turbine community to address the issues through projects of common interest. Further details on projects mentioned in this section may be found on the ETN website.

Air Filtration

The objective of the project is to contribute to the development of an ISO standard for air filtration, with the vision to enable three years of gas turbine operation without any filtration issues. It allows the GT users to have a single point of reference for state-of-the-art filtration technology and to address air filtration issues through projects of common interest.

Exhaust Systems

The aim of this project is to create an ISO standard on exhaust system designs for gas turbines. In 2015, ETN issued a standard on *Gas Turbine Exhaust Systems with or without waste heat recovery equipment for oil & gas, chemical and process industries*. This standard has then served as basis for an ISO document that is now in progress.

Micro Gas Turbines

The vision of the MGT project is to bring together the whole Micro Gas Turbine supply chain in order to explore further co-operation opportunities among stakeholders in research and developments. Its objectives are to explore markets opportunities and solutions, implement cooperation projects, set-up conferences and workshops to strengthen this cooperation, and investigate funding opportunities.

Hot Corrosion

The goal of the Hot Corrosion Working Group is to understand the likely causes of hot corrosion and address hot corrosion damages on the hot gas path parts of the gas turbine, particularly off-shore or in coastal regions. The involved ETN members will be able to share issues, participate in the metallurgical analysis of damage mechanisms, and influence the outcomes of the project. They will receive direct feedback from leading technical experts in the R&D and GT Users' community on the most effective mitigation options and the potential ways to overcome the problem in the future.

Additive Manufacturing

The objective of the ETN Additive Manufacturing Working Group is to enable and optimise the use of additive manufacturing technologies for turbomachinery components. In particular, it shall exchange knowledge and experience focusing on the added value that AM could generate and cooperate on additive manufacturing practices.

Ammonia/Hydrogen

The aim of the Working Group is to share technical information and address issues related to ammonia and hydrogen combustion in gas turbines. By cooperating, ETN members will be able to develop and implement advanced combustion technologies to enable the operation of gas turbines fuelled by ammonia and/or hydrogen used as energy carrier from Renewable Energy Sources.

EU Strategic Energy Technology Plan

European Union and its member states aim at building an Energy Union, based on 5 pillars: energy market, security of supply, energy efficiency, greater inclusion of renewables and research & innovation. This last pillar is implemented partly thanks to the Strategic Energy Technology Plan launched by the European Commission. ETN has been very actively committed in its design and development.

Representatives of ETN have been contributing to several of the actions carried out within this framework, namely in the following actions:

- Action 4 – Increase the Resilience, Security, and Smartness of the Energy System
- Action 5 – New Materials and Technologies for Buildings
- Action 6 – Energy Efficiency in Industry
- Action 9 – Carbon Capture Utilisation and Storage.

Technical Committees

The Technical Committees (TC) cover the most crucial areas of future gas turbine technology development. They serve as forums where the ETN Members meet to share experiences and discuss ideas and initiatives, which can later be developed into individual projects or Working Groups.

- TC1 – Low Carbon Gas Turbine Operations
- TC2 – Operational and Fuel Flexibility
- TC3 – Material Degradation, Repair Technologies and Manufacturing
- TC4 – Condition Monitoring and Asset Management.

For any submission of project idea or interest in ETN activities, please contact the ETN Office.

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