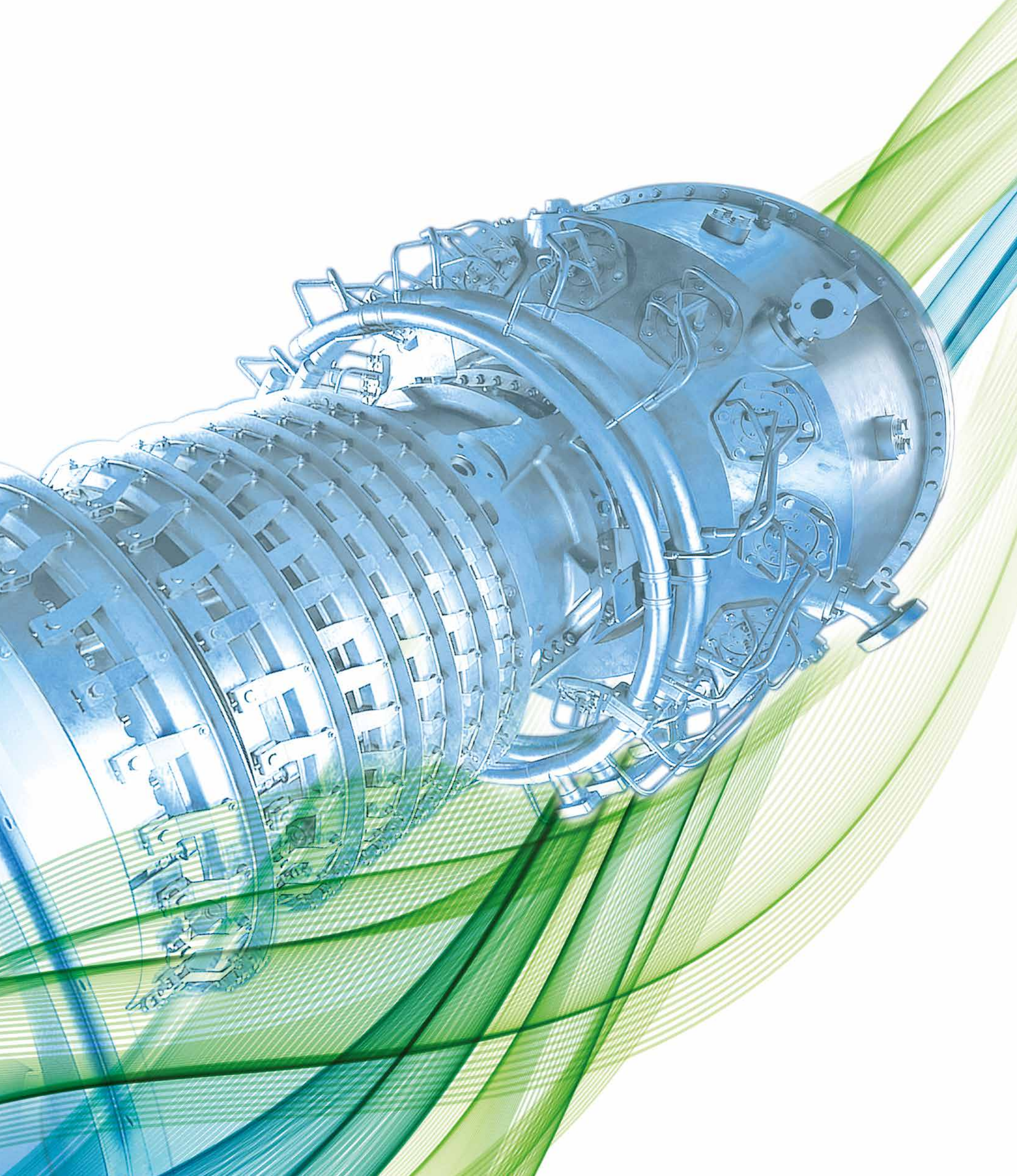
ETN R&D RECOMMENDATION REPORT

2021 EDITION



Safe, secure, affordable and dispatchable carbon-neutral energy solutions by 2030, implemented globally by 2050

ETN vision

Cover page: © Solar Turbines

Table of contents

1. Introduction

ETN's vision is to contribute to the development of *safe, secure, affordable and dispatchable carbon-neutral energy solutions by 2030, implemented globally by 2050*. Therefore, continuous research and innovation efforts in the gas turbine sector are of paramount importance to ensure the key role of turbomachinery technologies in the energy transition era and beyond. This includes the deployment of carbon-neutral energy services and products. After having analysed the impact that gas turbine-based solutions can have in the future, the ETN Board 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. In accordance with this, the growing importance of *Systems Integration and Energy Storage* is now addressed in a dedicated chapter that reviews overall performance improvements that can be obtained by the integration of gas turbine technology in other systems.

The report lists topics in technical areas relevant to gas turbine systems being used in Oil & Gas, Power Generation and Industry; the business segments in which ETN members are active. 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. As such, it provides a sounding board for these ideas and initiatives that have originated from the entire ETN community of members. Indeed, the Project Board advises on how to maximise the potential of new initiatives and gives recommendations for future actions, in line with the strategy proposed by the ETN Board and adopted by the General Assembly.

The ETN Project Board also leads ETN's Working Groups and provides technical and strategic advice to the ETN Technical Committees, which cover the most crucial areas of future gas turbine technology development (*see the chapter ETN Support Schemes: Projects and Working Groups*).

The Project Board 2020-2022 consists of the following members who have all contributed to the various parts of this edition of the ETN R&D Recommendation Report:

Project Board

Peter Breuhaus (Chair)
NORCE, Norway

Technical areas:
Fundamentals of aero and thermodynamics; Gas Turbine technology and design; Power plant monitoring and diagnostic systems; Power systems and systems integration; Process technologies

Peter Jansohn (Co-chair)
Paul Scherrer Institute (PSI), Switzerland

Technical areas:
Fundamentals of Combustion; Gas Turbine Cycles; Process Technologies; Integrated Power Generation Systems; Environmental systems (for exhaust gas clean-up and emission reduction)

Dominique Orhon
Total, France

Technical areas:
Turbomachinery design, integration in process, operation, and troubleshooting; Gas turbine qualification as new product for Company; Oil and gas plant design, construction, commissioning and operation

Marco Ruggiero
Baker Hughes, Italy

Technical areas:
Turbomachinery Experimental Verification; Test Systems Engineering; Measuring Techniques; Gas Turbines design and operation; Centrifugal Compressors design and operation; Control systems and instrumentation

Olaf Bernstrauch
Siemens Energy, Germany

Technical areas:
Turbomachinery package development (GT, ST, Gen, Aux); Storage technologies and plant integration; Hybrid plants; (Waste) Heat recovery (sCO2, ORC, HTHP, …); Co-Generation CHP

Peter Kutne
DLR, Germany

Technical areas:
Gas turbine combustion; Optical and laser based diagnostics; Micro gas turbines; Decentralised combined heat and power; Innovative gas turbine cycles; Utilisation of biomass based and renewable fuels

Chris Dagnall
DNV, United Kingdom

Technical areas:
Gas Turbine performance and emissions; Compressor performance; Condition monitoring and vibration

Olaf Brekke
Equinor, Norway

Technical areas:
Gas Turbines and auxiliary systems; Gas Turbine performance, operation and condition monitoring; Turbomachinery in the Oil & Gas industry

Elisabet Syverud
University of South-Eastern Norway, Norway

Technical areas:
Grid interconnections certifications; Exhaust recovery; Fuel conditioning and compression; Combustion with the fuels and emission standards

David Sánchez
University of Seville, Spain

Technical areas:
Power plant Engineering, with a focus on steam and gas turbines and on advanced cycles for Concentrated Solar Power and Waste Heat Recovery (Supercritical Carbon Dioxide Cycles, Organic Rankine Cycles); Micro Gas Turbines; Techno-Economic Assessment of power systems; Water & Energy Nexus

Stefano Sigali
Enel, Italy

Technical areas:
Grid interconnections certifications; Exhaust recovery; Fuel conditioning and compression; Combustion with the fuels and emission standards

Enrico Bianchi
Ansaldo Energia, Italy

Technical areas:
Microturbine; CHP package; Renewable energy; Certification; Production; Quality; Heat recovery; Power electronics

Tom Kavanagh
Uniper, United Kingdom

Technical areas:
Generation Technologies R&D; Asset Risk Management; Electrical Engineering; Power Plant Operations and Maintenance

Christian Haecker
Oerlikon AM, Germany

Technical areas:
Additive manufacturing production technologies; Qualification and certification processes; Design to cost AM in turbomachinery and oil&gas application

This report has also benefitted from the valuable contributions of Andy Williams (Chromalloy), John Oakey (Cranfield University), Nigel Simms (Cranfield University), Mitch Dorfman (Oerlikon Metco), and Herwart Hoenen (Hoenen CS).

2. Market Conditions & Policy Framework

Energy systems are undergoing fundamental changes across the world. With increasingly more countries and companies pledging and acting towards carbon neutrality by mid-century, political, economic, and societal transformations are ongoing.

The following key trends can be identified: decarbonisation, decentralisation, digitalisation as well as system integration and sector coupling. 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. Digital solutions are being developed and become available on a widespread basis, transforming energy systems to make them smarter, more reliable, more interconnected also across sectors, safer and, above all, more efficient.

Ambitious climate strategies combined with the already ongoing research efforts and promising development opportunities of the gas turbine technology position it to play a key role as a dispatchable source of power & heat in the energy systems of the future. This chapter outlines topics which have a strong influence on gas turbine technology development, as well as gas turbine deployment and use.

The strategic role of gas turbines in the energy transition...

While the share of RES will keep growing around the world, gas-fired power generation is foreseen to continue playing a strategic function[1]. Currently the largest gas-consuming sector worldwide, gas turbine-based generation provides a reliable, cost-effective, and dispatchable power source that offers valuable decarbonisation options.

In the transition towards a fully decarbonised energy system, the role of gas turbine power stations will evolve as the share of electricity produced from renewable sources becomes predominant: they will provide reliable and affordable power during doldrums when wind and sun energy are scarce and consumption is high, thus securing supply and grid stability with extremely high ramp rates.

In addition, the market for heat will become highly attractive for investments as wind and PV energy do not provide waste heat for industrial processes or district heating. Highly efficient and flexible gas turbine power plants provide already a dispatchable alternative to more carbon-intensive fossil fuels and supply necessary heat for industrial processes or urban areas achieving an energy effectiveness of up to 90%.

Gas turbine-based generation will therefore play an essential role in the energy transition by providing stable electricity and heat supply throughout the year, which becomes particularly relevant during major energy system transition displacing coal- or nuclear-based generation. Several countries are currently undergoing such changes, as for example Germany, phasing out its nuclear and coal fleets in 2023 and 2038 respectively; Belgium, closing its nuclear power plants by 2025; and Poland, facing the challenge of replacing ~ 80% share of coal in its electricity mix.

In addition, affordable retrofit solutions are progressively developed and made available to improve the efficiency of existing gas turbine plants over the operating range and to expand their fuel flexibility allowing an increasing mix of renewable fuels to be used. These solutions will be attractive to users in industry, oil & gas, and power generation markets in order to reach their goals for CO_2 emission reduction and support the energy transition.

… and beyond

Gas turbines are a sustainable investment for security of supply, operating today with natural gas and in the future with green alternatives, such as hydrogen, synthetic methane or other green fuels. It is paramount for policymakers to propose an ambitious plan to accelerate the ramp up of the hydrogen blend in the gas mix to meet the continuously increasing demand of hydrogen in the power sector. This journey has already started with hydrogen blending in industrial turbines, which due to their small size combust smaller – and already available – amounts of hydrogen, and is further supported by OEMs' commitment to the development of 100% hydrogen gas turbines by 2030[2]. This requires R&D for safe turbine technologies, combustion systems, leak detection, safety systems, hydrogen storage and infrastructure readiness.

[1] IEA (2020), Natural Gas-Fired Power, IEA, Paris *https://www.iea.org/reports/natural-gas-fired-power*
[2] cf. "The Gas Turbine Industry's Commitments to drive the transition to renewable-gas power generation", *https://powertheeu.eu/*

The industry also relies on gas turbines for mechanical drive applications or decentralised flexible power and heat generation. The gas turbines used today for oil & gas production or to drive large compressors in transportation pipeline systems will benefit from the transition towards the hydrogen economy. Thanks to advanced combustion systems, they will be able to deal with any admixture of hydrogen to the fuel up to 100% hydrogen and participate in the decarbonisation of industry.

Ambitious policy frameworks to decarbonise the energy systems

On 4 November 2016 the Paris Agreement, a legally binding international treaty on climate change, entered into force, strengthening the efforts and the policies worldwide towards an energy transition to a low-carbon energy system. In 2021, five years later, the National Determined Contributions will be revised, and we should expect the 197 countries who signed the agreement to raise the level of their national ambitions. The necessity of setting more ambitious targets becomes clear based on IEA's Sustainable Development Scenario projections, which outline the required carbon intensity reduction of electricity generation, falling from 463 grammes of CO_2 per kilowatt-hour (gCO_2/kWh) in 2019 to below zero in net terms around 2055[3]. While many studies conclude that this is both technically and economically feasible, a clear trajectory line is required to alleviate uncertainties and stimulate further investments. Therefore, these decarbonisation goals call for an enabling policy framework strategically oriented to long-term objectives that provides pathways towards new power market designs and concrete and long-lasting public investments on new technologies and new energy systems.

Indeed, it is unanimously recognised that technologies' development, transfer, deployment and scale-up will play a pivotal role in the energy transition. In one of its latest reports, the IEA stressed that achieving net-zero requires not only a greater deployment of already available technologies such as RES, but also of other clean energy solutions currently under development, such as greater application of hydrogen and CC(U)S[4]. Carbon Capture and Storage (CCS), Carbon Capture and Usage (CCU) and low CO_2 emission technologies will be essential for the transition to net neutrality, ensuring that power generation and industrial processes are secure, reliable and sustainable.

Carbon rates sending appropriate price signals will help incentivise investments in low-carbon technologies and power generation. Carbon pricing policies in Europe combine the EU Emissions Trading System (EU ETS), a wide cap-and-trade scheme, with national carbon taxes currently in place or being developed (France, UK, and Scandinavian countries). The global carbon market landscape is expected to change dramatically in the coming years as new national trading systems are launched, others are reformed, and the UN battles to complete a set of guidelines for nation-to-nation trading.

The EU has clearly stated its objective of global leadership in the fight against climate change and has set some of the most ambitious carbon emission reduction targets in the world with the European Green Deal, progressively aiming at making the EU climate neutral by 2050. The Green Deal encompasses actions such as investments in environmentally friendly technologies, decarbonisation of the energy sector, and support to the private sector in its innovation's efforts. In detailing its 2050's long-term strategy, the EU has outlined stepping-stone legal-binding 2030 targets towards carbon-neutrality and enabling policies, with relevance of topics such as CCS, hydrogen, and natural gas for hydrogen production.

Key EU targets for 2030

- At least 55% emissions reduction from 1990 levels
- At least 32.5% energy efficiency increase, relative to a 'business as usual' scenario
- At least 32% renewable energy share of the EU's gross final consumption
- Interconnection of at least 15% of the installed electricity production in the Member States

To achieve these targets, a systemic and comprehensive approach across all sectors have been put in place. From strategies like the energy system integration strategy, the hydrogen strategy, and the methane strategy (establishing the reduction of methane emissions as one of the priority initiatives), to market and financial tools, such as Sustainable Finance and the

[3] IEA (2020), Energy Technology Perspectives 2020, IEA, Paris *https://www.iea.org/reports/energy-technology-perspectives-2020*
[4] IEA (2020), Energy Technology Perspectives 2020, IEA, Paris *https://www.iea.org/reports/energy-technology-perspectives-2020*

Carbon Border Adjustment Mechanism, the EU is creating a long-lasting framework for sustainability.

Among the most pressing items for internal market regulation, it is important to mention the upcoming update of the EU Emissions Trading System, which should also feature low-carbon funding mechanisms for industry and power sector, and a revised version of the Sustainable Finance's Taxonomy. Those policies will be complemented by a Carbon Border Adjustment Mechanism, aimed at preserving the competitiveness of the European industries and operations, while externalising Europe's climate ambitions.

Next to these initiatives, the review of the Industrial Emissions Directive, expected by the end of 2021, is likely to increase minimum performance standards in terms of air pollution, taking into account the impact of hydrogen blending, and to review best available techniques in terms of efficiency.

Moreover, new policies aimed at ensuring stronger investor certainty, greater transparency, enhanced policy coherence and improved coordination across the EU are to be expected. These should deliver new indicators for the competitiveness and security of the energy system, diversification of supply, and interconnection capacity between EU countries. They should also be complemented by a new governance system based on national plans for competitive, secure, and sustainable energy based on a common EU approach.

Last, but not least, significant funding packages for the commercial demonstration of innovative low-carbon technologies are put in place. Programmes like the Innovation Fund, which will provide over 10 billion euros of support between 2020 and 2030, or the Just Transition Mechanism are fundamental in translating policy and legislative objectives into realities.

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 target of a carbon-neutral EU. However, a new legislative proposal will be presented by the European Commission by July 2021, adapting the policies to the goal of 55% reduction of GHG emissions in comparison to 1990 by 2030.

Integrating gas turbine technology into the energy systems

Gas turbines are a viable and secure option both economically and environmentally for power and heat generation. In future energy scenarios, renewable energy from wind and solar will play a much more significant role than in the past, which will bring further challenges due to their weather-dependent behaviour. As these resources provide fluctuating non-controllable power, it is crucial to have additional controllable electricity production technologies available which can compensate the variable electricity production and therefore maintain a balance between electricity production and consumption. Even if large electric storage systems become economically viable in the future, flexible controllable electric power generation technologies, like gas turbine power plants, will still be required to provide sufficient generation capacity necessary to maintain grid stability and security of supply for electricity.

The increasing share of intermittent RES is changing the pattern of electricity generation. The consideration of the entire gas turbine portfolio, from Micro Gas Turbines (MGT) to Large Gas Turbines (LGT), can support the integration of variable RES into the energy system by absorbing the fluctuations of climate-dependent power sources in the grid by load levelling and power generation on demand as well as by using any kind of synthetic gases (from power-to-X) applications. Gas turbine 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 more secure system. However, achieving their full potential requires new approaches to policy and regulation. Power-to-gas technologies could also provide significant amounts of renewable or low-carbon hydrogen and/or synthetic natural gas (SNG) making it necessary to adapt gas turbines for their future use. Gas turbines are therefore an important lever for fully climate neutral power and heat generation (*more details in chapter Extended Fuel Spectrum*).

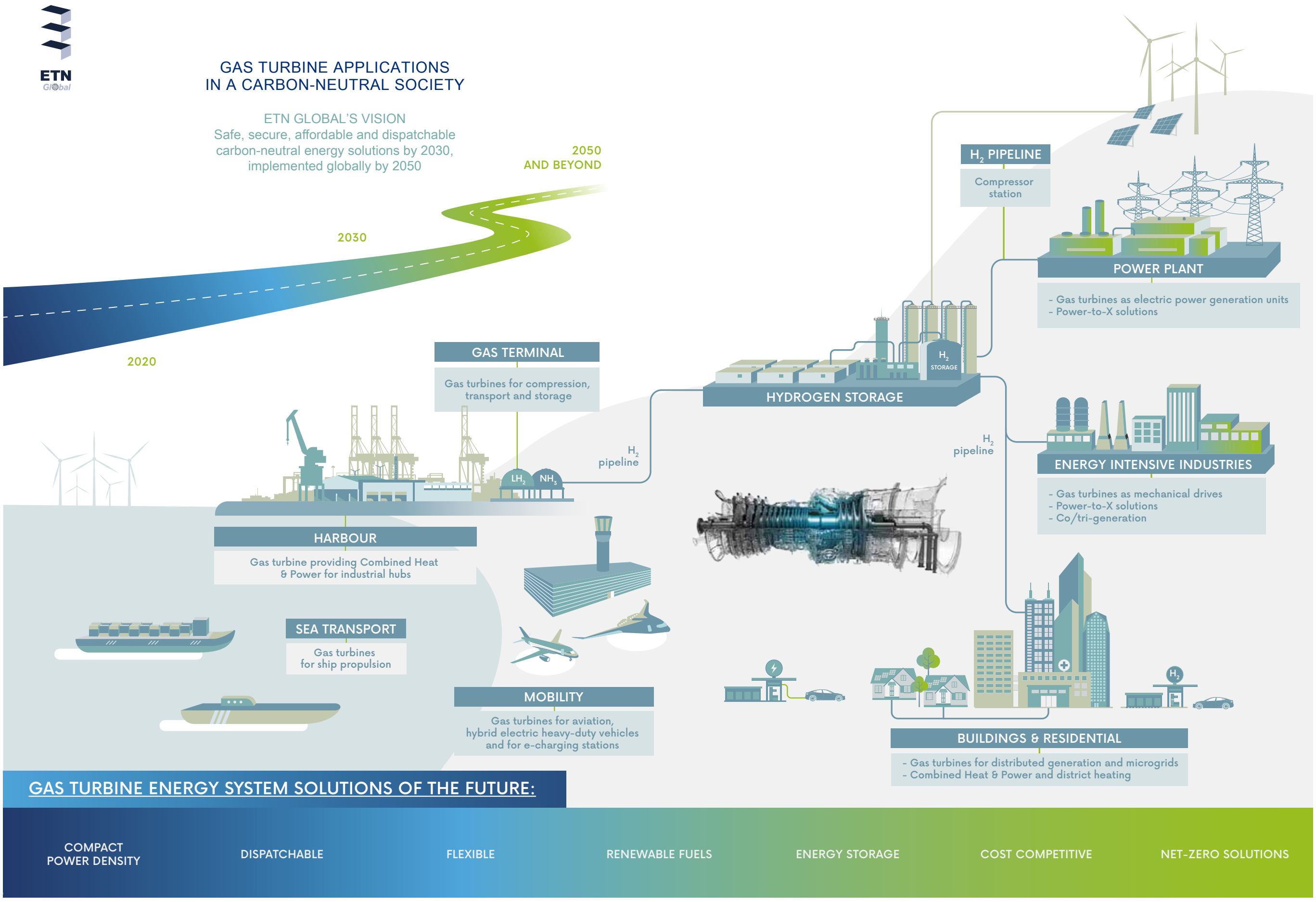


Figure 1: ETN vision of gas turbine integration into the energy systems

We are currently moving from a highly centralised to a more decentralized energy system relying on more distributed generation, energy storage, sector integration 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.

All features above 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

Future energy scenario forecasts see it dominated by Renewable Energy Sources (RES), among which the two main growth contributors will be solar and wind. Annual electricity generation growth over the past 3 years has been steady at around 12% for wind, and has ranged from 16 to 33% for solar PV[5]. Historical data puts wind production in 2019 at around 1400 TWh (on-shore and off-shore) while solar's was around 720 TWh. Projections shows that RES will become the largest energy source by 2025, supplying one third of the world electricity[6]. The inherent non-dispatchable nature of RES poses the question of ensuring grid stability; to answer that, back-up solutions are needed. For short periods of RES unavailability or shortage, large-scale energy storage is expected to be used. With increasing size, energy storage solutions become commercially not viable or, looking at some schemes like power-to-X, require an energy conversion which could be a "conventional" power plant. As such, these "conventional" power plants will cover a large portion of the backup needs for the next decades. Some of the contemporary power plants will see their role in the future reduced; nuclear and coal fuelled power plants are planned to be phased out in a number of countries. Consequently, open cycle gas turbines (GTs) or combined cycle power plants are considered the most suitable ones to provide the major part of flexible back-up in a near future scenario. The role change in the energy market is also going to force these power plants to change their operational flexibility in order to be commercially viable. Current designs and future ones will need to take into account this required shift from baseload to load cycling, adopting solution for existing (retrofits) and future power plants.

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:

Fast load changes

One of the key features power generation equipment will need to support to be fully integrated in the future energy market is the capability to react quickly to load changes as required by the grid. As counterpart to RES partial dispatchability, power plants based on GT-derived technology will be required to start up and shut down quickly (recently built combined cycle plants feature 15-30 minutes hot start-up, 60 minutes warm start-up), react to load changes (some case studies suggest up to 40-50 MW/minute) while minimising the impact on components life consumption and emissions. The latter can be tackled both looking at component level ("design to Life") and system level (hybridisation with a battery pack for fast start up, for example. See chapter on *Systems Integration and Energy Storage* for more details).

Extended operational envelopes

Along with the capability to adapt to load in a rapid manner, a successful integration in the future energy market will also be dependent on both efficiency and emissions across the operational envelope.

As traditional power plants will move in the future toward grid balancing, the number of hours they will operate at partial load is bound to increase; this will require, again, a system-level research effort to integrate the plants with features that will enable them to mitigate this aspect, either by using the energy produced in a different way or decrease the efficiency penalty at partial load conditions.

Integration of energy storage solutions in thermal power plants is a perfect fit to increase ramp capabilities and allow operation at nominal maximum and minimum loads while maintaining the possibility of providing ancillary services.

There are many different schemes that might be integrated; including compressed air energy storage, liquified air energy storage, batteries, power-to-X-to-power schemes. This integrated system will further improve a flexible plant operation in peaking mode, increase ramp rate/ frequency response and will minimise complete machine shutdown, therefore potentially reducing mechanical fatigue.

The hybridisation with batteries could provide another advantageous opportunity by replacing traditional black-start engines with electric motors.

[5] Source: IEA (2020), Global Energy Review 2020, IEA, Paris *https://www.iea.org/reports/global-energy-review-2020*
[6] Source: IEA (2020), Renewables 2020, Analysis and forecast to 2025, IEA, Paris *https://www.iea.org/reports/renewables-2020*

Emissions will be another element to take into account. The (extended) minimum environmental load (EMEL) will need to be further reduced as regulation is bound to become more stringent in the near future (for example, current EU Taxonomy is indicating a very challenging 100 gCO_2/kWh). Combustion technology will need to step in that direction, developing incremental or disruptive new technologies (pressurized flameless combustion, for example). Integration of storage systems will also be beneficial in reducing the EMEL both in peaking operations and part load ones.

Frequent start-up and shutdown at high start-up reliability

The modifications in the operating profiles of gas turbines towards more fast cycling operation will bring an increased risk of material and component fatigue. It will therefore increase the probability of severe harm, such as damage accumulation on hot gas path components, degradation of thermal barrier coatings, creep-fatigue of turbine buckets, cracking and degradation of combustor.

In order to prevent this increased risk of failure, further design developments are required for key components. In particular, improvements should address challenges in flow path optimisation, advanced material selection, and repair options.

Besides, operational considerations are required to facilitate the adaptation to the changes in operational requirements. Substantial reliability benefits are expected from the future optimisation of plant operation and control schemes for fast start-up, shutdown, and cyclic operation.

Additionally, the integration of heat storage could provide solutions for extended warm standby or hot standby.

Increase operational flexibility while reducing the costs (CAPEX and OPEX)

The continuously increasing share of renewables and the competition with gas engines further reduces the operating hours of the gas turbines. Gas turbines are needed to provide heat and power on demand and to provide grid services. To enable a reasonable return on investment, the capital expenditure (CAPEX) and operational expenditure (OPEX) have to be reduced while improving reliability, flexibility and lifetime.

R&D is also required to address the entire plant, including the bottoming cycle. On this regard, emerging contenders for the classical water-steam bottoming cycle are Organic Rankine Cycles (with a variety of different fluids) and CO_2 based cycles (either pure or with dopants, Rankine and Brayton) with different cycles configurations. As they are addressing potentially different temperature ranges, a combination of these could also be envisioned.

Computational tools

The capability to accurately model the behaviour of power plants down to the individual part level during operation is a key enabler to optimise asset operation including maintenance concepts, thereby leading to a more sustainable use of natural resources. This requires advanced, multi-disciplinary, multi-scale and fidelity computational tools - including high performance computing - that can also model unsteady conditions, such as during start-ups or power ramps. Real-time capability can be achieved by making use of reduced order models or machine-learning algorithms, which in turn requires both high-quality data (synthetic and from actual operation) as well as suitable methods and tools to process the data, e.g. in training the developed models. Due to the intrinsic uncertain nature of component durability that usually depends on a vast number of input variables such as material properties, actual manufactured component geometries as well as engine boundary conditions, the role of stochastic methods, such as probabilistic methods for component life and efficiency prediction, will also increase in the future in order to be able to accurately predict system reliability and performance.

Technologies for advanced control

An area of increasing interest for R&D is the use of advanced instrumentation and new sensor technologies to monitor and improve the control and operation of power plants (e.g. with higher time resolution for transients). This includes developments in the processing and visualisation of the large datasets produced by these sensor arrays, a field of Data Science known as Big Data (for more details, see chapters *Sensors & Instrumentation* and *Digitalisation*).

Further improvement potential could be realised by automatic tuning system, e.g. self-learning' or 'self-adapting' control systems based on advanced IT / artificial intelligence technol-

ogies. This is important for flexible fuel composition changes, relative to content share of hydrogen or other carbon-neutral fuel components.

Combustion of these sustainable, but also more challenging combustion dynamic fuels - e.g. 7 times higher flame speed for H_2 in gas turbine engines and higher likelihood of flashback events - would significantly benefit from improvements in combustion pressure and flame monitoring. Combustor improvements already have and will continue to take advantage of new manufacturing methods like additive manufacturing enabling a complex design that optimises fuel flow homogenisation. These complex designs will need new methods of flashback and other combustion dynamic detection that go beyond currently used thermocouples. Analysing combustion dynamics with high bandwidth and comparing it to advanced acoustic models in real time – such as edge computing – is important to protect engine health and for the turbomachinery performance.

Figure 2: Siemens Energy Hydrogen Power Plant

4. High Efficiency Power Generation

Gas turbines are set to play a pivotal role in the transition towards a grid dominated by renewable energies, providing the flexibility, reliability and security of supply that the users need. Last generation heavy duty gas turbines are able to achieve efficiencies in excess of 42.5% (ISO standard) in simple cycle configuration and above 62.5% in combined cycle mode, according to data reported by OEMs. This is a significant performance enhancement with respect to the current average efficiency of the combined cycle fleet worldwide, achieved by higher firing temperatures and enhanced performance of the constituent components. Nevertheless, in Europe, the number of new installations in recent years is very low and, therefore, the average efficiency of the fleet is much lower (~50%) than the aforecited values. In addition to this, the increasing share of renewables in the grid, and the associated oscillations in power demand, have caused a large reduction of the operating hours of combined cycle power plants. This means frequent operation in partial load conditions, which implies a further reduction of efficiency.

Nonetheless, the requirements for operational flexibility do not lessen the need to continuously strive for higher power generation efficiencies from gas turbines and combined cycle power plants. This technology will remain, for years to come, to be the most efficient technology to produce electric power from fossil fuels. Hence, regardless of the foreseen reduction of operating hours and the very high maturity of gas turbines, it is mandatory to carry out research to find new solutions or to improve the existing technology in order to enable further efficiency gains. Some focus areas of research are highlighted below.

Thermodynamic cycles

Most contemporary gas turbines run on simple, unrecuperated cycles with just a few engines making use of compressor intercooling, reheat (sequential combustion) or internal heat recovery through a recuperative heat exchanger. For this simple cycle, small efficiency gains occur for every new generation of gas turbines thanks to higher turbine inlet temperatures and enhanced component performance. Nevertheless, these incremental efficiency gains require increasing technical and economic efforts that are on the verge of proving uneconomical given inherent thermodynamic and material limitations. Based on this, some voices from the industry are already calling for other cycles such as the reheat Brayton cycle to be considered for future combined cycle gas turbines, enabling similar efficiencies without reaching to such higher operating temperatures. The implications on cycle performance at rated and off-design conditions, combustor operation, cooling flow management, turbine thermal management and, very importantly, operational flexibility must be explored further.

Gas path design

The gas path design of compressors and turbines in contemporary gas turbines has achieved unforeseen levels of refinement for the core isentropic flow (flow far from the annulus). Highly three-dimensional blades and vanes obtained through multi-objective topological optimisation are now commonly used, yielding unprecedented aerodynamic efficiencies. Further internal efficiency gains will be moderate, in particular in the compressor.

Still, there are some secondary flow features from which further efficiency gains can be attained. Turbine clearance control is one of these, with an estimated potential for a 0.25% combined cycle efficiency gain to be untapped through active clearance control systems. Today, active clearance control systems are available for new gas turbines and as upgrades to existing units; some of them rely on axial displacement of the rotor whereas others work radial-wise. Regardless of the particular method, both face the challenges of transient temperature distributions of engines subjected to load changes or, more frequently nowadays, frequent start/stops. Future systems able to further minimise tip-leakage flow at the compressor and, more importantly, the turbine whilst avoiding physical contact between rotating and stationary parts are needed.

Cooling system

About 20% of the compressor flow is bled off the gas path for cooling and sealing of the (high-pressure) hot section of the engine. The majority of this is used to cool the vanes and blades of the first turbine stage. Nevertheless, at the root of the gas path within the high-pressure section of the turbine, hot gas ingestion can potentially lead to mechanical failures and aerodynamic losses as well. Mechanical failure could be triggered when highly stressed components of the engine like the rotor disks are overheated by the hot gas ingested from the gas path. Rim seals are typically used along with internal cooling/sealing air bled from the compressor to prevent ingress flow into the cavity but this also reduces engine efficiency. Bleeding air from the compressor incurs thermodynamic losses due to the higher compression work whilst the interaction between ingress and sealing flows in the cavities and, more importantly, egress and core flow in the gas path generate further aerodynamic losses. These phenomena are also affected by transient operation in as much as this modifies the distributions of pressure and temperature of all the flows involved, as well as the tolerances of the sealing elements.

Improved designs of the secondary gas path, multi-objective topological optimisation and active control of cooling flows are therefore areas in need of further research, in order to enhance the performance of existing and new engines further.

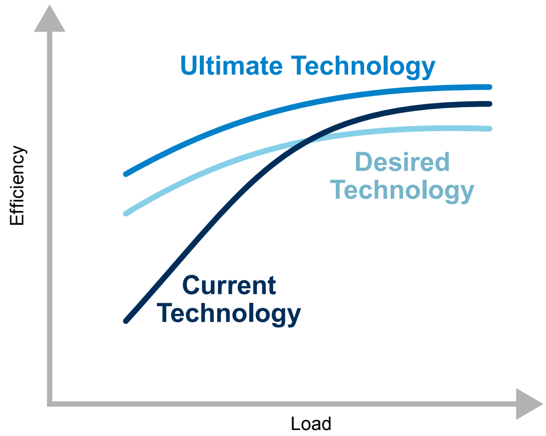


Figure 3: Efficiency versus load

Bottoming cycles

Contemporary heat recovery steam generators producing steam at three pressure levels and incorporating reheat are currently able to recover as much energy as it is technically feasible, bounded by the minimum stack temperature that would trigger condensation problems in the flue gas stream. From a second law perspective (i.e. exergy destruction), supercritical high-pressure evaporators could reduce this irreversibility but the cost associated would probably not be compensated for by the marginal performance enhancement (estimated at 0.5 combined cycle efficiency points for state-of-the-art technology).

Multiple-pressure heat recovery steam generators (HRSG) are most interesting at low exhaust temperatures of the gas turbine. As this temperature increases the performance gain when moving from single pressure to multiple pressure decreases and, at hot gas temperature (HRSG inlet) in the order of 700ºC, the difference between both layouts vanishes. With the increasing exhaust temperatures of gas turbines (now exceeding 650ºC) and the need to significantly reduce the capital cost of combined cycle power plants now operating with lower capacity factors, there might be an opportunity for single pressure, reheat bottoming cycles with either subcritical or supercritical live steam pressures and maybe duct firing for enhanced flexibility.

Additional remarks

High efficiency power generation in combined cycle power plants will rely, in the coming decades, on part-load efficiency rather than on rated efficiency. Therefore, enhancing part load performance and transient response (the ability to transition to higher loads as fast as possible in order to reduce the operating hours at lower loads) will become critical not only for operational flexibility and the benefit of the grid, but also for fuel economy. The same applies to the need to reduce the minimum environmental load of gas turbines, thereby reducing the number of starts and shutdowns and the associated consumption of fuel and useful life and larger emissions. This is all related to enabling higher overall efficiency of combined cycle and simple cycle gas turbines but is not covered in this chapter. Dedicated chapters in this report provide more information about each specific topic and the associated areas in need of research.

5. Extended Fuel Spectrum

Gaseous fuels will remain indispensable in the long term as a source of power generation and reserve energy even in decarbonised future energy systems. Gas turbines are important components for the conversion of (synthetic) methane and any other fuels into electricity. They offer highly efficient generation and help to stabilise and secure an energy system based on variable renewable energy sources. Today, gas turbines mainly use natural gas as fuel. However, by 2030 the gas turbine OEMs want to make all gas turbines much more fuel flexible, e.g. even capable of running on 100 percent hydrogen[7]. In this way the changeover from natural gas to alternative fuels like hydrogen can take place gradually, while maintaining full fuel flexibility. With such approach, gas turbines and combined cycle power plants represent a sustainable investment and the ideal instrument for entering a CO_2-neutral energy system, where gas turbines become the technology of choice for backing up intermittent renewables.

Modern gas turbines have to comply with extended economic and environmental requirements: operational flexibility, high availability and reliability, extended fuel flexibility and high efficiency at low emissions (with the long-term target to reach zero CO_2 emission, while maintaining low NO_X/CO) have all to be ensured using an extended range of gaseous and liquid fuels. Fuel gas mixtures (syngas, hydrogen) and diluents (CO_2, H_2O) come on 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. These add to the already large variety of natural gas quality specifications, including gas compositions with higher content of higher hydrocarbons or with higher content of inert species (referring to compositions with respectively more than 1%vol. of so-called C_2+, like ethane C_2H_6, propane C_3H_8 and butane C_4H_{10}, or more than 10%vol. of N_2, CO_2), which cover a wide range of Wobbe Index values (35 - 55 MJ/Nm³). Moreover, liquid fuels remain of interest for mobile applications (aero engines, marine engines), oil & gas industries, island/off-grid operation, and as back-up fuels.

Meanwhile, the spectrum of fuels is expanded by carbon-neutral products from biomass-to-liquid and power-to-X (PtX) production schemes – comprising hydrogen or a variety of hydrocarbon products/synthetic fuels. These can be added stepwise to fossil fuels until they completely replace fossil fuels as a primary energy source. This opens opportunities for carbon-neutral and finally carbon-free power generation and sector coupling.

The opportunity of a wide fuel spectrum capability of gas turbines is strongly coupled with operational challenges such as

[7] Cf. "The Gas Turbine Industry's Commitments to drive the transition to renewable-gas power generation", https://powertheeu.eu/

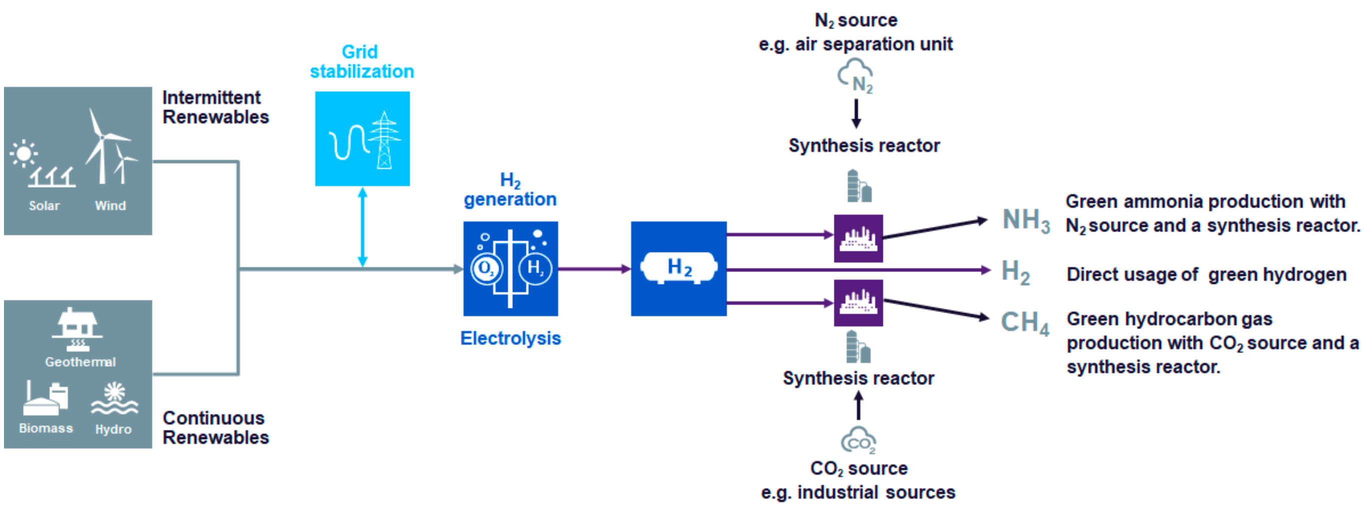


Figure 4: Simplified process flow diagram for power-to-gas applications

flame stability and emission compliance, and can be exacerbated if flexible fuel switch-over procedures are to be considered. Main R&D focus is currently led on flexible admixture of hydrogen to the fuel, even up to 100% and the emission compliant combustion of ammonia (NO_X in particular).

Typically, achieving ultra-high efficiency requires very narrow fuel specifications, whereas the use of fuels with fluctuating quality generally requires trade-offs translating into slightly lower performance and possibly a redesign of key components in order to reach a fuel-flexible gas turbine set-up.

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

Natural gas/hydrogen mixtures

With large capacities of wind & solar PV installed, the storage of intermittently produced surplus electricity is an important challenge. Storage via hydrogen production from water electrolysis and later re-electrification (power-to-gas-to-power) is one option being considered. This would require consumers to cope with an increasing H_2 content in natural gas especially in decentralised small gas grids or dedicated hydrogen grids. This approach also demands increasing hydrogen combustion capabilities of modern gas turbines (pure, premix or diffusion combustion with inert gas dilution), which involves addressing issues such as combustion performance and control (flame stability, flashback, combustor cooling, thermo-acoustics), NO_X emission behaviour, and operational safety. Safety in particular cannot be compromised, and further developments are required to address the risk of leakage, self-ignition, and material embrittlement.

In order to guarantee full operational flexibility, modern combustion system should ultimately be able to deal with the entire range of fuel changes: from 100% methane to 100% hydrogen for all operating points (from extended minimum environmental load to peaking operation, ramping and fast start-up). But high hydrogen concentrations (> 50%vol.) require significant changes to the fuel-air mixing and combustor design of gas turbine systems. First European projects are ongoing to develop and demonstrate the applicability at full scale/full pressure of potential low emission, reliable (safe ignition, stable flames) combustion technologies. For more details about the way towards hydrogen gas turbines please refer to the ETN report "*Hydrogen Gas Turbines*"

Low calorific gases

While the majority of gas turbines will run on natural gas and hydrogen, their fuel flexibility and robustness also allow the use of a large variety of low calorific gases. These gases become increasingly important, especially for decentralised applications as the fuel sources are distributed and transportation to a large central power plant would not be economically feasible.

Biomass-derived syngas – CO/H_2 mixtures from biomass or wood gasification – is considered CO_2-neutral and thus can 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, combustion performance is influenced and therefore requires addressing the issues of safe combustion performance (flame stability, flashback, combustor cooling, thermo-acoustics), as well as emission behaviour (NO_X, CO) and material degradation due to fuel contaminants (particulates, corrosive species like sulphur, chlorine, sodium).

Unconventional natural gas, such as shale gas or coalbed methane, is another gas fuel with high concentration of inert species, but without hydrogen. Such gas can show even wider composition variations than conventional natural gas natural gas and expands the gas quality range towards Wobbe Index values well below 35 MJ/Nm^3 due to its higher content of inert species (N_2, CO_2) which can also vary temporarily depending on the exploration conditions. For these gases, flame stabilisation and the operational range of the combustion system has to be improved.

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 mainly of methane and thus reduces any impacts due to inert species, but higher hydrocarbons (e.g. C_2H_6/ C_2H_4), although at low levels, can cause operability issues due to the reduced reactivity of the fuel. LPG consists of propane and butane in various ratios and exhibits strongly different physical and chemical properties compared to methane, heavily modifying the combustion characteristics. Flame stability, flame speed and ignition delay times can be sufficiently different as to require the re-design of key combustor components. Re-gasified LPG may be an attractive alternative to liquid fuels in locations where a natural gas supply is not available.

Alternative liquid fuels from biomass and power-to-liquid

Syngas derived from biomass gasification or power-to-gas processes can be used to produce liquid fuels such as hydro-processed esters and fatty acids (HEFA), alcohols, dimethyl ether (DME), or Fischer-Tropsch products. Other liquid fuels like pyrolysis oils can directly be formed in pyrolysis processes of various types of biomass. All these liquid fuels feature a high energy density in mass and volume but their significant range of physical properties (viscosity, lubricity), and chemical properties (combustion chemistry, flame speed) can vary widely and is not yet fully characterised. Further work is needed to assess their associated operational limits, such as lean blow-out and flashback, or NO_X, CO, SO_X emissions.

The mentioned biomass-based fuels will most likely have limited supply, therefore narrowing their use to decentralised applications – which would also limit the transportation needs and allow higher rates of net-CO_2 reductions. Additional differences have to be considered for these fuels, like S/N/Cl content or acidity and corrosivity. The composition of the fuel is affected by the type and quality of biomass and can potentially vary over time, therefore robust combustion systems are necessary to allow for a broad fuel spectrum.

Power-to-X fuels on the other hand can offer new possibilities as their physical and chemical properties can be tailormade for specific applications. The co-optimisation of fuel and combustor design potentially allows for lower emissions and higher combustion stability. PtX fuels have great potential to substitute a significant amount of fossil fuels in the future.

Non-carbon fuel (e.g. ammonia)

Ammonia's combustion characteristics strongly differs from those of conventional hydrocarbon and hydrogen fuels – such differences include significantly reduced fuel conversion rates. Ammonia is attractive for energy storage because it is carbon-free, and it can be liquefied and stored at moderate temperatures and pressures. Gas turbines can be used to convert the ammonia back into electrical power, and there are essentially two ways to so: direct usage of ammonia as fuel, or reconverting ammonia to nitrogen/hydrogen mixtures, via thermal cracking for example. The main drawbacks of using ammonia for combustion is the high production of NO_X due to the fuel-bound nitrogen contained within NH_3: this issue is severe if pure ammonia is burnt, and it still exists for the crack gases in case any residual ammonia is present. Special low-NO_X combustion processes need to be explored to minimise fuel bound nitrogen conversion. For direct usage as fuel, ammonia has demonstrated to have a very slow reaction and hence low flame speed, thus one option is to dope the fuel with a more reactive molecule such as hydrogen, which conveniently can be obtained from (partial) cracking of ammonia or from the reforming of natural gas.

Combustion of ammonia is a topic which is currently under investigation in the EU-funded project FLEXnCONFU, which will develop innovative, economical, viable and replicable power-to-X-to-power solutions, converting electricity into hydrogen or ammonia. A small-scale power-to-ammonia-to-power solution will be developed and coupled with a micro gas turbine properly modified to burn ammonia. Based on the results of this project, further investigations will be necessary to learn more about the combustion of ammonia in advanced combustion systems of gas turbines, including: combustion dynamics, burner and combustion system design, safety issues, fuel handling, emission, etc.

Special fuels with fuel pre-treatment

Economic reasons can push for the use of poor quality fuels for power generation. Despite the fact that fuel pre-treatment is often necessary to avoid problems in gas turbines, low-grade fuels such as heavy fuel oil, crude oil, sour gas can be cheap to provide and be sufficient for the intended use.

The use of low-grade liquid fuels such as crude oils in gas turbines is particularly difficult due to their content of sulphur, and alkali and heavy metal salts. These components cause severe hot gas path corrosion resulting in significant maintenance costs or efficiency losses. In cases where sour gas needs to be utilised in gas turbines, it is crucial to address the treatment of toxic and/or corrosive elements such as sulphur. Besides the aggressive properties of sulphur species, burning H_2S can produce SO_X emissions beyond acceptable levels.

The emission of harmful components and their combustion products are typically controlled by legislation to limit their environmental impact. A fuel pre-treatment that removes these undesired components is often the best choice as it promises significant maintenance costs reduction, power plant efficiency improvements, and a reduction of emissions, including the CO_2 footprint.

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 the new version of the Industrial Emission Directive (IED) of the EU, which is expected to be published in 2021, 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. Last but not least, the EU Taxonomy Regulation sets certain emission standards ("performance thresholds") which need to be met in order for companies, project promoters and users be able to access green financing (*more details in chapter Market Conditions & Policy Framework*). The EU Taxonomy is one of the most significant developments in sustainable finance and will have wide ranging implications for investors, OEMs and users working in the EU, and beyond.

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

Emission limits at part load and in dynamic operation schemes

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. Transient operation and fast load changes are expected to become more important due to the compensation of intermittent renewable energy sources. Thus, maintaining low emission values for NO_x (as well as for CO) down to very low part load and during transient load operation has become very important for gas turbine operators, and therefore a key selling argument for gas turbine products. Issues to be addressed are safe combustion performance (flame stability, thermo-acoustics) in combination with maintained low emission (NO_x, CO) characteristics over a wide load range (from below 50% up to 100% load). Excursions beyond accepted emissions limits will be less and less tolerated and need to be avoided in cyclic operation modes as much as possible.

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, i.e. with no additional flue gas treatment via selective catalytic reduction (SCR). Issues to be addressed are liquid fuel atomisation/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. "Trade-offs" between gas and particle emissions should be avoided due to the complexity of emission regulations and possible adverse health effects. As particulate emissions are typically very low, the challenge of measuring such low levels in a reliable way is not yet fully resolved. Feasible monitoring strategies will be essential to support the development of future evaluation standards and keep public acceptance.

Hydrogen and hydrogen-rich fuel gases / natural gas-hydrogen 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 and combustor systems in order to avoid this (*see more details in a recent review paper of the ETN Working Group on Hydrogen*). This issue is especially important for highly efficient gas turbines with high turbine inlet temperatures. Because high turbine inlet temperatures – and thus high flame temperatures – cannot be compromised for efficiency reasons, new combustion concepts focusing on short residence times or other innovative solutions (e.g. internal/external flue gas recirculation) are necessary to keep the emissions low. If dilution with steam or nitrogen (N_2) is not an option, issues regarding safe combustion performance (flame stability, flash-back, combustor cooling, thermo-acoustics) 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 localised 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 of fuel & air is imperfect or not applied at all. Volumetric heat release also provides more favourable conditions to avoid thermo-acoustic 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, highly flexible generation solutions are required 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 still little support and interest to develop such solutions (specifically for gas turbine-based processes) via public funding, but opportunities might be found in connection with programs for integrated energy systems.

Reducing CO_2 emissions from gas turbines can be achieved through improvements in efficiency, process hybridisation, the use of low-carbon fuels, or by the integration of CO_2 capture technologies. The first two points are addressed in other sections of this document, while the third is linked to challenges of fuel flexibility (more details in chapters *High Efficiency Power Generation*, *Systems Integration and Energy Storage*, and *Extended Fuel Spectrum*). The integration of CO_2 capture into renewable fuel-based power generation (e.g. biofuel) results in negative CO_2 emissions and might be an interesting option when considering emission trading as part of the business plan.

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 represent significant challenges. Among others, the following options should be further researched:

- Integration of 'conventional' post-combustion amine scrubbing, or competing liquid-based technologies, to minimise costs and energy penalties.
- 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. Other options should also be investigated, such as CO_2 separation membranes.
- Exhaust gas recycling including enhanced recycle options (e.g. using CO_2 separation membranes), to increase 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 operability, materials and component lives.

Two key elements are particularly important to the mentioned technologies. The first is linked to the energy efficiencies of the integrated gas turbine and the capture process that need to be optimised in order to minimise performance penalties, and the second relates to the combined optimisation of operational flexibility and capture technology performance which require further investigation. Transient operation and its impact on capture performance and their impact on control strategies is of interest especially as gas turbine power plants are seen as the most flexible solution to balance the grid and provide back-up power for the increasing share for fluctuating renewables.

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

With limited or no upgrading and gas cleaning to reduce overall plant complexity, biomass-derived gases are often less clean than their fossil-derived counterparts. This can lead to combustion and hot gas path challenges, which would connect to the required research aimed at improving gas turbine fuel flexibility.

Besides, further investigation is needed on the use of hydrogen in gas turbine, either in direct firing or in dilution. This hydrogen, pure or in blends (possibly even from natural gas distribution networks up to a certain level), can originate from multiple sources : reformed natural gas, H_2-rich syngas from gasification processes, water electrolysis from unused renewable electricity, or biomass-derived. To be considered low-carbon solutions, the first two options would require pre-combustion capture to be involved.

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 of such implementation include supercritical CO_2 power cycles where the exhaust gas CO_2 is recycled (e.g. the NetPower cycle), 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. 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.

In addition, the integration of gas turbines with the necessary O_2 production process is an area of research to optimise the larger system towards overall efficiency and flexibility. Integration with other processes such as green hydrogen production might be worth to be evaluated.

8. Advanced Cycles

The increasingly ambitious emission reduction targets of the European Commission for 2030 (*more details in chapter Market Conditions & Policy Framework*) along with the falling prices of renewable energy technologies set the need for more efficient power generation technologies. Incremental efficiency gains will not be enough to achieve the environmental targets; in addition, technologies delivering leaps in system efficiency are needed. With the rapid rise of renewables (in the European Union they account for about 70% of the newly installed power generation capacities in their 2030 scenario[8]), there is a need to provide backup power and grid stabilisation while increasing overall cycle efficiency and reducing CO_2 footprint.

Advanced cycles are one key element to comply with the increasing requirements, and different technologies provide opportunities both from a pure thermodynamic point of view and from a system integration perspective. Particular attention will need to be devoted to upgrade and conversion applicability considering that most of the current installed capacity, mainly composed of traditional power plants, will continue to serve in a 2030 energy landscape and beyond.

Most advanced cycles gas turbines (GTs) are interconnected to other systems and components, or even processes such as 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. Three aspects come to mind.

First, 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.

Second, 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 it is necessary to combine components with very different response characteristics in energy systems. Higher complexity and higher flexibility needs during startups and transients support this requirement.

Third, 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:

Supercritical CO_2 cycles

Supercritical steam turbine technology was originally demonstrated in the early 1960s and incorporated into the portfolio of major OEMs in the 1990s. Today, it has become the standard for new power plants, enabling live steam pressures and temperatures over 300 bar and 600ºC, and 5 percentage points higher efficiency than their subcritical counterpart. Now, the industry is targeting pressures and temperatures of 400 bar and 700ºC, with the ambition to get close to the 50% efficiency landmark.

Parallel to this technical effort, a new generation of closed cycles working at supercritical pressure and temperature make use of carbon dioxide as working fluid. These systems, usually grouped under the general term of supercritical carbon

[8] In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. European Commission, 2018.

dioxide (sCO_2) technology, work at similar peak pressures and temperatures to ultra-supercritical steam turbines but yielding increasingly better performance as turbine inlet temperature increases above 600ºC and beyond. From a technical standpoint, sCO_2 systems sit halfway from steam and gas turbines and enable smaller footprints than the former and higher efficiency and fuel flexibility than the latter, even enabling cost-effective carbon capture in natural gas applications. There is consensus between the academia and industry that efficiencies higher than 50% are well within the capabilities of the technology for turbine inlet temperatures in the order of 700ºC.

Supercritical CO_2 cycles are currently being explored theoretically and experimentally for applications as diverse as Gen IV nuclear reactors, concentrated solar power (CSP), pulverised coal, natural gas and waste heat recovery, with varying maturity in each of them. Commercial systems are currently available for waste heat recovery at the five to ten megawatt scale (TRL9) whilst the technology is in the precommercial phase (TRL7-8) for natural gas applications, both for small (1 MWe) and large applications (25 MWe). In In CSP applications, several projects are currently taking the technology to TRL6 through demonstration in relevant environments. Only in nuclear, there are no on-going large experimental projects except for some interesting tests at lab-scale (TRL4), given the usually longer timescales of the technology.

Numerous cross-cutting areas of research can be identified, which are applicable to the different applications cited. Compact, highly-efficient, cost-effective heat exchanger designs are needed to reduce the large share of heat exchanger costs and also to reduce the thermal inertia of the system, burdened by this bulky equipment. High temperature oxycombustion systems ensuring combusting stability for extended turndown capabilities are needed in systems operating on natural gas. Turbomachinery designs must be improved, not only for the aerothermal characteristics of the gas path but, most importantly, the secondary elements like bearings and seals whose design is challenged by the specific characteristics of this type of machinery (very high density and pressure gradients, high surface speeds and unit loading). System integration as a function of scale must also be better understood, insofar as this turns out critical to optimise the type of drive of compressors and pumps and the operation of the system in off-design conditions. Part-load operating strategies must also be developed, as they have a very strong impact on performance and flexibility whilst, at the same time, being very sensitive to output range. Just recently, different initiatives to identify additives that could be added to the working fluid are also being investigated in order to improve the performance of these cycles when operating in warm and hot environments; the initial results are promising but more research is needed to understand the thermal stability and long-term degradation of the resulting mixture, as well as the impact on the design and performance of turbomachinery and heat exchangers.

Pressure gain combustion

Historically, efficiency gains in gas turbines have been realised by demonstrating higher turbine inlet temperatures. Nevertheless, from a thermodynamic standpoint, heat addition at constant pressure (Brayton cycle in a gas turbine) yields lower thermal efficiency than heat addition at constant volume (Humphrey and Reynst-Gülen cycles). This is exploited by pressure gain combustion, which has the potential to achieve the same time-averaged combustor exit temperature as conventional Brayton cycles but at a higher pressure level. This leads to a lower compression ratio (across the compressor) and higher overall cycle thermodynamic efficiency for an identical turbine-entry temperature, whose limit is dictated by materials and cooling technology.

Theoretically, the potential simple cycle efficiency gain of pressure gain combustion over state-of-the-art gas turbines is estimated between ~5 (if the Humphrey cycle is used) and ~10 (if the more efficient Reynst-Gülen cycle is adopted) percentage points. This higher thermal efficiency is nevertheless not achievable due to the difficult realisation of constant volume heat addition. In practice, different technologies have been considered for the simultaneous pressure and temperature rise. Pulse detonation combustion (PDC) creates detonation waves at high frequency in the combustor, but this incurs inherent mechanical and acoustic problems compromising the efficiency and mechanical integrity of the downstream turbine. Rotating detonation combustion (RDC) tackles this problem by having the detonation waves travelling continuously around an annular channel in an oblique direction, thereby suppressing the need to continuously create detonation waves as in the PDC case. Whilst this alleviates the inlet conditions to the turbine, it still brings non-negligible fluctuations of the flow field at the outlet from the combustor: exit Mach numbers ranging between 0.9-1.7, pressure fluctuations above 75%, temperature fluctuations of 50%, and flow angle fluctuations of 60; these are unprecedented turbine inlet boundary conditions challenging the industrialisation of PGC. Finally, wave rotors rely on a cellular drum rotating inside a housing with inlet and outlet ducts in between. Inside the channels of the drum dynamic waves travel further compressing the compressor delivery air upstream of the combustor, and expanding combustion gases to a lower pressure and temperature downstream of the combustion process.

Amongst the different technologies, PDC is acknowledged to hold the largest potential for efficiency gains but, given the challenging design and operating conditions, RDC seems to offer a better compromise between enhanced performance and feasibility. However, the extremely unsteady chemical energy conversion rate and elevated exit velocities present severe challenges using conventional industrial turbines: transition from deflagration to detonation combustion mode (in particular, PDC); fuel injection and air mixing; combustor integration with the upstream axial compressor; combustor integration with the downstream turbine; control the pressure gain, and pressure losses, wave directionality (RDC); NO_x and CO emission control; unsteady heat transfer and cooling flow management. These are all areas as in need of further research at the fundamental and applied levels, calling for solutions to be developed.

Wet cycles

The characteristic feature of wet cycles is the extraordinarily high water content of the working fluid. This water is aimed globally at increasing the specific power output of the cycle while, depending on the selected humidification technology, gains in net power output, electric efficiency, and environmental performance (reduced NO_x emissions) can also be attained.

Three categories of wet cycles are usually identified depending on the humidification technology used; i.e., where in the cycle and in which form (liquid or steam) water is injected. The first category involves cycles where liquid water is injected for full evaporation downstream of the injection point; examples of this concept are Water Atomizing inlet air Cooling (WAC), wet compression (TOPHAT), Regenerative EVAPoration cycle (REVAP) of water injection for power increased behind compressor or in the combustion chamber). Another option is to inject steam into the combustor, as it is done in the Cheng Cycle. Finally, cycles such as the standard, advanced or cascaded Humid Air Turbine cycles (HAT/AHAT/CHAT) inject liquid water in a saturation tower with a water recovery loop. This latter option is proven to have the highest potential for cycle performance improvement.

The state of development of these different options is dissimilar, yielding varying TRLs between TRL2 and TRL9: TRL 2 for CHAT, TOPHAT, REVAP technologies; TRL4 and TRL7 for the HAT and AHAT layouts respectively; TRL9 for the Cheng cycle. Therefore, further R&D is needed on different components and also at system level. First and foremost, around the combustor in order to ensure the stable operation close to stoichiometric conditions and with high water content. For turbomachinery, the impact on off-design behaviour (reduction of surge margin) caused by the mass imbalance between turbine and compressor must also be better understood; finally, downstream of the injection station, the ability of materials and coatings to withstand the wet conditions and deal with the modified thermal properties of the working fluid must be verified, and it is very likely that new materials resistant to this environment will be needed. Research of materials is also aimed at removing/alleviating the need for demineralised water, thus simplifying system integration, easing operation and largely reducing costs.

(Cascaded) Organic Rankine cycles

Rankine cycles using water/steam are not suitable when the energy source available is at low temperature or when the power output of the generator is small. This is due to the reduced thermal efficiency of the cycle and the more challenging design of turbomachinery, in particular the turbine. When these conditions are met, using an organic compound in lieu of water becomes an interesting alternative to enhance thermal performance and to enable simpler component designs. This is thanks to the characteristics of organic compounds (higher molar mass and molecular complexity than steam), which yield larger volumetric flow rates and lower enthalpy drops than steam. Organic Rankine Cycles (ORCs) are therefore typically used or proposed for small/medium-scale applications, from few kWe up to tens of MWe, and applications where the energy source is at moderate to low temperatures, up to 300°C.

ORCs for stationary power generation are currently commercial and their maturity is firmly set to TRL9. In the last two decades, the optimisation of both the cycle and the components has allowed to achieve significant performance improvements and energy cost reduction. Nevertheless, there are several areas where further research is needed to both enhance system and component performance, and improve cost effectiveness. New cycle concepts enabling higher thermal efficiency are needed through the exploitation of features such as supercritical vapour generation, cascade layouts or cycles including wet expansion, tailored to the singularities of certain applications like waste heat recovery. A lot of research is also going on in relation to working fluids: development and testing of new working fluid compositions pushing the current thermal stability limits, including mixtures -seemingly holding a large potential to enable higher thermal efficiencies-; development of turbomachinery design methods accounting for the non-ideal behaviour of organic working fluids; deeper understanding of nonclassical gas dynamics expected from BZT vapours, including experimental demonstration of the numerical predictions obtained from computational fluid dynamics.

Application-wise, the interest of the heavy-duty automotive industry to use mini-ORC systems for waste heat recovery also opens up new research opportunities: development of new system and component concepts able to cope with the inherently variable operating conditions, in particular efficient volumetric expanders able to manage larger expansion ratios and system dynamics.


© Solar Turbines

9. Systems Integration and Energy Storage

An area that needs R&D attention is the integration of different energy conversion schemes, also looking at energy storage. Indeed, the integration of gas turbine technology in other systems can offer innovative solutions to improve overall performance.

While the focus of research would be how to seamlessly operate the resulting system, several technical challenges need to be tackled also at single technology level.

Energy storage

One of the integration schemes looks at a primary energy conversion system coupled with an energy storage system, which is used to level production and to support peak demands.

Some of the technologies that have been around for some years are based on compressing or liquifying a fluid and storing it for later reconversion (Compressed Air Energy Storage CAES or Liquified Air Energy Storage LAES, for example). Two commercial level pilot plants are in the works and expected to be in operation soon. The challenges here lie mostly in the areas of fluid storage and heat/cold storage.

Thermal storage itself could be used in a number of different power cycles; both for heat and cold storage. Heat storage faces challenges regarding the maximum temperature it can be conveniently stored at. The current state of the art of high temperature storage includes phase change (molten salts) technology; while different salt combinations (binary and ternary) are being looked at to go above 520°C and other media are being investigated (like the promising silicon-based technology or calcium/carbon looping salts based technology). Stability, maintenance requirements and material compatibility are all issues to be addressed in this field.

Heat storage also offers the possibility of creating solar hybrid gas turbines, offering opportunities to design unique cycles taking advantage of a decarbonised external high temperature heat source (e.g., concentrated solar power). The main challenges here reside in designing such unique cycles, requiring separating the combustion system of the gas turbine unit to allow thermal input from the heat storage, as well as managing the balance between solar and chemical energy in transient operations.

Thermal storage can be supplemented by heat pumps systems for upgrade of waste streams. Current state of the art is limited to lower temperatures (upgrade from 40-80°C to 180°C) and the ambition would be to push the upper temperature above 550°C. Supercritical carbon dioxide cycles make excellent candidates for this application.

Cold storage technologies could be used both as a power augmentation tool for gas turbines and to increase the efficiency of some other storage schemes (i.e. storing cold from liquified air in a LAES to reduce energetic cost of cryogenic liquefaction in the process itself). One promising technology here is absorption refrigeration.

Power-to-X technologies converting excess electrical energy into chemical energy provide promising schemes for their integration in power generation. The product can be either a carbon free chemical (hydrogen, ammonia) or some other fuel (methanol, methane). In both cases, converting back this chemical energy into the power plant requires further research in the areas of combustion (*see chapter Extended Fuel Spectrum*), materials (*see chapter Materials*) as well as efficient and scaled up conversion to chemical. Safety aspects are also to be investigated and taken into account.

Batteries can also be used to complement power generation; they are relatively widespread and there are several commercial offerings on the market.

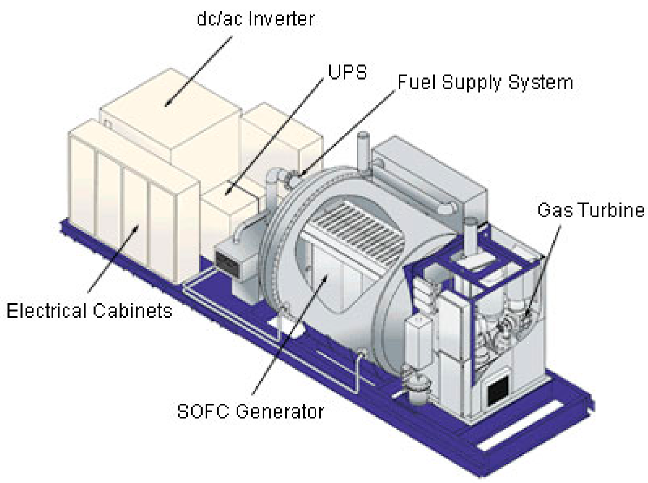
Overall, all energy storage schemes are limited in terms of turndown and/or operational flexibility. In addition to having a limited installed capacity, some suffer from a limited variability in terms of rate of storing or releasing energy.

System integration

Another integration scheme looks at combining different energy conversion systems.

The most promising one is using fuel cells in different parts of a "conventional" energy conversion plant. Even though scale is still limiting overall power output, fuel cells can be used to work as a surrogate "combustion" system for gas turbine derived technology, as they work (especially the Solid Oxide Fuel Cells) at high temperature. There are already some higher TRL examples in the micro turbine world. One other big challenge is transient management as the two conversion systems have very different reaction times, gas turbine being the most reactive.

Another integration of fuel cells could be at the exhaust of gas turbines / fossil plants to capture CO_2 in the flue gases. In this case, the main challenges to overcome are the required high temperature flue gas (lower for molten carbonate fuel cells but still considerably above current gas turbine exhaust temperature), and the presence of excess oxygen (problematic for solid oxide fuel cells).



© Siemens Energy

Figure 5: Scheme of hybrid system with a Solid Oxide Fuel Cell generator and a downstream Micro Gas Turbine

10. Decentralisation

While the increasing share of renewable energy has transformed the energy market from a centralised to a more decentralised 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 stabilise the power grid on the low and mid voltage level while providing relief to the high voltage network. Decentral biomass, other renewable energy sources, and renewable energy carriers like hydrogen 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 decentralised units are connected to a “virtual power plant”, the reliability of the power supply can be further increased.

While gas turbines in the range from 1 MW to 20 MW are well established in industrial applications (industrial gas turbines), micro gas turbine (MGT) technology has the potential to provide effective distributed power generation systems to smaller consumers, thanks to their fuel flexibility (e.g. biofuel stock) and compatibility with solar power generation. Micro gas turbines cover the range from 1 kW to 1 MW and are typically based on the classical recuperated Brayton cycle, which differentiates them from larger gas turbines. Industrial gas turbines are part of the portfolio of the large gas turbine manufacturers. The R&D needs are similar to that of the larger gas turbines and are covered by the R&D needs described in the other sections of this report. 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. 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 turbine 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 optimised for performance are used by some manufacturers, 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.

The research challenges are related to three categories. The first is mainly related to the general cycle efficiency resulting from the system configuration for given component characteristics which affect both design and off-design performance in addition to fuel flexibility. The second is related to the individual components’ performances which also affect cycle efficiency and fuel-flexibility, but also system operation, cost, reliability, operability, and lifetime. The third has to do with the developments necessary to cope with the potential new applications introduced by the opportunities related to smart grids, e-mobility, green/blue hydrogen etc.

Consequently, the following areas should be the focus of more intense research and innovation efforts.

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. In decentralised applications the focus is even more on fuel flexibility and robustness of the combustion process, as there is a broad range of different fuels from local sources including biofuels and stranded/associated gas, which are of variable composition and quality (i.e., calorific value, impurities and potentially corrosive). Due to the preheating of the compressed air prior to combustion, the MGT combustor inlet conditions differ significantly compared to larger gas turbines (inlet temperatures of up to 800°C, at pressures around 5 bar. MILD combustion is also emerging as important development area for MGTs as it benefits from high inlet temperatures.

Heat exchangers

Used as recuperators or as the main heating unit in externally fired MGTs, heat exchangers for high inlet temperatures 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 foil-air 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 high development costs. The successful application of magnetic bearings and foil-air bearings in some single systems demonstrate the principal applicability for MGTs, but further research is needed to reduce the costs and complexity of such bearing systems.

Figure 6: Active magnet bearings (AMB) significantly reduce the maintenance needs of MGTs

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 gearboxes. The result is a very compact, high efficiency system. High-speed permanent magnet 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 stabilised 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 optimise an inverter suitable for grid interconnection with the capability to support synchronous motor drives and variable solar radiation input.

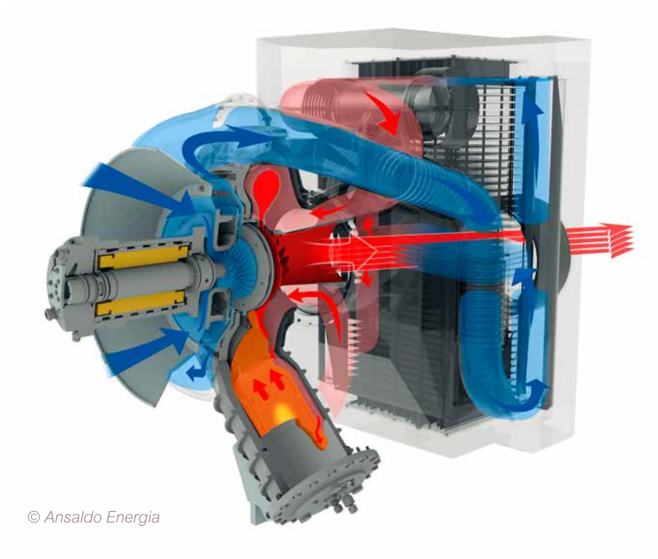


Figure 7: AE-T100 Micro Turbine power train running principles – Compressed air enters the recuperator and is preheated by the hot exhaust gas (blue); fuel is added to the preheated air and is burned in the combustion chamber (red)

Figure 8: AE-T100 Micro Turbine

11. Materials

In the recent years, the raised international ambitions towards emissions reduction, efficiency gains and renewables integration have caused changes in operational requirements for gas turbine technology. In existing gas turbine power plants, the modified supply and demand patterns have focused attention on specific materials issues resulting from plant cycling, the use of low-carbon fuels including biofuels and hydrogen, and factors affecting components lives and costs. With the changeover from natural gas to alternative fuels in the near future[9], the impact of those fuels on components' materials should be evaluated (*See also the chapter Extended Fuel Spectrum*).

On modern gas turbines, the ever-increasing requirements for more efficient turbines and reduced CO_2 emissions have led to new materials, fabrication and process technologies, and surface modification techniques. However, advances in materials and process technology, such as directionally solidified and single-crystal alloys, are currently operating near their design limits. Turbine inlet temperatures and the temperature capabilities of high temperature alloys have increased by approximately 500°C and 220°C, respectively, over the last four decades. Today, turbine blades and vanes are subjected to operating gas temperatures of 1600°C and future targets aim at 1800°C. Unique materials, processes and manufacturing skill sets will be needed to reach the targeted performance and reliability levels.

Besides, the developments and implementation of advanced thermodynamical cycles need to address material challenges resulting from the changes in the chemical composition of the working fluid and the operating conditions (*see also the chapter Advanced Cycles*). The materials and coatings of the gas turbine have to be tested regarding their ability to withstand those changes, and innovative solutions will need to be developed in most severe cases.

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 varied 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. In some cases, additional flexibility has been enabled by additive manufacturing technologies, which require adapting to a new mindset but can provide greater flexibility and shorter lead time to respond to the rapid changes in requirements from the gas turbine sector.

The following topics further describe specific materials issues worth considering for further R&D activity:

Improved alloys, coatings and ceramics

There is a steady need for improved alloys and coatings, including: bond-coats, corrosion resistant coatings, thermal barrier coatings (TBCs), etc. These materials improvements have to provide support to meet the increased efficiency and/or reliability requirements associated with changes in operating patterns, higher operating temperature, introduction of alternative fuels, or a combination of these factors.

The design aspect of components for use in the hot gas paths of modern gas turbines of all sizes and for all applications involves the production of parts with complex shapes to meet performance needs. In order to meet the required mechanical and chemical properties, the complete systems of compatible materials that can be manufactured to produce the desired shapes need to be considered while minimising the use of critical raw materials. Finally, inspection and repair also need to be taken into account in this process. As a result, understanding the behaviour of these materials systems, comprising base alloys, bond-coats/corrosion resistant coatings and TBCs during component manufacture and also 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

[9] Gas turbine OEMs have committed to the development of gas turbines capable of running on 100% hydrogen by 2030. Cf. "The Gas Turbine Industry's Commitments to drive the transition to renewable-gas power generation", *https://powertheeu.eu/*

CO_2 and steam. In particular, materials research should address the high temperature and pressure operation in harsh conditions, including components corrosion resistance, compact turbomachinery design including cooling, compact and highly-efficient heat exchanger – all of whom would need to prove affordable as well. Significant changes in design of the required turbomachinery combined with the significant changes in the operating environments will mean that translating existing materials knowledge will require qualification.

Additional developments are required in advanced materials systems, such as Ceramic Matrix Composites (CMC) with environmental barrier coatings (EBCs) or advanced high temperature metallic systems using exotic alloys, such as Niobium based alloys or other refractory based alloys. This will be important in cases where operating temperatures surpass the temperature limits of superalloys, but also for micro gas turbines where uncooled parts are required.

Thermal barrier coatings (TBCs)

In recent years, the added value of legacy solutions involving 7-8 wt% YSZ coatings with MCrAlY bond coats has decreased and new TBC systems are needed. Phase instability at critical temperatures results in thermal expansion issues leading to coating failures in service. To prevent this either multilayer advanced TBC systems with unique chemistries are being designed with more stable top coats (Cubic/ Pyrochlore) or unique duel layer systems.

Further research should focus at improving the durability of TBCs, in particular towards spallation. TBC spallation reduces component life and increases costs through increased need for blades and vanes refurbishment. Premature spalling is mostly observed in cases where additional thermal cycles were needed to meet the cyclic demand in flexible plant operation, or when operating with sulfur-containing gases. 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.

General coating applications are expected to benefit from improved closed loop control of process and material properties as well as through sensors and modelling. Improvements have already been achieved through developments in plasma, combustion and high velocity oxy-fuel (HVOF) guns. Arc stability improvements in plasma guns, such as cascading arc gun (SinPlexPro technology) allow for more stable plasma flame plumes over time resulting in more uniform and consistent microstructures. Other new gun technologies have also allowed greater spray distance flexibility, which is important for complex geometries and the need for diverse microstructures, such as dense segmented TBC for combustor components. These new technologies in plasma guns along with sensors and diagnostics have greatly improved coating reliability in recent years.

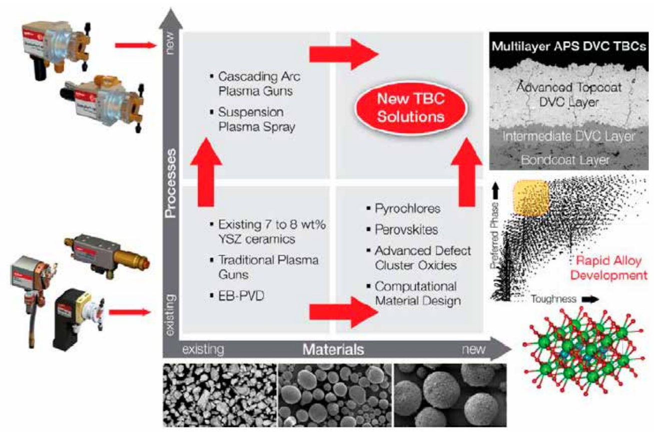


Figure 9: The increasing demand on thermal barrier coating performance and reliability require solutions that are beyond conventional

Hot corrosion behaviour

Hot corrosion of blades and vanes, arising from the use of sulfur-containing gas in offshore operations or biofuels in distributed power applications, is a major cause of damage, and service failures. Hot corrosion 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 adequately treated through filtration or other means and reach the gas turbine's hot gas path. The resulting formation of deposits and gaseous operating environments can lead to very aggressive forms of 'hot' corrosion which can rapidly lead to failures.

The successful elimination of damage mechanisms must be tackled through a combination of approaches to ensure that the aggressive combinations of contaminants do not reach the gas path and by 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) allows the production of components with alternative materials compositions and with geometries which are impossible to produce using conventional manufacturing, through a layer-by-layer material addition process. This process requires a different design approach, opening up new 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.

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

There is an on-going 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 avoid problems. Relating ex-service component microstructures to monitoring/inspection data, and its application in predicting the remnant life of the component remains an important area of research (see also chapters *Condition Monitoring and Lifting* and *Sensors & Instrumentation*).

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 will 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 lifecycle may lead to alternative strategies which have potential to reduce operating costs. Promising approaches include the introduction of energy storage in the system to reduce thermal cycling (*see also chapter Systems Integration and Energy Storage*).

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 Substances of Very High Concern (SVHC, substances that are considered carcinogenic or pose a health risk) along with some 26 other base materials or alloying additions found in 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 hexavalent chrome release is an area of concern.

Hydrogen capability and impacts

To enable decarbonisation through fuel switching, research is required into impact and suitability of gas turbine components and systems to transition to higher levels of hydrogen in the fuel, up to 100% hydrogen capability. Risks include combustion effects and by-products together with embrittlement of components exposed to high levels of hydrogen. This must include existing as well as new designs and materials.

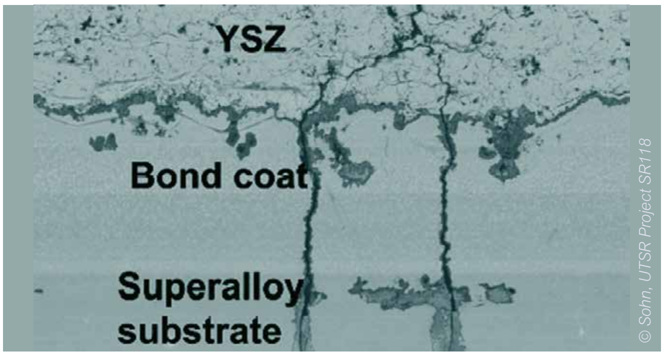


Figure 10: Scanning electron micrograph of cross-section of coated blade material expose in a combusted syngas environment showing deposit penetration

Figure 11: Siemens V64.3 gas turbine blade being used for coating demonstration trials in the EC FP7 H_2-IGCC Project

12. Advanced Repair

Gas turbine maintenance costs have substantially decreased over the years through the implementation of advanced component repair and coating processes resulting in improved product yield and extended product life. Improvements in productivity, continuous improvement and market competitiveness have also driven suppliers to implement lean manufacturing principles and continuously seek improved automated technology to reduce overall product cost but also overall through life cost leading to extended time between overhauls.

This drive to reduce the through life cost has further been supported by a better understanding within the part design process. Advancements in computer technology utilising computational fluid dynamics and finite element analysis has enabled OEMs and service providers to link operational degradation to design practices allowing modifications to be implemented, leading to improved operational performance especially on the legacy engines.

This concept has also been adopted in the design of the later more advanced turbines enabling turbine inlet temperatures, pressures and efficiencies to be increased without losing part and turbine integrity. This has not just been achieved through improved cooling, materials and design practices but a significant advancement has been adopted in the manufacturing processes and protection systems.

Although many of the repair technologies have been around for decades and are tried and tested there are numerous new techniques and processes being utilised which continue to drive the industry forward leading to a more sustainable future.

The following sections discuss the state of the repair industry and look at some of the new technologies being considered.

Inspection

Advanced repairs start with an extended inspection. 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, however where this is not possible small sections of the material can be removed in reparable areas which provide a reasonable understanding of the material condition. This is not wholly ideal but prevents the scrapping of a whole turbine component with the costs that this entails. These sections are normally evaluated both under optical and scanning electron microscopy to evaluate the level of material degradation and to determine whether rejuvenation is possible through extended thermal cycles. In many of the single crystal alloys heat treatment to recover material properties is limited due to any level of significant degradation can only be recovered through high temperature solution treatments and exposing these advanced materials to this level of temperature can lead to recrystallisation of the material and loss of mechanical properties.

Traditionally many of the dimensional inspections were carried out utilising hard gauges or coordinate measuring machine (CMM) analysis but in later years techniques such as white light, blue light and computed tomography (CT) scanning have been adopted to create 3D models of parts which can be directly compared to the initial designs leading to an improved understanding of the levels of distortion the part has experienced.

Residual wall thickness measurements of cooled parts are also essential to understand part residual life. This analysis is completed once the old protective coating has been removed and the parent material exposed. Techniques used to measure this feature include eddy current, ultrasound or Hall effect thickness gauges. The stripping process itself today is predominantly a combination of a mechanical and chemical processes. Grit blasting is utilised to remove the engine debris and oxide layer which then allows the complex acid solutions to attack the surface of the coating reducing the oxide structure and weakening the lattice allowing removal by further mechanical processes. It is recognised that exposing parts to corrosive chemicals is not ideal and holds a degree of risk and a whole host of processes have been identified as potential improvements. Although many of these work exceedingly well, the commercial model is not ideal as they rely on one part being stripped at one time whereas chemical removal as previously described is a batch process and therefore more cost effective. Much more work is ongoing in this area to find a process that is both technically capable and commercially viable.

Once the parts are free of coating and have been dimensionally checked the level of surface degradation and cracking must be evaluated. Visual inspection, fluorescent penetrant inspection and X-ray are all processes utilised today to categorise surface indications although there are multiple other techniques including magnetic particle inspection (MPI), ultrasonics, acoustic emission, borescopes, etc. that are widely used dependent on the component type and specification.

Repair

Once the parts have been inspected and the level of degradation understood the next phase of the repair process can begin. Normally there are two key processes adopted to repair cracks and distortion. Welding and high temperature vacuum brazing are utilised widely today both for legacy and advanced engine components. Tungsten inert gas (TIG) welding has formed the backbone of crack repair for decades and it continues to be that way today. Filler materials, equipment and techniques however have significantly improved, meaning that alloys once deemed unweldable are readily welded under protective systems. Automation of this process utilising laser technology, electron beam technology or standard robots also has driven improvements and led to extending reparable limits through the ability to weld at much lower temperatures and stresses.

For many fine cracks and surface restoration vacuum brazing is the process of choice. This process relies on the parts being metallurgically clean and this is achieved through either vacuum cleaning, hydrogen cleaning or hydrogen fluoride ion cleaning. These processes, and especially the latter two, reduce the surface oxides retained deep within cracks leading to a slightly depleted but clean surface layer. Powder metallurgy is then used to create filler materials which are chemically aligned to the specific superalloy and which when heat treated and diffused create a repaired crack with similar mechanical properties to the parent material.

Recreation of distorted features often requires complex re-machining activities to occur to ensure parts can be re-installed back into the engine meeting blueprint dimensions. Typically milling (3 and 5 axis), grinding, electro-discharge machining and electro-chemical machining are all technologies utilised in today repair facilities. Adaptive machining using high technology vision systems is now also becoming a machining system of choice leading to improved accuracy and repeatability within the machining process.

The use of additive manufacturing in both the new manufacture of components and in the repair of existing degraded parts is also set to have a significant impact on the way the industry processes parts going forward. This will lead to further gains in sustainability and product life.

Coating

Application of coatings is extremely essential for the lifetime of advanced parts to be achieved. Coating systems continue to be evolved based on field experience. With an increase in inlet temperatures and the requirement to extend time between overhauls, thermal barrier coatings have been increasingly used on the critical parts within the engine. These are applied over an oxidation and/or hot corrosion bond coating which provides the correct environmental protection for the particular application. There are significant research and development activities ongoing to further optimise coating chemistry. Coatings have become more complex in their chemistry over the years and their application techniques and continue to develop aligning with the everchanging need of the industry and environment and operational demands.

13. 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, heat, steam, 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 of paramount importance to the user communities because it impacts their day-to-day results and, eventually, yearly earnings. All areas of RAM would benefit from further developments in the concept of maintenance optimisation, based on the interaction between fault detection algorithms and risk-based maintenance tools.

A constant effort from Universities, Equipment Manufacturers, Services Providers and OEMs is necessary to improve gas turbine RAM. The following technologies and developments should be considered and advanced through active R&D:

Reliability

Gas turbine operation relies on tools, such as sensors, data evaluation algorithms, and procedures to detect faults and evaluate the remaining useful life of components. Beyond the expected improvements in accuracy, further developments are needed to take advantage of the advance in the digitalisation of power plants, and make these tools easier to operate and directly usable by an operator or pool of operators.

Reliability of the gas turbine will also be improved with more robust instrumentation having longer service life and reduced requirements for redundancy, but also better capability to sustain operation in severe environments, for example in the hot gas path.

See also the chapters *Digitalisation*, *Sensors & Instrumentation*, and *Condition Monitoring and Lifing*.

Availability

Improvements in the availability of a gas turbine unit will be driven by developments allowing longer service intervals, thanks to limited shut-downs or increased time between overhaul (TBO).

Key development should look at improving the capability of the gas turbine 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). Materials improvements should also play a role, leading to advances in slippery, advanced nano coating on compressor airfoils, which would reduce fouling and thus the need for operational interruptions, such as shut-down for a compressor wash. Besides, filtration system addressing industrial conditions like hydrocarbon vapours or soot would improve air intake filter performances and enable longer service time between maintenance at high efficiency.

Besides, more developed availability forecasts taking into account the degradation process of components would require further digital developments with machine learning and artificial intelligence applied to operational data and plant models. Operators would benefit from such improvements to better plan for required shut-downs.

Further progress could be delivered by auto-run calibration for low emission systems, or systems and algorithm eliminating rotor lock-in.

See also the chapters *Digitalisation*, *Sensors & Instrumentation*, and *Materials*.

Maintenance

Major maintenance requirements of end-users are linked to extending the scope of reparable components, while lowering the cost and time for repairs and reducing their overall environmental impact. Innovative developments should target the adoption of new component design approaches allowing 100% of components being reparable and reusable.

Modelling and algorithms for predictive analysis (e.g., thermal engine performances, sub-system performances) require further improvement to provide the complete set of benefits that operators expect from the developments in condition moni-

toring and remaining useful life evaluation. The integration of different digital tools available provide opportunities enabling the adoption of condition-based maintenance. Complementary to this approach, further model improvements are needed in investigate risk-based maintenance, which takes into account the probability and the economic consequences of the potential failure modes. Combining all these should also provide opportunities for engine sub-system life extension depending on operating conditions, and better projections for advanced optimisation in spare part management.

Another approach may come from the development of maintenance standards delivering benefits across the sector thanks to a large scale of adoption for the developed practices. Besides, technology and methodology transfer from other industries considered to be best in class (nuclear, aviation, etc.) can provide large benefits to the gas turbine sector.

The Covid-19 pandemic and forced changes in transport patterns has also accelerated the need for remote assistance implementation. While it may not become common practice everywhere in the long term, several activities have benefited from the faster response or cost reduction opportunities. This change in has spotlighted the already existing need for improvements for online transfer of data from remote locations and communication with centralised experts.

See also the chapters *Advanced Repair*, *Condition Monitoring and Lifing*, and *Digitalisation*

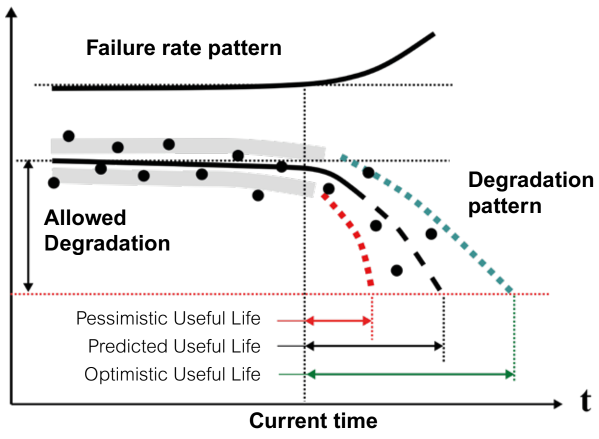


Figure 12: Degradation and prognostic model

14. 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 digitalisation 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 often refers to a digital replica of a corresponding physical system. It represents numerically the detailed elements of the physical system, as well as its dynamic behaviour, operation, and degradation throughout its life cycle. This field 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, design criteria, artificial intelligence, 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. Further effort is required to develop and evaluate the technologies for data storage, data cleansing, quality control, data transfer via internet, data receiving, data security, and information extraction and processing.

Cyber security

Developments in the cyber security domain should be considered for 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, further effort should be allocated to 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. Additionally, digitalisation allows non time series data to be collected and compared to operational data, for example maintenance and inspection records which may be useful in predictive maintenance strategies.

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 his field should review the connectivity opportunities that digitalisation/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. Innovative digital solutions should be further investigated to support end-users, and additional benefits may be revealed in the process.

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. Continuous developments in this domain require regular reviews, opening the door to innovative business solutions.

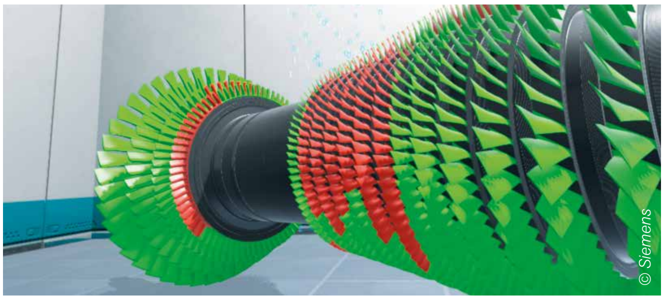


Figure 13: In a virtual reality representation of a gas turbine, complex sensor data is translated into colors to make the meaning of information in this case temperature differences easy to understand

15. Sensors & Instrumentation

Sensors play a fundamental role in the control of industrial machineries and processes. Gas turbines, with their concentration of technology, require sensors that are highly accurate, fast responding and temperature resistant. 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.

Sensors data form the basis of machinery diagnostics and performance monitoring. Anomaly detection and fault diagnostics algorithms, either based on machine learning or on subject matter experts' knowledge, must count on reliable data to be able to provide accurate predictions.

The optimisation of the operation, allowed by the availability of a greater number of accurate measurements, reduces fuel consumption and consequent CO_2 emissions while bringing economic benefits. The incoming transition to carbon-free fuels will require specific sensors to guarantee safe and reliable operation of the plants.

Sensors and instrumentation developments should focus on the following areas:

Instrumentation for operation and maintenance optimisation

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.

With the continuous reduction of NO_X emission limits, combustion stability remains a critical issue for gas turbines. Further developments are required in the field of ultra-high temperature dynamic pressure sensors, based on piezoelectric or optical probes, to allow for more precise measurements, and potential control of pressure fluctuations inside the combustion chamber. Downstream, more accurate emission sensing techniques such as Fourirer-transform infrared (FTIR) spectrometry spectrometry create opportunities for the on-line analysis of exhaust gas composition.

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 and maintenance intervals.

Power plants cycling results in additional accumulation of fatigue and creep damage in thick components, such as 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 gas turbine and steam turbine 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.

Instrumentation for inspection

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.

Sensors and instrumentation for gas turbine 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.

Wireless sensor networks

The advent of low-power processors, intelligent wireless networks, 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. They require low installation cost due to the absence of wiring, and low maintenance cost – often limited to changing the battery. This also provides high flexibility to the operators to relocate devices or 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.

Figure 14: Piezoelectric Pressure Transducer

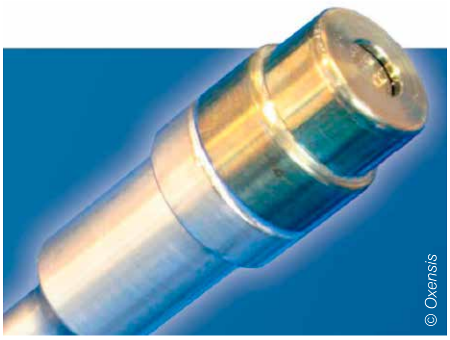


Figure 15: Optical Dynamic Pressure Transducer

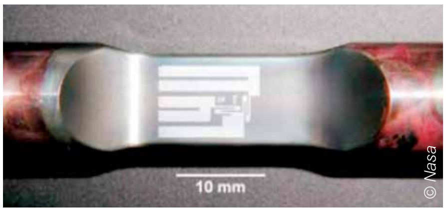


Figure 16: PdCr thin-film strain gauge on a turbine engine alloy test specimen

16. 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 also affect 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 information from condition 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 detailed resource planning and identification of required spare parts. When it comes to 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 or 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 mean 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.

Suggestions of specific topics for research and development activities are developed below.

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. Further research 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 level, 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 consequent 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 a small scale combined heat and power (CHP) as a base for further developments.

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. Further research should target the 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.

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. Therefore, further focus should be put 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 initiative could also be used to refine the determination of consumed & remaining lifetime of the plant and/or components. A suggested target would be 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 on the gradient of the change.

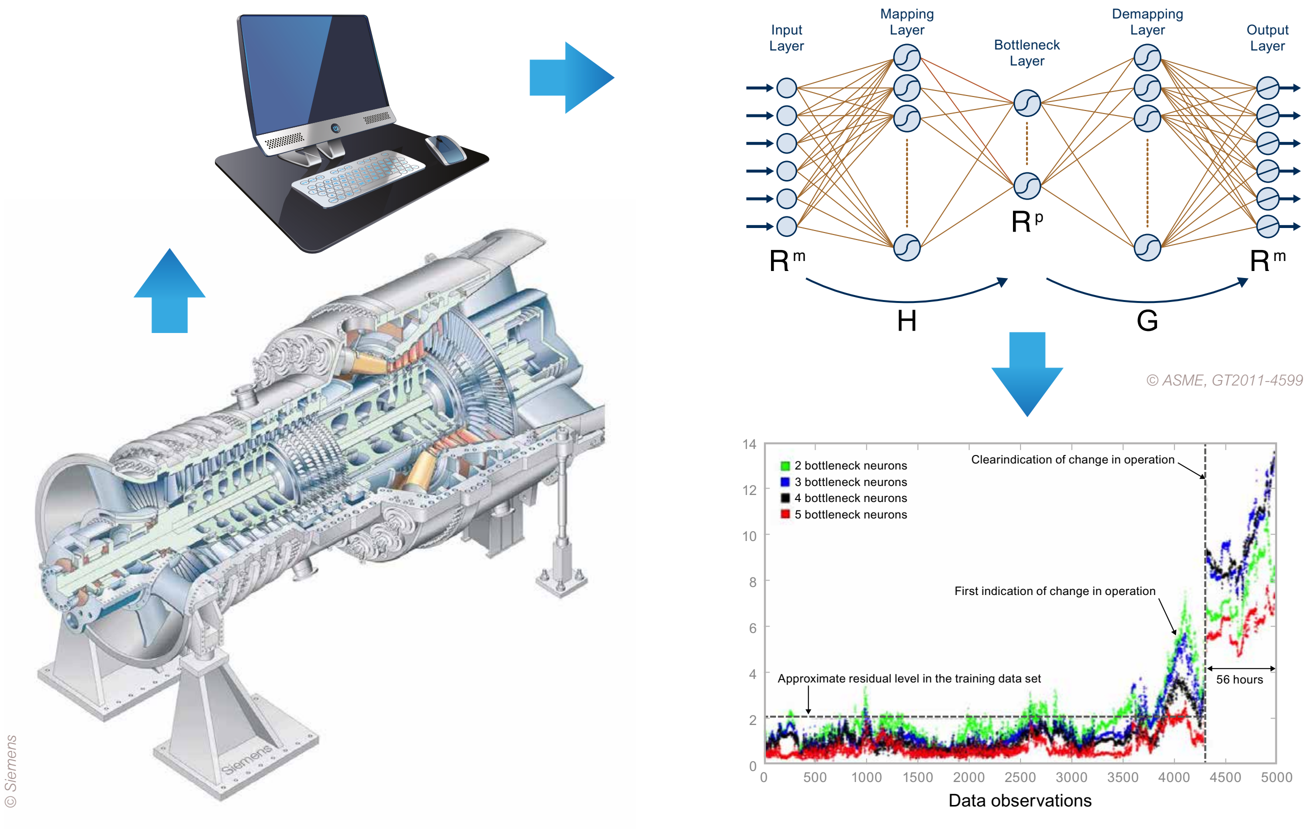


Figure 17: Collecting data and using a neural network for condition monitoring and early detection of upcoming faults

17. ETN Support Schemes: Projects and Working Groups

ETN facilitates and assists in the development process of any project initiatives that are brought to the ETN platform by our members. The ETN Project Board acts as a consultative forum, providing independent guidance, strategic advice and information to any collaboration initiative. A wide range of goals can be pursued, such as an increased level of knowledge, general dissemination of information, development of tools, or demonstration/proof of concept.

Research and innovation projects

Research and innovation projects play an important role in progressing towards ETN's overall vision and are incentivised as an innovative and cost-efficient way to accelerate the required developments. Collaboration can vary 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
- Demonstration projects

Ongoing projects

CO2OLHEAT (2021-2025)

Supercritical CO_2 power cycles demonstration in Operational environment Locally valorising industrial Waste Heat

The main objective of CO2OLHEAT is to unlock the potential of unused industrial waste heat and transform it into power. The development of innovative and cutting-edge supercritical CO_2 (sCO_2) technologies will be used to design and demonstrate in a real industrial environment the EU-first-of-its-kind sCO_2 plant. *www.co2olheat-h2020.eu*

ROBINSON (2020-2024)

Smart integration of local energy sources and innovative storage for flexible, secure and cost-efficient energy supply on industrialized islands

ROBINSON aims to help decarbonise islands through a smart modular energy management system (EMS), as well as innovative storage and energy technologies. The EMS will ensure an efficient and smart integration of all distributed energy resources, coupling locally available energy sources, electrical and thermal networks. ROBINSON's integrated system will ensure a reliable, cost-efficient and resilient energy supply contributing to the decarbonisation of European islands by helping to decrease CO_2 emissions. *www.robinson-h2020.eu*

FLEXnCONFU (2020-2024)

Flexibilize combined cycle power plant through power-to-X solutions using non-conventional fuels

The FLEXnCONFU project aims to develop and demonstrate innovative, economically viable and replicable power-to-X-to-power solutions. FLEXnCONFU combines all available options for the effective and flexible use of surplus power, from renewable energies to levelling the power plant load by converting electricity into hydrogen or ammonia, prior to converting it back to power. This will enable the design and operation of an integrated power plant layout that can untap additional combined-cycle flexibility. *www.flexnconfu.eu*

NEXTOWER (2017-2021)

Advanced materials solutions for next generation high efficiency concentrated solar power tower systems

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 (2017-2021)

Performance Untapped Modulation for Power and Heat via Energy Accumulation Technologies

The aim of the PUMP-HEAT project is to increase the flexibility of the combined-cycle power plants and the operation of gas turbines. The innovative concept is based on the coupling of combined-cycle power plants with a fast-cycling highly efficient heat pump equipped with thermal energy storage.
www.pumpheat.eu

Completed projects

OMSoP (2013-2017)

Optimised Microturbine Solar Power System

The objective of the OMSoP project was to provide and demonstrate technical solutions for the use of state-of-the-art CSP system coupled to micro gas turbines to produce electricity. The system was designed with a modular approach, capable of producing electricity up to 30kW per unit for domestic and small commercial applications.
www.etn.global/research-innovation/projects/omsop

Thermal Barrier Coatings (2012-2015)

This project focused on performing an in-depth literature survey into thermal barrier coatings and provided, based upon operator's feedback, an overview of TBC related topics of interest to them.
www.etn.global/research-innovation/projects/#thermal-barrier-coating

H_2-IGCC (2009-2014)

Low Emission Gas Turbine Technology for Hydrogen-Rich Syngas

The H_2-IGCC project has advanced the 'technology-readiness' of all aspects when burning hydrogen-rich syngas in gas turbines, including the development of combustion processes, materials, turbomachinery and the optimisation of the whole plant. Several results of the project can also be used for spin-off applications, especially when it comes to the results of the more basic research in combustion, materials, turbomachinery, systems analysis and techno-economical evaluation.
www.etn.global/research-innovation/projects/h2-igcc

Working Groups

ETN Working Groups are created in technical areas of high importance to our members, where it will be strategically important to progress on collaboration initiatives in a focused way. The Working Groups connect the key stakeholders and experts in the gas turbine community to exchange experiences and explore new initiatives and project ideas of common interest. Further details on the Working Groups mentioned in this section may be found on the *ETN website*.

Air Filtration

The objective of this Working Group 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 gas turbine users to have a single point of reference for state-of-the-art filtration technology and to address air filtration issues through activities of common interest.

Hydrogen

The aim of the Hydrogen Working Group is to share technical knowledge and experiences to progress towards the overall objective of safe and flexible low-carbon solutions for 0 to 100 vol.% of hydrogen blends and other sustainable fuels, such as ammonia. Through research collaboration and sharing of best practises, from an operational and maintenance perspective, the aim is to accelerate the development and implementation of economically viable solutions, for retrofit as well as for new and advanced technologies and solutions, in line with the user community's needs.

Supercritical CO_2

ETN's new Supercritical CO_2 Working Group, launched in 2020, aims to develop, enable and optimise the use of supercritical CO_2 power cycles by highlighting potential use, applications and benefits; paving the way for funding opportunities; addressing operational issues/effects on components; exploring market opportunities; assessing and addressing operational safety aspects; fostering the use of sCO_2 as working fluid for power generation; and creating a database of European open test beds.

Additive Manufacturing

The objective of ETN's Additive Manufacturing Working Group is to strengthen the cooperation between stakeholders of the turbomachinery value chain on additive manufacturing (AM) topics. Members of this Working Group benefit from cooperating on AM practices and exchanging knowledge and experiences on the added value that AM could generate, such as short delivery time, efficiency increase by optimised design and delivery of obsolete or "urgent" parts to shorten maintenance outages and overhauls.

Exhaust Systems

ETN's Exhaust Systems Working Group issued a standard on gas turbine exhaust systems in 2015. In March 2020, the International Organization for Standardization published a new standard *"ISO 21905:2020 Gas turbine exhaust systems with or without waste heat recovery"*, based on the work carried out by the ETN Exhaust Systems Working Group.

Decentralised Energy Systems

The goal of the Decentralised Energy Systems Working Group is to bring together stakeholders of the value chain for decentralised energy solutions involving micro and small gas turbines, with the objective to accelerate the development of cost-efficient integrated technology solutions in line with the market needs. The Decentralised Energy Systems Working Group aims to explore market opportunities and solutions, initiate cooperation projects to reduce cost and increase the technology readiness level of individual components, the gas turbine system and its integration into decentralised and multi-vector energy systems.

EU Strategic Energy Technology Plan

In 2007, European Union launched a research and development strategy targeting the energy sector, the Strategic Energy Technology (SET) Plan, which was updated in September 2015 and integrated to be part of the five pillars of the EU's Energy Union, aiming at achieving the 2050 energy and climate targets: energy market, security of supply, energy efficiency, greater inclusion of renewables and research & innovation. Representatives of ETN have actively contributed to several SET Plan actions carried out within this framework.

ETN is involved in the following SET Plan Actions and European Technology and Innovation Platforms:

- SET Plan Action 5 – New Materials and Technologies for Buildings
- SET Plan Action 6 – Energy Efficiency in Industry
- SET Plan Action 9 – Carbon Capture Utilisation and Storage
- European Technology and Innovation Platform Smart Networks for Energy Transition (ETIP SNET)
- European Technology and Innovation Platform on Renewable Heating and Cooling (RHC-ETIP)
- European Technology and Innovation Platform - Zero Emissions Platform (ETIP ZEP)

Technical Committees

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

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

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 a student thesis.

Best practice guidelines

Open issues about tasks which are performed repetitively, and by many 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 that aim to broaden their customer basis and are willing to promote their business by showcasing their 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. 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.

Other ETN publications

ETN publishes reports and publications on a regular basis, covering topics addressed in our Working Groups and projects. All reports are available on ETN's *website*.

For any submission of project idea or questions about ETN activities, please contact the ETN office: ***info@etn.global***

ETN a.i.s.b.l.
Chaussée de Charleroi 146-148/20
1060 Brussels, Belgium
Tel: +32 (0)2 646 15 77
info@etn.global
www.etn.global