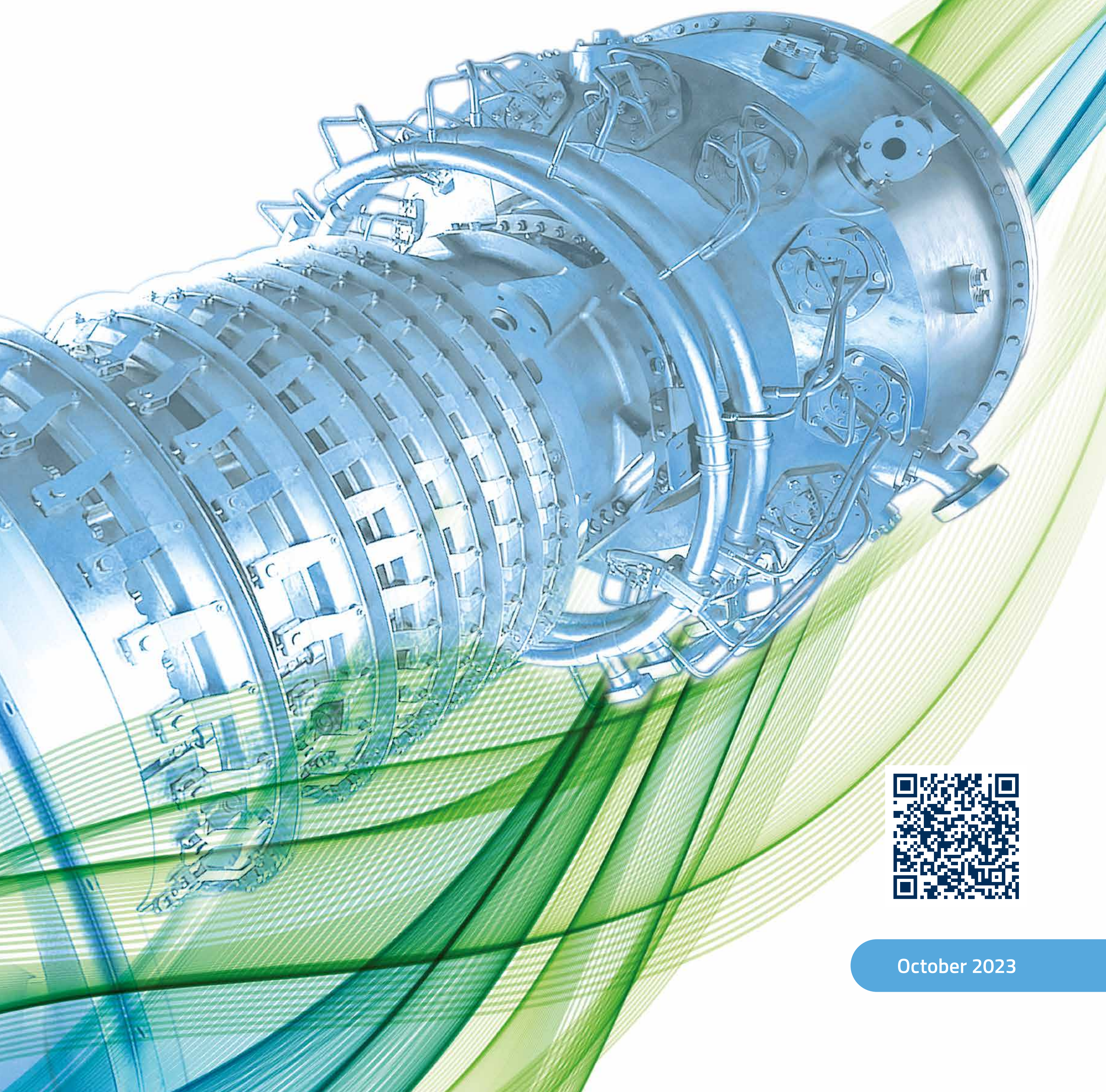
ETN R&D RECOMMENDATION REPORT

2023 EDITION



October 2023

ETN Global is a non-profit membership association that, through cooperative efforts and by undertaking collaborative activities and projects, encourages and facilitates knowledge sharing and cooperation among its members. It aims to accelerate research, development, and demonstration of safe, secure, affordable, and dispatchable carbon-neutral energy solutions within the next decade.

Table of Contents

List of Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Networks
AM	Additive Manufacturing
BZT	Bethe-Zel'dovich-Thompson vapours
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenses
CEMS	Continuous Emissions Monitoring Systems
CCGT	Combined Cycle Gas Turbine
CCPP	Combined Cycle Power Plant
CCS	Carbon Capture and Storage
CCUS	Carbon Capture and Storage
CH_3OH	Methanol
CHP	Combined Heat and Power
CMM	Coordinate Measuring Machines
COP26	Conference of the Parties 26
CPSC	Constant Pressure Sequential Combustion
CSP	Concentrated Solar Power
CV	Computer Vision
DLE	Dry-Low Emission
DME	Dimethyl Ether
EB-PVD	Electron Beam Physical Vapour Deposition
EGA	Exhaust Gas Aftertreatment
EGR	Exhaust Gas Recirculation
EMEL	Extended Minimum Environmental Load
EMS	Energy Management System
ETIP SNET	European Technology and Innovation Platform for Smart Networks for Energy Transition
EU ETS	EU Emissions Trading System
FTIR	Fourier Transform Infrared Spectroscopy
GDPR	General Data Protection Regulation
GT	Gas Turbine
HEFA	Hydro-Processed Esters and Fatty Acids
HRSG	Heat Recovery Steam Generator
IED	Industrial Emission Directive
IIoT	Industrial Internet of Things
IRA	Inflation Reduction Act
LCOE	Levelized Cost of Energy

LCP	Large Combustion Plants
LGT	Large Gas Turbines
LNG	Liquefied Natural Gas
LPBF	Laser Powder Bed Fusion
LPG	Liquefied Petroleum Gas
MGT	Micro Gas Turbines
MILD Combustion	Moderate or Intense Low-Oxygen Dilution Combustion
ML	Machine Learning
N_2	Nitrogen
NH_3	Ammonia
NDC	National Determined Contributions
NDE	Non-destructive evaluation
NZIA	Net-Zero Industry Act
ODS	Oxide Dispersion-Strengthened Alloy
OEM	Original Equipment Manufacturers
OPEX	Operating Expenses
ORC	Organic Rankine Cycles
PDC	Pulse Detonation Combustion
PDE	Pulse Detonation Engines
PM	Permanent Magnet
PtX	Power-to-X
PV	Photovoltaic
RAM	Reliability, Availability and Maintenance
RDC	Rotating Detonation Combustion
RDE	Rotating Detonation Engines
RES	Renewable Energy Sources
RUL	Remaining Useful Life
SAF	Sustainable Aviation Fuels
SCO_2	Supercritical Carbon Dioxide
SCR	Selective Catalytic Reduction
SNG	Synthetic Natural Gas
SVHC	Substances of Very High Concern
TBC	Thermal Barrier Coating
TBO	Time Between Overhaul
TIT	Turbine Inlet Temperatures
TRL	Technology Readiness Levels
UHG	Unburned Hydrocarbons

1. Introduction

In the Ten-Year Development Plan (TYNDP 2022), the European electricity and gas TSO foresee a gas turbine capacity of 150 GW in 2050 [1]. 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.* To achieve this vision, continuous research and innovation in the gas turbine sector are vital to ensure the enduring significance of turbomachinery technologies in the energy transition era and beyond. This includes the deployment of carbon-neutral energy services and products. Following an analysis of the role and impact of gas turbine-based solutions in the future, the ETN Board assigned to ETN's Project Board the task to update the previous Research & Development (R&D) Recommendation Report, initially published in 2021 and accessible on the ETN website. The purpose of this report is to provide fresh insights and recommendations for R&D topics aligned with user community needs, energy policy targets, and the transformative potential of gas turbine-based solutions.

The report lists topics in technical areas relevant to gas turbine systems used in Power Generation, Oil & Gas, and Industry sector; the business segments in which ETN members are active. It considers topics related to the integration of turbomachinery into new energy systems, 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 (including demonstration of new technologies), 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 brought to its attention. As such, it provides a sounding board for these ideas and initiatives that have originated from the entire ETN member community. 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 provides technical and strategic advice to the ETN community and leads ETN's Working Groups, which cover the most crucial areas of future gas turbine technology development [2].

The Project Board 2022-2024 consists of the following members who have all contributed to 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

Olaf Brekke

Equinor, Norway
Technical areas:
Gas turbines and auxiliary systems; Gas turbine performance, operation, and condition monitoring; Turbomachinery in the Oil & Gas industry; Low carbon power generation for Oil & Gas production

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)

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

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

Stefano Sigali

Enel, Italy
Technical areas:
Digitalisation and Industry 4.0 in power generation; Diagnostics and prognostics; Gas turbine combustion; Materials and life consumption

Olaf Bernstrauch

Siemens Energy, Germany
Technical areas:
Turbomachinery package development (GT, ST, Gen, Aux); Storage technologies and plant integration; Hybrid plants; (Waste) Heat recovery (sCO_2, ORC, HTHP, …); Co-generation CHP

Enrico Bianchi

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

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

Tom Kavanagh

Uniper, United Kingdom
Technical areas:
Generation technologies R&D; Asset risk management; Electrical engineering; Power plant operations and maintenance

Chris Dagnall

DNV, United Kingdom
Technical areas:
Gas turbine performance and emissions; Compressor performance; Condition monitoring and vibration

Siavash Pahlavanyali

RINA Tech UK, United Kingdom
Technical areas:
Gas turbine/steam turbine life assessment and extension, advanced repair, and remanufacturing; turbine alloy and coating; Root cause analysis (RCA) Operational risk analysis

Valuable contributions on relevant topics such as sensors and instrumentation, condition monitoring and lifing, and decarbonisation were also provided by the following ETN Members:

Yiguang Li

Cranfield University, United Kingdom
Technical areas:
Gas turbine performance; Gas turbine gas path condition monitoring; Gas turbine life consumption analysis; Gas turbine combined cycle performance; Application of CFD to gas turbines.

Ian Macafee

Oxsensis, United Kingdom
Technical areas:
Sensors and instrumentation; Manufacturing

Mohammad Mansouri

University of Stavanger, Norway
Technical areas:
Energy system integration; Process modelling, simulation and performance analysis; Energy efficiency improvements in industrial processes

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 from now to 2050, the associated political, economic and societal transformations are ongoing.

The following key trends can be identified: decarbonisation, decentralisation, digitalisation, system integration and sector coupling. Security and diversity of energy supply, 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 made available on a widespread basis, transforming energy systems to make them smarter, more reliable, more interconnected across sectors, safer and, above all, more efficient.

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

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

While the share of RES will continue growing around the world, gas-fired power generation is foreseen to maintain its strategic function [3]. Currently the largest gas-consuming sector worldwide, gas turbine-based generation provides a reliable 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, predictable, and dispatchable power during doldrums when wind and sun energy are scarce and consumption is high, thus securing supply and grid stability with high ramp rates.

In addition, the market for heat will become highly attractive for investments as wind and solar photovoltaic (PV) energy do not produce waste heat for industrial processes or district heating. Highly efficient and flexible gas turbine power plants currently provide a dispatchable alternative to more carbon-intensive fossil fuels and supply necessary heat for industrial processes or urban areas achieving energy efficiencies 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. This becomes particularly relevant during the major energy system transition, as coal- or nuclear-based generation is displaced in line with national strategies. Several countries are currently undergoing such changes. For example, Germany is phasing out its nuclear and coal fleets in 2023 and 2038, respectively. Belgium is closing its nuclear power plants by 2025. Poland faces the challenge of replacing ~80% share of coal in its electricity mix. And the United Kingdom (UK) will phaseout coal in 2024 whilst building new nuclear power plants.

In addition, affordable retrofit solutions are progressively developed and made available to improve the efficiency of existing gas turbine plants 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 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 alternative fuels, 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 clean hydrogen blending in pipeline natural gas to meet the continuously increasing demand of hydrogen in the power sector. This journey has already started with hydrogen blending in industrial gas turbines, which due to their small size require lower – and already available – volumes of hydrogen. The hydrogen journey is further supported by OEMs' commitment to the development of 100% hydrogen gas turbines by 2030 [4]. This requires R&D for turbine technologies, combustion systems, leak detection, safety systems, hydrogen storage and infrastructure readiness.

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 also benefit from the transition towards the hydrogen economy. With advances in combustion systems, gas turbines will be able to operate with any blend of hydrogen in natural gas up to 100% hydrogen and therefore contribute to 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 efforts and policies worldwide for the transition to a low-carbon energy system. The 196 countries that signed the agreement submit their National Determined Contributions (NDCs) and many of these were revised for COP26 held in 2021. For example, prior to COP26, the UK committed to reducing economy-wide greenhouse gas emissions by at least 68% by 2030, compared to 1990 levels. Germany's latest NDCs commit to 65% national emissions reduction below 1990 levels by 2030, an interim target of 88% below 1990 levels by 2040 and climate neutrality by 2045, five years earlier than its previous 2050 net zero date. The necessity of setting more ambitious targets becomes clear based on the 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. While many studies conclude that this is both technically and economically feasible, a clear trajectory is required to alleviate uncertainties and stimulate further investment. 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, long-lasting public investments in new technologies and energy systems.

Indeed, it is recognised that technology development, transfer, deployment and scale-up will play a pivotal role in the energy transition. In its 2020 Energy Technology Perspectives report, the IEA concluded 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 [5]. 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 safe, secure, reliable, and sustainable.

Carbon pricing policies in Europe combine the EU Emissions Trading System (EU ETS), a wide cap-and-trade scheme, with additional national carbon taxes now in place in most EU countries and the UK. The global carbon market is expected to continue to develop in the coming years as new national trading systems are launched, others are reformed, and the UN strives to complete a set of guidelines for nation-to-nation trading. Carbon price mechanisms will help incentivise investments in low-carbon technologies and power generation by sending appropriate price signals to carbon emitters.

The EU has clearly stated its objective of global leadership in the fight against climate change and has set world-leading targets for carbon emission reduction with the European Green Deal, progressively aiming to make 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 efforts. In detailing its long-term strategy, the EU has outlined 2030 targets towards carbon-neutrality along with enabling policies, with relevance to topics such as CCS, hydrogen, and natural gas for hydrogen production.

The EU recently implemented the EU Taxonomy – a classification system, establishing a list of environmentally sustainable activities. To date, the EC adopted two delegated acts, covering two of six environmental objectives – climate change mitigation and climate change adaptation. The first delegated act is in application since 2022. In the energy sector, it prioritises RES. However, electricity generation, cogeneration of heating/cooling and power, and production of heating/cooling from renewable non-fossil gaseous and liquid fuels are particularly relevant for the gas turbine industry. The second delegated act, applying from 2023, complements the activity list with additional specific transitional natural gas activities, among others. Specifically, it recognises (under certain conditions), the following three activities: (1) Electricity generations from fossil gaseous fuels; (2) High-efficiency co-generation of heating/cooling and power from fossil gaseous fuels; and (3) Production of heating/cooling from fossil gaseous fuels in an efficient district heating and cooling system.

As a reaction to Russia's invasion of Ukraine, the EU adopted a plan in May 2022 for EU energy independence from Russia – REPowerEU. It is built on four main pillars: (1) Save energy; (2) Diversify supplies; (3) Quickly substitute fossil fuels by accelerating Europe's clean energy transition; and (4) Smartly combine investment and reforms. Moreover, it develops on the Fit for 55 proposals (i.e., reduction of net greenhouse gas emissions by at least 55% by 2030 compared to 1990). It does not modify the headline ambition but proposes to raise the energy efficiency and renewable energy targets to 13% and 45%, respectively (from 9% and 40%).

In August 2022, the Inflation Reduction Act (IRA), offering funding, programs, and incentives to accelerate the transition to a clean energy economy was signed in the USA. To counterbalance the IRA, the EU adopted The Green Deal Industry Plan in February 2023. It aims to enhance the competitiveness of Europe's net-zero industry and support the transition to climate neutrality. The Net-Zero Industry Act (NZIA) is one of its pillars. It was introduced in March 2023, and it sets a goal to domestically produce at least 40% of clean technologies as well as speed up permitting and increase access to finance for clean technologies. NZIA is widely discussed and will likely be revised in the future.

Finally, significant funding packages are in place to achieve the stated policy aims. The EU Innovation Fund, one of the world's largest funding programmes, will provide around 40 billion euros of support from 2021-2030 for the commercial demonstration of innovative low-carbon technologies. Multiple funding rounds are being held regularly. The Just Transition Mechanism is a key tool to ensure that the transition towards a climate-neutral economy happens in a fair way. It provides targeted support in the most affected regions (i.e., coal production or former power generation sites) over the period of 2021-2027. The Recovery and Resilience Facility may also be of interest for the gas turbine technology industry. This temporary instrument offers grants and loans to support reforms and investments focussed on sustainability, resiliency, and the digital transition.

Integrating gas turbine technology into the energy systems

In the evolving landscape of future energy scenarios, renewable sources such as wind and solar power will play a more prominent role. However, their intermittent nature poses challenges, highlighting the need for integration of controllable electricity production technologies. In these scenarios dispatchable technologies like gas turbines becomes essential for compensating for the variability of renewable energy sources, ensuring a stable balance between electricity production and consumption. Even if energy storage systems will become more economically viable, the role of flexible and controllable electric power generation technologies, such as gas turbines, remains crucial for maintaining grid stability and securing the energy supply.

The power-to-X process is an revolutionary way that enables the conversion of renewable electricity into storable fuels, providing access to CO_2-neutral energy available whenever and wherever it is required. The dispatchability and wide range of sizes in the gas turbine portfolio, from Micro Gas Turbines (MGT) to Large Gas Turbines (LGT), in combination with the adaptability to operate on any kind of synthetic gas or hydrogen makes it an ideal technology to support and enable a large integration of variable RES.

Rapid improvements in low-carbon, demand-response, and storage technologies can lead to a smarter, more efficient and more secure system. However, achieving this 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, if using biogenic carbon or direct air capture) making it vital to adapt gas turbines for their future use. This versatility of gas turbine technology is therefore an important lever for fully climate neutral power and heat generation [6].

Society is currently moving from a highly centralised to a more decentralised energy system, which will rely 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.

The integration requirements outlined above are captured in the Vision 2050 of the European Technology and Innovation Platform for Smart Networks for Energy Transition (ETIP SNET), which highlights the value of integrated smart network schemes for the ongoing energy system transition. ETN has produced its own vision, emphasising the significant and versatile role of gas turbine technology within a future carbon-neutral energy system, as shown in *Figure 1*.

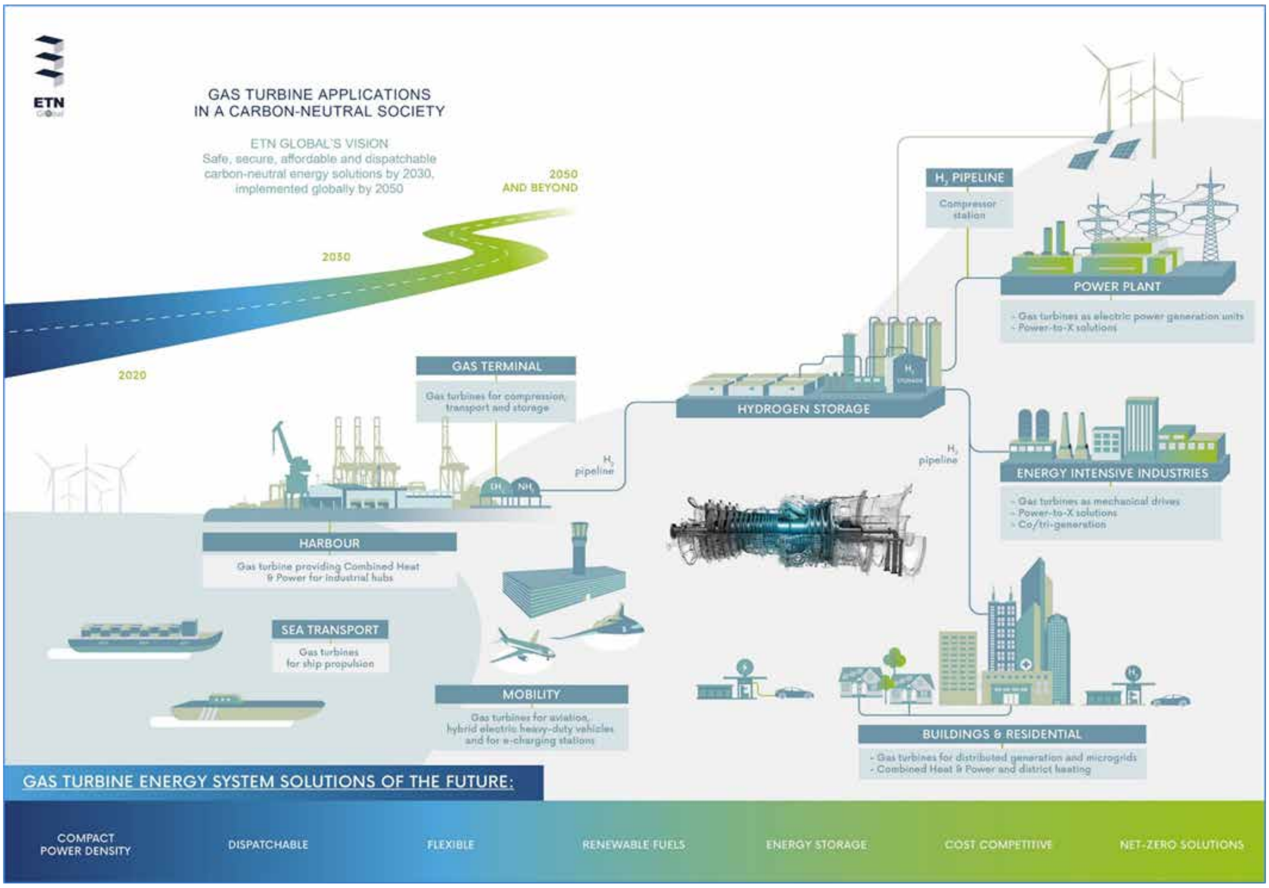


Figure 1: ETN vision of gas turbine integration into a carbon-neutral energy system

3. Operational Flexibility

The IEA's future energy scenarios are dominated by RES, among which the two main growth contributors will be solar and wind. Annual electricity generation from not programmable RES is expected to grow at a fast pace, with solar PV growing from 4% in 2021 to 20% in 2030 worldwide (or from 160 GW in 2021 to 600 GW in 2030 at European level) [7]. 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 unviable or, considering schemes such as Power-to-X-to-Power, require re-electrification in conventional power plants. These conventional power plants will cover a large portion of the backup power needs for the next decades. Some of the contemporary power plants will see their role in the future reduced, e.g., coal power plants are being phased out in several countries, while the future of nuclear power plants is being discussed in various countries. Consequently, open cycle gas turbines or combined cycle power plants are considered the most suitable solution to provide the majority of flexible back-up in a near future scenario. The role of CCGTs has already shifted from baseload to load cycling in many countries. This trend is expected to continue, with gas plants further moving from the energy market to the service market. Therefore, the design of new plants and retrofits will need to take this operational flexibility into account. *Figure 2* below shows a Siemens Hydrogen GT Power Plant.

Figure 2: Siemens Hydrogen GT Power Plant
© Siemens Energy

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 rapidly evolving topic to identify areas of future R&D. The following areas have been identified as active R&D topics related to operational flexibility.

Fast load changes

One of the key features that power generation equipment must 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 the partial dispatchability of RES, GT-based power plants must start-up and shutdown quickly (e.g., new combined cycle plants feature 15-30 minutes hot start-up, 60 minutes warm start-up), and furthermore react quickly to load changes (e.g., modern CCPP: 6-9%/min, modern GT: 13-14%/min, aeroderivative GT: up to 50%/min) while minimising the impact on component life consumption and emissions. The former can be tackled both looking at component level ("design to life") and system level (e.g., hybridisation with a battery pack for fast start-up [8]).

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 operating hours at partial load is expected to increase. This will require efficiency improvements and the reduction of unburned hydrocarbons (UHC) which could lead to CO_2eq emissions at partial load conditions.

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

There are many different schemes that might be integrated, including thermal energy storage, compressed air energy storage, liquified air energy storage, batteries, or power-to-X-to-power schemes. This integrated system will further improve flexible plant operation in peaking mode, increase ramp rate/ frequency response and 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.

Emissions will be another element to consider. The (extended) minimum environmental load (EMEL) will need to be further reduced as regulation is bound to become more stringent in the near future). Combustion technology will need to meet stricter regulations, developing incremental or disruptive new technologies (e.g., pressurised flameless combustion). Integration of storage systems will also be beneficial in reducing the EMEL in peaking and part load operations.

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

The modifications in the operating profiles of gas turbines towards faster 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 blades and rotor discs, and cracking and degradation of combustors.

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

Operational considerations are required to facilitate the adaptation to the changes in grid 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 RES and competition with gas engines could further reduce the operating hours of 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 CAPEX and OPEX must be reduced while improving reliability, flexibility, and lifetime.

R&D is also required to address the flexibility of the entire plant, including the bottoming cycle. In this regard, emerging technologies to replace 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.

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 load 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 (i.e., 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 intrinsically uncertain nature of component durability, dependant on a vast number of input variables such as material properties, manufactured component geometries and engine boundary conditions, the role of stochastic methods, such as probabilistic methods for component life and efficiency prediction, will also increase in the future 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), as well as for component integrity monitoring and life consumption analysis.

Further improvement could be realised by automatic tuning systems, e.g., 'self-learning' or 'self-adapting' control systems based on advanced IT or artificial intelligence technologies. This is important for flexible fuel composition changes, such as H_2 or other low-carbon fuel components.

Combustion of these sustainable fuels can lead to challenging combustion dynamics, e.g., 7x higher flame speed for H_2 in gas turbine engines compared with natural gas and higher likelihood of flashback events, and therefore gas turbines would significantly benefit from improvements in combustion pressure and flame monitoring. Combustor improvements will continue to take advantage of new manufacturing methods like additive manufacturing (AM) to enable complex designs that optimise 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, improve turbomachinery performance, and enable wider fuel flexibility.

4. High Efficiency Power Generation

The latest generation of large heavy duty gas turbines can achieve electrical efficiencies in excess of 43% (ISO standard) in simple cycle configuration and above 64% in combined cycle mode. 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 remains low and, therefore, the average electrical efficiency of the power generation gas turbine fleet is ~50%, lower than the efficiency of the technological front runners.

In addition to this, the accelerated phase out of coal power plants has not been fully compensated for by additional RES which pose the added challenge of intermittency and the associated variations in residual power demand (i.e., not covered by RES). This has translated into higher operating hours of power plants based on gas turbines in certain locations, notably open cycle gas turbines that have recently achieved the highest capacity factors in decades in Europe and worldwide. Large projects based on multiple aeroderivative engines running in simple cycle (e.g., Germany) and even heavy-duty gas turbines originally aimed at the combined cycle market (e.g., Morocco) are currently under construction. These all imply frequent operation in partial load conditions as well as numerous start/stops, which brings about a significant further reduction of efficiency. Whilst this represents an opportunity for the gas turbine industry, it also poses a need to develop engines that are more efficient across the full load range.

The increased requirements for operational flexibility are in addition to the need for higher power generation efficiencies from gas turbines and combined cycle power plants. This technology will remain, for years to come, the most efficient technology to produce electric power from chemical energy carriers (e.g., C_xH_y, H_2, or NH_3). Hence, it is necessary to carry out further research to improve the existing technology and/or to find new solutions in order to enable additional efficiency gains, particularly for part load operation. Selected focus areas for further R&D are highlighted below.

Thermodynamic cycles

Most contemporary gas turbines run on simple open cycle with relatively few engines making use of compressor intercooling, reheat (i.e., sequential combustion) or internal heat recovery through a recuperative heat exchanger. For this standard cycle, small efficiency gains occur for every new generation of gas turbines due 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 an upper ceiling given inherent thermodynamic and material limitations. Based on this, modifications, and extensions to more advanced cycles (such as the reheat Brayton cycle and sCO_2 bottoming cycles [9]) have been considered for future combined cycle gas turbines to enable improved cycle efficiencies. The implications on cycle performance at rated and off-design conditions, combustor operation, cooling flow management, turbine thermal management and, crucially, operational flexibility are still to be explored further.

Gas path design

The gas path design of compressors and turbines in contemporary gas turbines has achieved increased levels of refinement for the core isentropic flow. Highly three-dimensional blades and vanes obtained through multi-objective topological optimisation are now commonly used, yielding significant improvement in aerodynamic efficiencies. Further internal efficiency gains will likely be moderate, in particular in the compressor, but innovative manufacturing and design routes (e.g., enabled by additive manufacturing) might open up new opportunities. Improved secondary (i.e., cooling air) flow features and turbine cavity flow management are just two examples from which further efficiency gains can be attained.

Turbine clearance control is another technology of growing importance, with an estimated potential for a 0.25%pts combined cycle efficiency gain (at steady state operation) to be achieved through active clearance control systems and new rim seal topologies enabled by additive manufacturing. 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 radially. Regardless of the particular method, both face the challenges of transient temperature distributions of engines subjected to(steep load changes or frequent start/stops. Future systems are needed which can further minimise (at all load conditions and during load transients) the tip-leakage flow at the compressor and, more importantly, the turbine whilst avoiding physical contact between rotating and stationary parts. This feature will allow a more uniform efficiency profile of agas turbine vs. load *(see Figure 3)*.

Cooling system

About 20% of the compressor flow is typically diverted from the main 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 blades and vanes within the high-pressure section of the turbine, hot gas ingestion – caused by an unbalanced distribution of cooling air - can potentially lead to mechanical failures and aerodynamic losses. 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 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 high 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 particularly affected by transient operation 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 (i.e., cooling air system), multi-objective topological optimisation and active control of cooling flows are therefore areas in need of further research to enhance the performance of existing and new engine products. The utilisation of innovative manufacturing (e.g., AM) will expand the boundaries of the design space, allowing for more sophisticated geometries for cooling, and seals to yield higher efficiency performance.

Bottoming cycles

Contemporary heat recovery steam generators (HRSGs) producing steam at three pressure levels and incorporating reheat can 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 with this is unlikely to be compensated for by the marginal performance enhancement (estimated at 0.5 combined cycle efficiency points for state-of-the-art technology). Other working fluids (e.g., organic fluids or CO_2) should also be explored for bottoming cycles, when combined with smaller (e.g., aeroderivative) gas turbines or in applications where multiple-pressure HRSGs are not feasible for technical or economic reasons. This can open new opportunities for compact, lower capacity combined cycle power plants with enhanced efficiency as compared to simple cycle gas turbines.

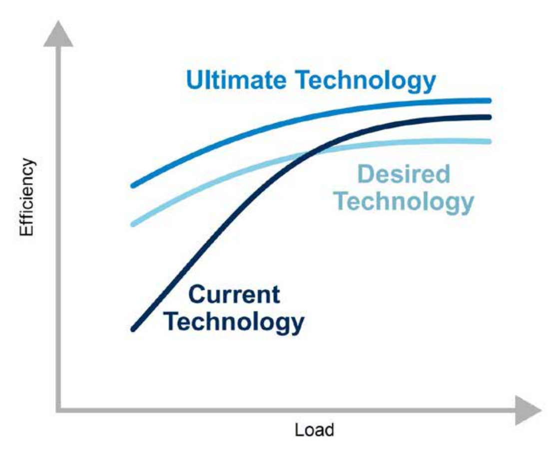


Figure 3: Gas turbine efficiency versus load

Additional remarks

In the coming decades, high efficiency power generation in combined cycle power plants will rely on part load efficiency rather than on rated base load efficiency. Therefore, enhancing part load performance and transient response (i.e., the ability to transition to higher loads as fast as possible to meet variable demand and to provide the grid with ancillary services, such as frequency control and balancing) 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 stops and the associated consumption of useful life. These considerations are also applicable to open cycle gas turbines.

5. Extended Fuel Spectrum

Modern gas turbines must comply with extended economic and environmental requirements: operational flexibility, high availability and reliability, extended fuel flexibility and high efficiency with low emissions, with the long-term target to reach zero CO_2 emission, while maintaining low NO_X/CO. These requirements must be ensured using an extended range of gaseous and liquid fuels.

Fuel gas mixtures (e.g., syngas or hydrogen) and diluents (e.g., CO_2 or H_2O) are emerging as new gas turbine-based processes and new fuel resources (e.g., biofuel, shale gas, or LNG) are proposed for power generation and industrial applications. These add to the already large variety of natural gas qualities, including gas compositions with higher content of higher hydrocarbons or with higher content of inert species (i.e., referring to compositions with respectively more than 1%vol. of so-called C2+, like ethane C_2H_6, propane C_3H_8 and butane C_4H_{10}, or more than 10%vol. of inert N_2 or CO_2), which cover a wide range of Wobbe Index values (35 - 55 MJ/Nm³). Moreover, liquid fuels remain of interest for mobile applications (e.g., aero, or marine engines), the oil & gas industry, 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 *(see Figure 4)*.

Gaseous fuels will remain indispensable in the long term as a source of power generation and reserve energy even in future decarbonised energy systems. Gas turbines will remain one of the most relevant solutions for the conversion of gaseous fuels (either fossil, renewable, or synthetic) into electricity. Today, gas turbines mainly use natural gas as fuel. However, GT OEMs are increasing the fuel flexibility of their gas turbines. They currently offer solutions where future hydrogen use is considered and which can be easily adapted for hydrogen in the future (i.e., "H_2-ready"), through design of new combustors capable of running on 100% hydrogen by 2030. In this way the changeover from natural gas to alternative fuels like hydrogen can take place gradually, while maintaining full fuel flexibility. With this approach, gas turbines and combined cycle power plants represent a sustainable investment and a critical instrument for delivering a CO_2-neutral energy system, where gas turbines become the technology of choice for backing up intermittent RES.

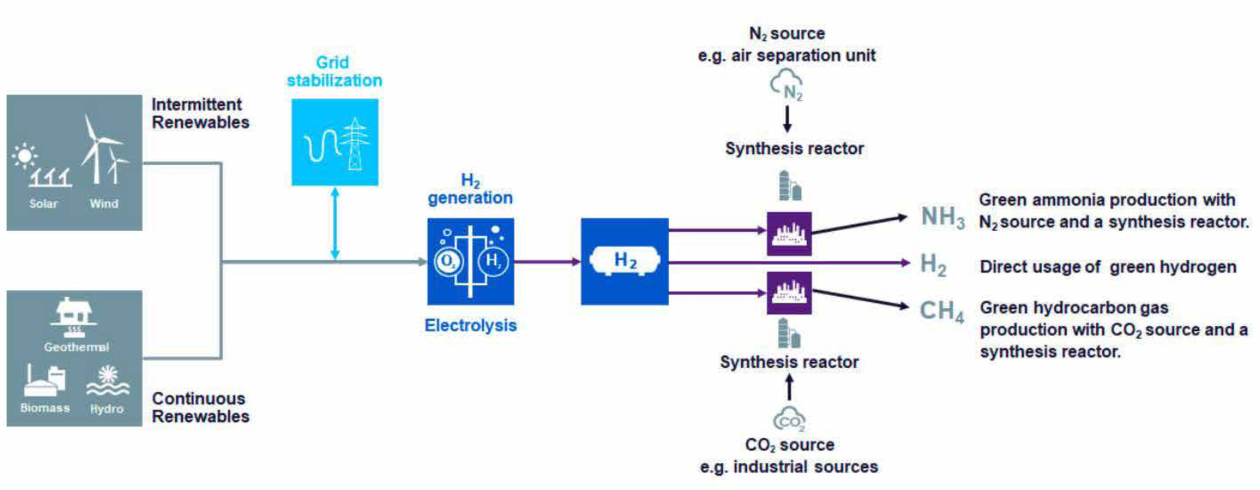


Figure 4: Simplified process flow diagram for power-to-gas applications

The opportunity of a wide fuel spectrum capability of gas turbines is strongly coupled with operational challenges such as flame stability and emission compliance. These challenges can be exacerbated if flexible fuel switch-over procedures are to be considered. The main GT fuel R&D focus is currently led on flexible admixture of hydrogen to natural gas, up to 100%.

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 to achieve a fuel-flexible gas turbine.

Specific research topics, which need to be addressed in this respect, are given below.

Natural gas/hydrogen mixtures

With large capacities of wind and 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. Moreover, it is foreseeable that not every country can cover their energy needs with self-produced renewable energy. Thus, importing and using chemical energy carriers like hydrogen, ammonia and e-fuels will be mandatory. This may require gas 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, which involves addressing issues such as combustion performance and control (e.g., flame stability, flashback, combustor cooling, and 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.

To guarantee full operational flexibility, modern combustion system should ultimately be able to deal with the entire range of fuel changes: from 100% natural gas to 100% hydrogen for all operating points (i.e., 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. Several European and international projects are ongoing to develop and demonstrate the applicability (at full scale/full pressure) of potential low emission, reliable (i.e., safe ignition, stable flames) combustion technologies [10].

Low calorific gases

While most 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 where 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 – can be considered CO_2-neutral (depending on the origin of biomass) 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 (i.e., flame stability, flashback, combustor cooling, and thermo-acoustics), as well as emission behaviour (NO_X and CO) and material degradation due to fuel contaminants (e.g., particulates and/or corrosive species like sulphur, chlorine, or sodium). As fuel standards for gas turbine application of such fuels are missing at the moment, there is a need for development of appropriate standards and norms.

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 and expands the gas quality range towards Wobbe Index values well below 35 MJ/Nm^3 due to its higher content of inert species (i.e., N_2 and/or 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 must be improved.

Liquified natural and petroleum gas

LNG (liquefied natural gas, LNG boil-off gas) and LPG (liquefied petroleum gas) have very peculiar compositions when re-gasified and used for gas turbine operation. Triggered by the recent gas crisis, the share of LNG in the European gas network is increasing and will likely continue to increase in the following years. LNG consists mainly of methane and thus reduces any impacts due to inert species. However, the low levels of higher hydrocarbons (e.g., C_2H_6 / C_3H_8) can cause operability issues due to the reduced reactivity of the fuel. The variability of the gas composition in the gas network is expected to increase, which further increases fuel flexibility expectations for gas turbines.

LPG consists of propane and butane in various ratios and exhibits different physical and chemical properties compared to natural gas, 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 biomasses. These liquid fuels feature a high energy density in mass and volume but their significant range of physical properties (e.g., viscosity or lubricity), and chemical properties (e.g., combustion chemistry or 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, and NO_X, CO, and SO_X emissions.

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 properties have to be considered for these fuels, like S/N/Cl content, 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 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)

The combustion characteristics of ammonia strongly differ from those of conventional hydrocarbon and hydrogen fuels – such differences include significantly reduced fuel conversion rates (flame speed). Ammonia is attractive for energy storage because it is carbon-free and 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 do so: 1) direct usage of ammonia as fuel, or 2) reconverting ammonia to nitrogen/hydrogen mixtures via thermal/catalytic cracking. One of the main drawbacks of using ammonia for combustion is the potential for high NO_X production 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 cracked gases if 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 rate hence flame speed, and thus flame stability issues arise. 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. Due to the toxicity and environmental effects of ammonia, any significant emission of unburned ammonia needs to be avoided under all operating conditions (e.g., fail-starts or flame outs), which requires changes to the gas turbine control and operating procedures. Due to its corrosivity, material changes might also be necessary if ammonia is used as a fuel.

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 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. Even though fuel pre-treatment is often necessary to avoid problems in gas turbines, low-grade fuels such as heavy fuel oil, crude oil, or sour gas can be cheap to provide and sufficient for the intended use.

The use of low-grade liquid fuels such as crude oils in gas turbines is particularly difficult due to the content of sulphur, 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 contributes to significant maintenance cost reduction, power plant efficiency improvements, and a reduction of emissions, including the CO_2 footprint (depending on the origin of the fuel).

As for any other hydrocarbon fuel, the above-mentioned fuel qualities would require additional measures for carbon mitigation in the future if used in gas turbine applications (e.g., pre-/post-combustion carbon capture or oxy-fuel firing techniques).

6. Emissions

NO_X emission levels from gas turbine engines have not featured in the R&D focus in recent years relative to previous decades. 25 ppm NO_X (about 50mg/Nm³) (corrected to 15%vol. O_2) is still accepted as industry standard (for gaseous fuel firing), though projects increasingly adopt 15 ppm (about 30mg/Nm³) NO_X as an emission target, and even single digit ppm NO_X levels are requested in certain regions. For liquid fuel operation, 42 ppm (about 84mg/Nm³) NO_X is long-established as the emission limit, and the new version of the EU Industrial Emission Directive (IED), published in 2022, finally adopted a similar value (90 mg/Nm³ for Large Combustion Plants (LCP) with more than 50 MW_{th} input). Legislation for CO emissions has been less stringent (e.g., in the new IED less than 100 mg/Nm³ CO is required), but in some cases CO emission limits (at base load) have been set as low as those for NO_x (about 25 ppm). The IED refers to several Best Available Techniques Reference (BREF) documents for various industry sectors setting expectations for further reduction in NO_X and CO for both existing and new plants. Finally, the EU Taxonomy Regulation sets certain emission standards ("performance thresholds") for CO_2 emissions which need to be met in order for companies, project promoters and users be able to access green financing [11]. 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 as follows.

Emission limits at part load and in dynamic operation schemes

As gas turbines are much more often required to run at part load and to cover a lot of cycling duties, including starts and stops, emission limits for these conditions are being given much more attention and emphasis. Thus, maintaining low emission values for NO_X (as well as for CO) down to very low part load (e.g., meeting emission compliance at 50% of design load or even below) and during transient load operation has become very important for GT operators, and therefore a key claim for gas turbine products. Issues to be addressed are safe combustion performance (e.g., flame stability and thermo-acoustics) in combination with maintained low emission (e.g., NO_X and CO) characteristics over a wide load range (from below 50% up to 100% load). Excursions beyond accepted emissions limits will be less tolerated in the future and need to be avoided in cyclic operation modes as much as possible. The IED provides quantitative limits for short term excursions (i.e., over-shooting) of emission limits for all air polluting species.

Liquid fuels (emission of NO_X, CO and particulates)

Very low NO_X emission limits (less than 42 ppm or 90 mg/Nm³) for liquid fuel operation of gas turbines pose a significant technical challenge if they should be achieved by combustion measures alone (i.e, 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 and flame stability should not be compromised, either with or without addition of water/steam, and a combined minimum of emission species (e.g., NO_X, CO, or particulates) must 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 maintain public acceptance.

Liquid fuel operation of gas turbines is especially important for mobile applications (i.e., gas turbine propulsion systems on land/sea/air) which – due to their typically very dynamic operation modes with steep and frequent load ramps – pose additional challenges.

Synthetic liquid fuels – like methanol (CH_3OH), ammonia (NH_3) and Sustainable Aviation Fuels (SAF) – each have their specific advantages and disadvantages with respect to their emission characteristics, and thus require customised combustion techniques *(see below)* in order to meet lowest emissions (e.g., NO_x, CO, soot, etc.) without jeopardising performance (i.e., efficiency, power rating, safe operation, or load variation).

H_2 and H_2-rich fuel gases / NG-H_2 mixtures

Combustion of fuel gas mixtures containing high hydrogen concentrations (> 50%vol.) tends to show higher NO_X emissions and require significant changes to the design of fuel-air mixing and combustor systems in order to avoid this [12]. 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 maintain low NO_x emissions. If dilution with steam or nitrogen (N_2) is not an option, issues regarding safe combustion performance (e.g., flame stability, flash-back, combustor cooling, or thermo-acoustics) need to be addressed while maintained low NO_X emissions.

As clean H_2 will likely become more abundantly available (e.g., via water hydrolysis driven by surplus electricity from RES) and be injected for energy storage in large amounts (> 20%vol.) into the natural gas grid, unambiguous data is required for such fuel mixtures (up to high shares 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 $NO_{X\,e}$mission 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 emissions and low load operating conditions need to be carefully addressed and managed.

Exhaust Gas Recirculation (EGR)

External recirculation of exhaust gases and admission to or partial replacement of combustion air has similar effects (as just described in the previous section) on NO_x/CO emissions, and thus needs to be considered as well as a viable option for emission reduction in the future. Despite the additional complication of the gas turbine process (additional components, piping) and the additional operational/control issues it requires, EGR offers various emission reduction options for highly reactive fuels (such as H_2), for high efficiency/high turbine inlet temperature gas turbine models, and for post-combustion carbon capture (PC-CC) solutions of gas turbine processes. With recirculated exhaust gas a part of the combustion air (typically up to 20%) can be replaced in the gas turbine process, which reduces the oxygen concentration (from 15 to 12%vol.) and increases the CO_2 concentration (from 2 to 4%vol.) in the exhaust. This has positive effects in terms of reduced NO_x formation and allows Post Combustion-Carbon Capture equipment to be reduced in size but is limited due to potential flame instabilities and impact on CO emissions.

Ammonia (NH_3)

Ammonia as a potential future fuel for gas turbines requires special attention and revised combustion technologies, as otherwise NO_x emissions can easily rise to hundreds or thousands of ppm in current state-of-the-art lean premixed combustors. Cracking/splitting of NH_3 before combustion into H_2/N_2 mixture can provide reduced NO_x emission, but in order to suppress the conversion of even low concentrations of (remaining) ammonia the combustion process needs to be tailored such that a zone of reducing conditions (with no/low oxygen concentration) is provided (allowing all nitrogen species – NO_x, NH_3, N_2O, ... – to be converted to harmless/stable N_2). Besides NO_x emission issues, the emission of other harmful N-containing species needs to be addressed as well, if ammonia is to be used as a future gas turbine fuel (or blended with methane or hydrogen). Additional catalytic exhaust gas aftertreatment (EGA) will be required in most of these cases but can only reasonably offer reduction efficiencies of 90-95% and needs to be carefully designed to not produce other unwanted or harmful N-species.

New combustion techniques – e.g., staged combustion, micro-mix combustion

With the use of future fuels (e.g., H_2 and NH_3) with significantly different combustion properties – and thus emission characteristics – current state-of-the-art lean premixed combustion technology (as well as conventional diffusion flames) have limitations in providing safe, low emission combustion operation for all load conditions. For this reason, other combustion technologies are being considered especially for these fuels, such as micro-mix combustion (i.e., the fuel gas is burned in a large number of small, short diffusion or partially premixed flames),jet-stabilised combustion (i.e., fuel and air are injected with high velocity without swirl into the combustion chamber) for high-H_2 fuel gas mixtures, and staged combustion for direct combustion of NH_3 as a fuel (i.e., air and/or fuel is provided in stages such that different stoichiometric conditions – rich/lean - are achieved). These combustion techniques require significant changes in the architecture of the gas turbine combustion system, and thus need major R&D steps before they can be considered in commercial gas turbine products. New manufacturing techniques (e.g., laser metal forming or additive manufacturing) have recently opened up new routes for burner and combustor designs to allow cost-competitive manufacturing of these new combustion technologies [13].

7. Decarbonisation

The need to reduce CO_2 emissions is continuously increasing [14], while at the same time pressure from policy and regulation is increasing. 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. While there was little to no support and interest to develop such solutions (specifically for gas turbine-based processes) via public funding (e.g., EU programmes), currently some EU calls cover the use of low carbon fuels in CHPs, and some aspects of carbon capture but with the main focus on transport and storage topics or in systems where GTs might be only one component. However, some opportunities might be still found in connection with programs for integrated low carbon energy systems.

Reducing CO_2 emissions from gas turbines can be achieved through improvements in efficiency especially during part load operation, 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 [15], while the third is linked to challenges of fuel flexibility requirements [16]. The integration of CO_2 capture into renewable fuel-based power generation (e.g., biofuel) could result 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, in combination with exhaust gas recirculation (EGR), with the capture unit located on the gas turbine exhaust; pre-combustion, where the CO_2 is largely removed after catalytic reformation of natural gas leaving a hydrogen-rich fuel gas; or by using oxy-combustion where the CO_2 is more readily separated from steam in the exhaust gas stream. The following decarbonisation priorities reflect those not covered in other chapters of the report.

Integration of post-combustion CO_2 capture technologies with gas turbines

The decarbonisation of gas turbines using CO_2 capture, whether in existing natural gas-fired units or in new build schemes, will increase operating costs (including fuel costs) and reduce cycle efficiency, mainly due to the energy penalties associated with CO_2 capture process. Selecting the most suitable capture technologies and optimising their integration with gas turbine systems while maintaining plant flexibility requires further investigation and qualification. Among others, the following options require further research:

- Optimum integration of 'conventional' post-combustion amine scrubbing or competing liquid-based technologies with heat recovery steam generator (HRSG) or other thermal sources to minimise costs and energy penalties.

- Alternative capture technologies, such as Ca-looping cycles, solid sorbents using pressure or temperature swing concepts, or CO_2 separation membranes that allow for improved heat integration, and hence lower operating costs.

- Exhaust gas recirculation (EGR) including improved recycle options (e.g., using CO_2 separation membranes) to increase exhaust gas CO_2 concentration. This approach can reduce the size, thermal energy usage, and costs of the capture plant and it can potentially reduce NO_x emissions and solvent degradation (i.e., in the case of CO_2 absorption process). However, it can lead to more complex gas turbine configurations and significant changes to combustion and hot gas path environments, and might also affect 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 that require further investigation. Transient operation and its impact on capture performance (during expected and unexpected events with special attention to start-up times), on process efficiency, and on control strategies is of interest especially as GT-based plants are seen as the most flexible solution to balance the grid and provide backup power for RES. Further important aspects of integrating carbon capture are the impact on plant CAPEX which is going to increase and the challenges of integrating carbon capture into existing units which might lack available space and accessibility.

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

With limited or no upgrading and gas cleaning (to reduce overall plant complexity and internal energy consumption), 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 CO_2 capture technologies to be involved [17].

Advanced high efficiency cycles using oxy-fired gas turbines

A range of advanced, high-efficiency cycles are under development to provide alternatives with inherent CO_2 separation to improve the application of post-combustion capture options. These cycles 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 the CO_2 or condensed steam may be recycled to the combustor to moderate combustion temperatures. Such cycles operate at very high pressures, up to 300 bar, 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 [18] cycle), or the Clean Energy Systems [19] 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, and control strategies. These systems are very different to conventional gas turbines 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 to provide a possible pathway for future turbine development. In addition, reliable operation of these complex plants under variable and transient conditions requires additional research, as such conditions are expected to become a standard due to the high share of fluctuating RES.

Furthermore, the integration of gas turbines with the necessary O_2 production process (i.e., the air separation unit) is an area of research to optimise the overall system towards improved efficiency and flexibility. Therefore, integration with other processes such as the green hydrogen production is worthy of evaluation.

8. Advanced Cycles

The portfolio of actions set forth by the European Union's Green Deal, implemented through the legislative package Clean Energy for all Europeans, has been reassessed in the face of the recent upsurge in natural gas (and electricity) prices and a reduction in dependency on fossil fuel imports from Russia (REPowerEU [20]) [21]. It is acknowledged that incremental efficiency gains will not be enough to solve the energy trilemma of energy security, environmental sustainability, and energy equity simultaneously. New advanced cycles are needed which can exploit untapped energy sources and provide backup power and balancing services to a grid with rapidly increasing shares of variable RES capacity (e.g., in the EU, they account for about 70% of the newly installed power generation capacities in their 2030 scenario [22]). Increasing overall generation efficiency and reducing CO_2 footprint is a general necessity at the same time.

The following promising advanced cycles, each with 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. In the last century, it has become the standard for new large-scale steam power plants, enabling live steam pressures and temperatures over 300 bar and 600°C, and 5 percentage points higher efficiency than their subcritical counterpart. Future targets of the industry are pressures and temperatures of 400 bar and 700°C, respectively, which would approach the 50% efficiency landmark figure.

Simultaneously, a new generation of closed cycles working at supercritical pressure and temperature which make use of carbon dioxide as working fluid are being developed. These systems, usually grouped under the general term of supercritical Carbon Dioxide (sCO_2) power systems, work at similar peak pressures and temperatures to ultra-supercritical steam turbines but yield increasingly higher efficiency for turbine inlet temperatures above 600°C and beyond. From a technical standpoint, sCO_2 systems sit between steam and gas turbines, and they enable smaller footprints than the former and higher efficiency and fuel flexibility than the latter. These power systems enable cost-effective, non-chemical carbon capture in natural gas applications if combined with oxyfiring[23]. Thermal efficiencies higher than 50% for turbine inlet temperatures on the order of 700°C are well within the capabilities of this technology.

Supercritical CO_2 cycles are currently being explored theoretically and experimentally for applications as diverse as Gen IV nuclear reactors, Concentrated Solar Power, pulverised coal, natural gas and waste heat recovery (i.e., either for unused thermal energy in industry or to bottom existing open-cycle gas turbines), with each application at varying levels of technological maturity. Commercial systems are currently available in the US market for Waste Heat Recovery applications in the five-to-ten-megawatt scale (TRL9) and for natural gas power stations with carbon capture larger than 25 MWe. In Europe, several demonstration projects are currently under development, aiming to demonstrate the technology at a commercially relevant scale (MWe) for the Concentrated Solar Power and Waste Heat Recovery industries. In the nuclear industry, there are no on-going large experimental projects except for tests at lab-scale (TRL4).

The maturity achieved by the required turbomachinery components is remarkable although research is still needed in the areas of turbine cooling (i.e., if turbine inlet temperatures higher than 650°C are to be accomplished) and dry gas seals (i.e., conventional labyrinth seals are not applicable). Rotor dynamics is another area where work is needed in order to develop design methodologies able to prevent dynamic instabilities triggered by sudden density changes of the working fluid (in particular if phase-change takes place in the machine). Internal heat exchangers like recuperators and condensers are currently available, although there is a need to work on optimised commercial solutions that provide the best techno-economic balance. Primary heat exchangers have on the contrary, lower maturity since they are specific to each application, and therefore the associated development has been slower.

Natural gas sCO_2 systems rely on oxy combustion of the fuel at supercritical pressure and temperature. These are very challenging conditions for combustion stability and more research is needed to ensure this and to increase the turndown capability of the system.

Material composition is another area requiring R&D. The very demanding combination of pressure and temperature compromises the mechanical integrity of high temperature components, in particular if the utilisation of very costly alloys is to be minimised. The corrosion potential of CO_2 in these operating conditions and in contact with certain coatings and metallic materials needs to be better understood.

Regardless of the application, substantial work is still needed to develop system integration schemes that enable system flexibility in terms of wide operating range and fast response capability, without compromising efficiency. In this regard, reliability of the supply chain becomes critical since the availability of large-scale balance of plant components meeting the requirements to operate at extreme pressures and temperatures is limited.

Finally, different initiatives to identify working fluid additives are currently under investigation, with the aim to increase the critical temperature of the working fluid, hence enabling compression near the critical point for higher cycle efficiency even when operating in warm or hot environments (condensation would also be possible, in which case highly efficient trans critical cycles would be adopted). The results obtained so far 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 (e.g., Brayton cycle in a gas turbine) yields lower thermal efficiency than heat addition at constant volume (e.g., 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 which challenge 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, controlling the pressure gain pressure losses, and wave directionality (RDC), NO_X and CO emission control, unsteady heat transfer and cooling flow management. These are all areas in need of further research at the fundamental and applied levels, calling for solutions to be developed.

In 2021, a research team in Japan accomplished the world's first space flight demonstration of detonation engines, successfully operating rotating detonation (RDE) and pulse detonation engines (PDE), whilst a major OEM of aero engines announced a new contract for the ground test demonstration of a rotating engine detonation concept aimed at high-speed propulsion. Experimental research for ground-based applications is at a lower technology readiness level but a large amount of research is currently under development, focused mostly on the combustion process/system and on the interaction between combustor and turbomachinery.

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 low. 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 given, using an organic compound in lieu of water becomes an interesting alternative to enhance thermal performance and to enable simpler cycle layouts and component designs. This is thanks to the characteristics of organic compounds (i.e., 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 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 enhance system and component performance and to 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. Research is also ongoing in relation to working fluids: development and testing of new working fluid compositions pushing the current thermal stability limits, including mixtures, with a large potential to enable higher thermal efficiencies. Another research topic is the development of turbomachinery design methods accounting for the non-ideal behaviour of organic working fluids including a deeper understanding of non-classical gas dynamics expected from Bethe-Zel'dovich-Thompson vapours (BZT). These efforts are supported by experimental demonstration and validation of the numerical predictions obtained from Computational Fluid Dynamics.

The commercial deployment of ORC power systems has been driven mostly by geothermal applications, yielding a large number of installations worldwide with progressively increasing unit output in addition to smaller units for decentralised heat and power applications. Nevertheless, the large amount of thermal energy that is released from industrial processes in Europe has recently been identified as a vast source of energy that can be converted into mechanical or electric power without incurring additional Carbon Dioxide emissions (i.e., carbon neutrally) [24]. ORC power systems can be tailored to the specific characteristics of different sources of thermal energy, through selection of existing or innovative cycle layouts and working fluids, rendering a fully flexible solution to harvest this energy efficiently.

9. Decentralisation

The increasing share of RES has transformed the energy market from a centralised to a more decentralised power production infrastructure. Besides large centralised combined cycle power plants, decentralised power production with smaller gas turbines is an increasingly attractive option, as they can contribute to stabilising the power grid on the low and mid voltage level while providing relief to the high voltage network. Decentralised biomass, other RES, and renewable energy carriers like green 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 primary energy consumption to cover electricity and heating demand 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 maintained.

While gas turbines in the range from 2 MWe to 20 MWe are well established in industrial applications (i.e., industrial gas turbines), micro gas turbine (MGT) technology has the potential to provide effective distributed power generation systems to smaller consumers, due to their fuel flexibility (e.g., biofuel stock) and compatibility with solar power generation. Micro gas turbines cover the range from 1 kWe to 1 MWe 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 manufactures. 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 R&D 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, system size and cost. Thus, their performance characteristics are limited to what is achievable when balancing R&D and production costs. Designs that are optimised for performance are used by some manufactures, 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 R&D is conducted to elevate 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 R&D 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 component performance which also affects cycle efficiency and fuel flexibility, but also system operation, cost, reliability, operability, and life. The third category relates to developments necessary to cope with the potential new applications related to smart grids, e-mobility, green/blue hydrogen, etc.

For the two first categories, the following areas are recommended for research and innovations in this field, while the third category will be covered by the ETN Decentralised Energy System Report.

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 and CO 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). Particular attention shall be paid to e-fuels, which are liquid or gaseous fuels of synthetic origin, produced through processes powered by renewable electricity. Hydrogen, ammonia, methanol, or ethanol with this origin will certainly be protagonists of the energy transition being CO_2 neutral [25].

Due to the recuperator preheating of the compressed air prior to combustion, the MGT combustor inlet conditions (i.e., temperatures up to 800K and pressures around 5 bar) differ significantly compared to larger gas turbines. MILD combustion is also emerging as an important development area for MGTs as it benefits from the inherent high combustor 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 reducing weight and cost. Dimensions are expected to be as limited as possible for the compactness of the MGT module and to contribute to the containment of production costs using smaller quantities of special materials. It is appropriate, if not strictly necessary, that the recuperator satisfies specific directives and standards (e.g., pressure systems regulations) to guarantee the safety of the machinery in which it is integrated.

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 R&D is required in this area. Another R&D area is in the use of metallic foam materials for producing compact heat exchangers.

A very important element is also to design the recuperator to allow a repair in the event of failure during the lifetime of the MGT. This could avoid the high cost of replacement and allows a service program capable of maintaining the recuperator performance.

Rotor dynamics 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 and reliable but requires an oil system and some technical solutions to limit the oil consumption. The second type, oil film bearings, are most common in automotive turbochargers. This bearing type is robust but has high friction losses making it unattractive for MGT applications. Magnetic bearing development has benefited significantly from research for larger engines, however, their development and implementation cost for MGTs has prevented them from being used despite their advantages of oil free operation and the inherent ability to control vibrations. Foil-air bearings have made significant progress during the last 25 years in many applications due to their reliability and oil free operation. However, despite their potentially superior performance, they are not typically used in MGTs due to the high development costs. The successful application of magnetic bearings and foil-air bearings in some systems demonstrate the principal applicability for MGTs, but further research is needed to reduce their cost and complexity. An active magnet bearing (AMB) developed by Aurelia Turbines is reported below in *Figure 5*.

Figure 5: Active magnet bearings (AMB) significantly reduce the maintenance needs of MGTs
© Aurelia Turbines

Generator and power electronics

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 (PM) generators are typically used due to their high-power density and high efficiency characteristics. Consequently, the choice of the best material and the right manufacturing technique is essential to guarantee the proper performance, lifetime, and reliability. Permanent magnet generators can be considered a consolidated technology but, in this case, the high rotation speeds make unique solutions necessary to avoid heating from eddy currents, rotor burst, and premature ageing. 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 or high temperature heat storage, 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. Since in most cases the power electronics are connected to the public grid, it is necessary that they are certified according to applicable directives and international standards, and that they satisfy the local grid codes.

Usability, Control Systems and Maintainability

Most of the machinery for distributed generation is controlled by custom systems specially developed to be robust, compact, and low cost. However, systems like these show a need for improvement for issues such as the growing interconnection needs, which can lead to cyber security problems, the need to perform certified safety functions, or the increasing demand to interface with smartphone app-based systems. Furthermore, decentralised energy system MGTs will often be integrated with other components like photovoltaics, energy storage, and charging stations utilising one main-control unit. Thus, interconnectivity and communication standards have to be developed and integrated.

Machinery for distributed generation must be designed to be used and maintained in a simple and smart way. In fact, in contexts where MGTs are installed, teams with the necessary training to carry out complicated installation and maintenance activities are very seldom present. Component design and packaging layout must focus on easy maintainability for recurrent maintenance activities. While MGTs in decentralised applications often face changing operating conditions and fuel quality, which can significantly affect the lifetime and performance of the components, another essential aspect of reducing the maintenance efforts would be the implementation of condition-based maintenance prediction, possibly based on artificial intelligence (AI). Such tools are successfully used for larger gas turbines but must be adapted to MGTs and implemented in the control system.

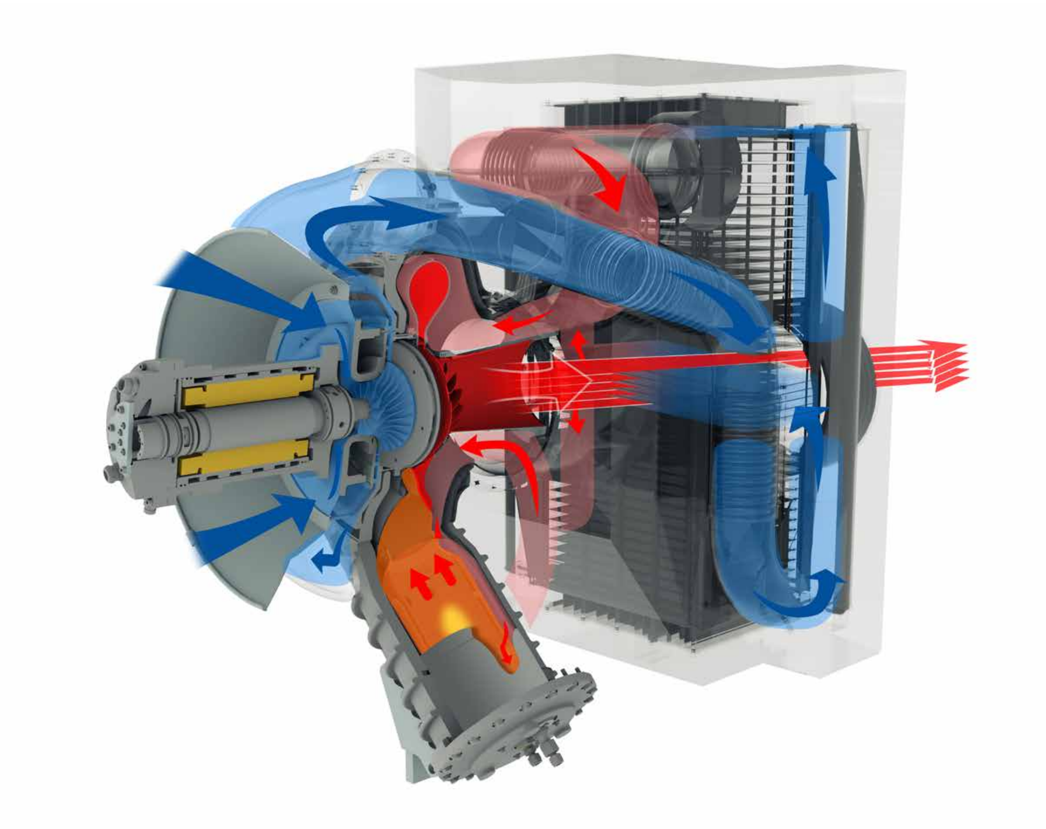


Figure 6: AE-T100 MGT power train running principles – Compressed air (blue) enters the recuperator and is preheated by the hot exhaust gas (red); fuel is added to the preheated air and is burned in the combustion chamber (orange)
© Ansaldo Energia

Noise

Decentralised installations are often built near residential areas or in areas where people are present for work or social reasons. Efficiency and energy savings cannot be done at the expense of the comfort of those who live in or frequent the areas where the systems are located. Noise emissions are often a topic treated after installation by utilising specific abatement systems appropriate for the single installation. However, the problem should be faced in the design phase of the single module, taking particular care in identifying systems capable of reducing noise emissions as far as possible while meeting regulatory requirements.

10. Materials

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. Turbine inlet temperatures (TIT) and the capabilities of high temperature alloys have increased by approximately 500°C and 220°C, respectively, over the last four decades. Advanced turbine blades and vanes are subjected to operating gas temperatures of 1600°C (in so called "H" class engines) and future targets aim at 1800°C. The hot gas path parts of the turbine highly rely on advanced cooling design and thermal barrier coating (TBC) systems. Additionally, increasing international ambition towards emissions reduction, efficiency gains and RES integration have led to some initial changes in operational requirements for gas turbine technology. This trend will further impact gas turbine operation toward more flexible (both fuel flexibility and loading regime), responsive units which would significantly impact the operational life of the gas turbine materials and coatings.

The blades and vanes of a gas turbine with frequent start cycles should be replaced at much shorter intervals than are traditionally practiced. The impact would be even higher for the parts of the turbine which are difficult to replace, such as the rotor and casing. The rotor life of most frame engines is limited to 3000-5000 starts (previously expected to be reached after 20-30 years of operation). However, for a unit with frequent starts, this could be reached over a span of 6-10 years. The rotor alloy and its fatigue life need to be re-evaluated and upgraded to accommodate the expected higher number of start cycles.

The following topics further describe specific materials issues for further R&D.

Improved alloys

Extensive research was conducted in developing the advanced single crystal blade alloy, which was required for turbines with a higher TIT. However, limited hot corrosion resistance (typically type II hot corrosion) and preferential oxidation at low temperatures (but at high stresses) were drawbacks which limited the life of these advanced superalloys. Minimal work was performed in understanding the alloy oxidation behaviour when operating at lower temperatures (400-600°C) but at high stresses (~600 MPa or higher). *Figure 7* shows the cracking of a single crystal blade alloy by preferential oxidation of gamma prime, at a relatively low temperature but highly stressed region of the blade. This type of cracking, which grows relatively fast, has affected several aero and industrial engines in recent years.

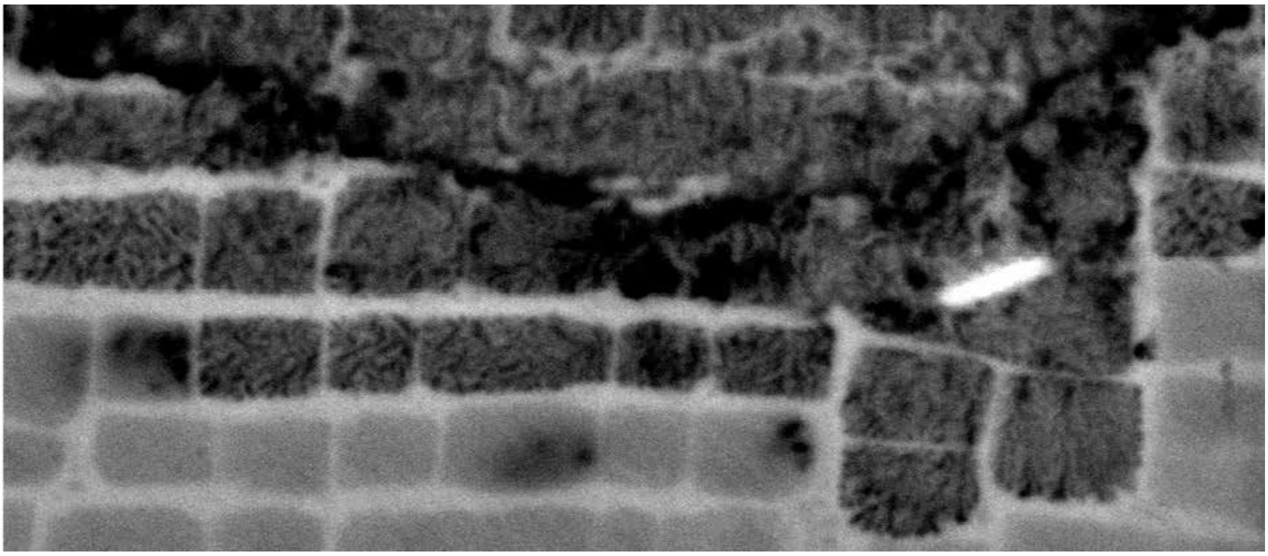


Figure 7: Preferential oxidation of the gamma prime at a low temperature and highly stressed region of an advanced single crystal blade leading to blade cracking

Most modern alloys are designed to sustain long creep life. However, for the future market demand (i.e., with fuel and start flexibility), alloys with higher thermal fatigue, oxidation, and hot corrosion life, with acceptable creep life would be more favourable. Other points such as the critical raw materials, repairability and sustainability are to be considered when developing the new alloys.

Ceramics or alternatives

For turbines with extremely high inlet temperatures (~1800°C or higher), 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 conventional nickel-based superalloys, but also for micro gas turbines, where uncooled parts are required.

Thermal Barrier Coatings (TBCs)

A thermal barrier coating (TBC) is an intrinsic part of the design for most modern gas turbine hot components. Comprehensive research has been carried out, and is in progress, on TBC development. Some newer coating solutions have emerged such as: segmented TBCs, super thick TBCs and low conductivity TBCs. The low conductivity TBC is a superior solution for gas turbine blades of engines with extremely high turbine inlet temperatures (>1600°C). While the durability of these coatings for aeroengines has been tested, their application for land-based gas turbines with alternative fuels has yet to be investigated.

Further research should focus on improving the durability of TBCs for units with higher numbers of start cycles (as the number of starts limits the coating spallation life) and developing non-destructive inspection techniques for assessment of the coating to assist with understanding the residual life of service-run components. Most TBCs have a short spallation life in the presence of contaminants due to acceleration of the oxidation and corrosion rates of the bond coat. Developing TBC systems which tolerate a moderate level of contamination in the hot gas stream would further benefit the industry.

TBC coating application by plasma spraying methods for industrial gas turbines (or Electron Beam Physical Vapour Deposition (EB-PVD) for smaller engine blades) is well established. However, further development is expected to improve the spraying yields, and produce longer life coatings, with further attention given to the segmented type coating.

Hot corrosion behaviour

Hot corrosion of blades and vanes, arising from traces of salt or contaminants such as Na, K, S, Cl, P, Pb, and V in the fuel or the intake air could be a major cause of damage and lead to premature service-related degradation. Most OEMs put certain restrictions on the level of contaminants which should be passed through the engine. Although no materials or alloys are fully immune to hot corrosion, some provide much better hot corrosion resistance. Hot corrosion could be a major issue for advanced single crystal blade alloys, where the chromium content is normally only around 6 wt.% or lower. When their coating is damaged or lost, the substrate material would corrode relatively rapidly and result in reduced life of the part. Further work around the oxidation and hot corrosion lives of the coatings for blades made from these materials would be beneficial when it comes to extending the maintenance interval or evaluating the integrity of the part.

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 material compositions/structures which otherwise cannot be achieved through conventional 'subtractive' manufacturing methods. Additive manufacturing (AM) allows the production of components with alternative material compositions and with geometries which are impossible to produce using conventional manufacturing, through a layer-by-layer material addition process. It is also worth mentioning that AM is already being used in GT combustion components and is likely to be essential for enabling hydrogen combustion.

An additional benefit of additive manufacturing is strengthening the alloy by oxide dispersive mechanism (i.e., oxide dispersion strengthened (ODS) alloy). ODS alloys were extensively researched in the 1960-70s. However, because of the difficulty in producing a uniform oxide dispersion in the alloy matrix, limited commercial development followed. With modern additive manufacturing technologies, a new generation of superalloys with advanced capability is expected to emerge for gas turbine applications.

With advances in AM technologies, which could be capable of producing complex through-wall cooled parts (which was not practical with the traditional investment casting), attention could be given to developing new superalloys with acceptable creep properties and improved hot corrosion/oxidation resistance and fatigue properties.

A final area of interest would be developing non-destructive techniques to assess additively manufactured turbine parts and developing AM process for repairing advance turbine components for extending the life to assure their integrity.

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

Further development of advanced non-destructive evaluation (NDE) techniques linked with evolution of the alloy/coating microstructures would be highly beneficial for predicting the consumed life of ex-service parts and preventing unnecessary repair and replacement.

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 chromium) and nickel (notably fine nickel oxide particles) are on the list of Substances of Very High Concern (SVHC, i.e., substances that are considered carcinogenic or offer risks to health) along with 26 other base materials or alloying additions found in GT 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 chromium release is an area of concern.

Additionally, the gas turbine alloys contain a large amount of strategically important, and difficult to source, elements such as Co, Mo, Ta, W, and Re. Reducing unnecessary replacement of gas turbine components, by re-evaluating the component life after service, will reduce the environmental impact and costs for the operators.

Hydrogen Capability and Impacts

To enable decarbonisation through fuel switching, research is required into the impact and suitability of GT components and systems to transition to higher levels of hydrogen in the fuel, up to 100% hydrogen capability. Hydrogen-related alloy embrittlement (and weld sensitivity) before combustion is to be reviewed and tested. However, after combustion, the impact of high levels of water vapour in the combustion gas on alloy and coating oxidation are yet to be understood. High water vapour tends to increase TBC spallation by increasing the bond coat oxidation/spallation rate. The behaviour of alloys and coatings in environments with high levels of water vapour, combined with traces of contaminants (such as Na, S, Cl, etc.) needs further research.

11. 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. Until recently, reducing maintenance costs was the main driver to repair the capital-intensive turbine parts and return them to service. However, it is equality important to consider the environmental sustainability and supply chain to repair and return more gas turbine parts for further safe operational cycles. Recent advances in inspection and repair technologies paved the way for more complex repairs. A decision to send a part for a repair is primarily made on an operational time interval rather than a condition-based assessment. This is also an important issue which should be considered to reduce the carbon footprint of gas turbine maintenance.

Advancements in computer technology utilising Computational Fluid Dynamics and Finite Element Analysis has enabled OEMs to improve the overall performance of the gas turbine leading to more complex part geometries and cooled thin wall parts. The drive for further operational improvements has pushed the design limits and introduced new materials protected by sophisticated coating systems. The critical components of a gas turbine such as 1st stage blades and vanes are designed on the basis that it can be inspected, repaired, and recoated after each operational cycle to achieve the nominal design life.

This implies that geometrical tolerances, material behaviour response and coating life have become more stringent and critical. The repair industry needs to have a full understanding of the damage and critical aspects of the individual components. Obviously, this requires extensive examinations of the ex-service parts and operational data. Extensive investments in metallurgical investigations, dimensional measurements and computational simulations are required to understand the weak spots in a design and define the repair limits. In addition, more than 100 different processes are applied to restore parts to the required metallurgical and dimensional conditions.

The following sections discuss the state of the repair industry and new repair technologies under consideration.

Inspection

Advanced repairs start with a detailed inspection of the individual component from a set of parts. The inspection needs to focus on the geometry of the part, the material condition and the damage observed on both internal and external surfaces. Full assessment of the material is only achieved if 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 and the heat treatment response. For the parts which have passed the nominal design life or parts with limited design margin, it is advisable to destructively test a representative part from a set to evaluate the condition of the part for a run, repair or replace decision. Metallurgical condition of the ex-service part is normally evaluated under optical and scanning electron microscopy to determine the base material, coating composition and evaluate the level of material degradation. From this analysis, a decision should be made if the parts can be returned to service for a further operational cycle or to be fully repaired and recoated.

In case of a full repair, the coating removal from the external surface (i.e., the so-called "stripping process"), 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 further assisted by mechanical processes. It is recognised that exposing parts to corrosive chemicals holds a degree of risk in case the stripping agent attacks the base material. Obviously, selective attack of the coating is a prerequisite and needs to be carefully assessed before applying the process to the low chromium containing materials. Furthermore, penetration of stripping agent into the internals of cooled parts needs to be avoided by proper masking. Partial removal of the overlay coating through dedicated machining should be considered as a potential option. However, this shall be assessed case by case.

Depending on the base material, the appropriate heat treatments are selected to stress relieve the components and solution heat treat the base material (e.g., create fine gamma prime and less grain boundary carbides). For particular single crystal alloys, these heat treatments are complex since existing residual stresses and high solution temperature can lead to recrystallisation of the material and loss of mechanical properties. This implies that a heat treatment applied during a repair cycle to rejuvenate the material structure may not necessarily be the same as the heat treatment used for the original manufacturing of the part.

Traditionally, many of the dimensional inspections were carried out utilising hard gauges or Coordinate Measuring Machines (CMM) analysis. This has been replaced by white light or blue light scanning. These techniques create 3D models of parts, which can be directly compared to the initial designs leading to an improved understanding of the levels of distortion or damage the part has experienced. Scanning is also a powerful tool to control the dimensions of the parts during the entire repair process. Costs are reduced through fully automated handling and processing of the data.

Residual wall thickness measurements of cooled parts are essential to understand part residual life. This analysis is completed once the serviced coating has been removed and the parent material exposed. Techniques used to measure the wall thickness include Eddy current, ultrasound, or Hall thickness gauges. Air flow (and water flow) testing of cooled parts is carried out to verify the cooling functionality of the parts or segments of those parts. This can be assisted by thermal imaging to detect individual blocked holes.

Once the parts are free of coating and have been dimensionally checked, the level of surface degradation and cracking must be evaluated. Visual inspection and fluorescent penetrant inspection are processes utilised today to categorise surface indications although there are multiple other techniques.

Evaluating the condition of the internal surfaces of the part, with particular attention to the advanced blades with complex cooling systems, is key to a successful repair. Standard crack detection of the internal surfaces is carried out through X-ray, however since the resolution of this technique is limited, additional technologies are used such as ultrasonics, acoustic emission, and borescopes inspections. Dedicated technologies such as active thermography and compensated resonance testing show promising results, however, still yet to be further developed. Therefore, a combination of techniques should be employed to understand the condition of the internal cooling cavity (and the cooling holes) before progressing with the repair.

The blade root and shank areas are to be properly evaluated. For advance blade alloys, which contain low amounts of chromium, the shank area is evaluated for pitting corrosion (type II hot corrosion). The contact face of the blade root and damping pin slot is evaluated for fretting damage and cracking. The fir trees might be inspected by dedicated Eddy current probes for high cycle fatigue cracks/indications.

Following a detailed inspection, a decision is to be made for applying an appropriate repair process on the parts. In some cases, the repair would be an opportunity to apply a simple redesign to the component, which would significantly improve the life of the repaired part in service (i.e., beyond the original design). Some experience and knowledge of the component design, operation and repair processes would help a decision on any redesign.

Repair

Once the parts have been inspected and the level of degradation is understood, the repair process phase can begin. There are two key processes adopted to repair cracks and to restore the geometry. Welding and high temperature vacuum brazing are widely utilised today both for legacy and advanced engine components. Tungsten Inert Gas welding has formed the backbone of cracks and welding of missing material such as blade tips and seals. Automation of this process (in line with some laser welding) is introduced in industry for tip welding applications. However, filler materials, equipment and techniques have significantly improved meaning that alloys once deemed unwedable are readily welded under a protective atmosphere. This is mainly attributed to a reduced heat input resulting in a smaller heat affected zone and less thermal strains. Further improvements are focusing on new weld materials that have a comparable strength as the parent material or even a better corrosion-oxidation resistance. New developed filler materials could also be applied by laser assisted processes and significantly increase the repair limits. In some cases, additive manufacturing has also been tried as an option to repair and restore the blade tip. This is a promising process and yet to be developed further, specifically when it comes to improve the cracking and oxidation resistance of the advance single crystal blade tip.

For many fine cracks and surface restoration vacuum brazing is the process of choice. However, this might be limited primarily to the stationary parts. This process relies on the parts being metallurgically clean. This is achieved by removing of the oxides through a reducing atmosphere at high temperature (HF or H_2 cleaning). The effectiveness of this process depends on the thermodynamics and chemical composition of the base material, as well as the type of contamination. Process qualification for a given case is essential. Powder metallurgy is then used to create filler materials, which are chemically aligned to the base material. Most of these powder compositions contain boron or silicon-based materials with a lower melting point than the base material. When heat treated, this material will melt and in the liquid phase sinter the "base material". Depending on the process, high strength joints or overlay thickness can be achieved. This process depends on many parameters and research remains ongoing to find the best solution for the given application. The interaction between the braze material and the parent alloy is of eminent importance and needs full attention and qualification. The overlay brazing process can be used for repairing some large linear defects. Any decision should be based on a knowledge of the process and the required integrity of the part in question.

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

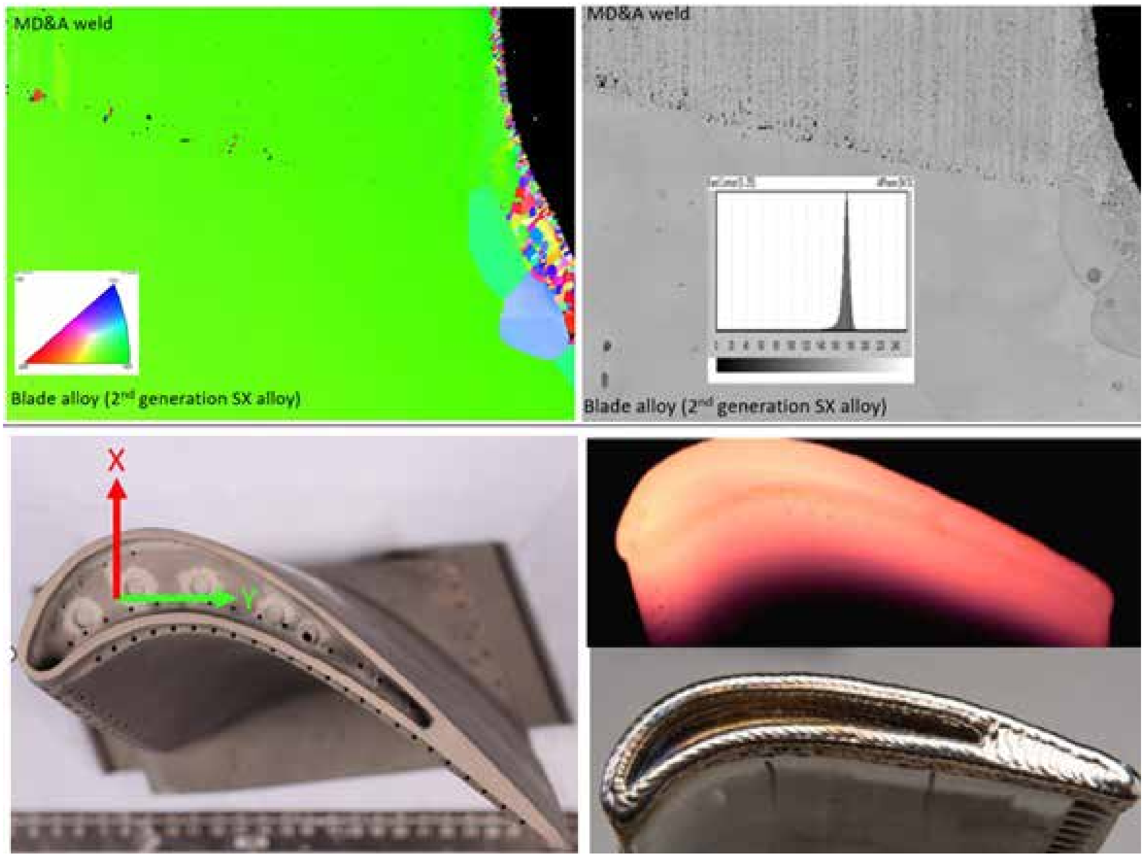


Figure 8: Advance weld repair development
© MD&A

Coating

Application of coatings is essential to achieve the lifetime of advanced parts. Coating systems continue to evolve based on field experience and with an increase in inlet temperatures. To extend time between overhauls, thermal barrier coatings (TBC) have been increasingly used on critical engine parts. These are applied over an oxidation and/or hot corrosion bond coating (MCRALY), which provides the correct environmental protection for the application.

There are significant ongoing R&D activities to further optimise coating chemistry and adhesion. The avoidance of coat down of existing small cooling holes with TBC is essential for the life of the part. Laser ablation and vision techniques play an important role to reopen these small holes, while avoidance of coat down through smart processing and new coating technologies are at lab scale and need further assessment. The final surface finish is achieved by various techniques, to produce a part with the desired surface roughness. A final aging heat treatment is applied after the coating.

Additionally, there is a need to better control the quality of internal coatings. The component life of thin wall cooled blades and vanes depend on a protective internal aluminide coating. In case of poor coating quality, the base material will be affected and lose its mechanical integrity, which might lead in turn to failure initiation at those locations. Process stability and quality assurance are of eminent importance during initial coating application, removal of the coating and reapplication.

Given the low cost of geometry scanning, it is recommended to perform a 3D scanning of the parts (or at least a sample of the parts), which are suspected to undergo creep deflection and deformation. This information would greatly help when it comes to decide on the condition of the parts for further repair.

The parts are finally inspected and boxed to be returned for another service interval.

In conclusion, the repair of complex parts requires an extensive knowledge of material science, inspections techniques, manufacturing technologies and computational analyses. The qualification of the repair process is component specific and needs a full development cycle. Next to the restoring of the material and coating properties, wall thickness of cooled parts is one of the most important parameters to control. The introduction of white light scanners within the repair process provides a strong tool to control these dimensions effectively.

The decision to repair ultimately relies on applying the knowledge and technologies to improve the integrity of the advanced gas turbine parts for further safe operation in the engine. If this is executed correctly, a large portion of the gas turbine parts can be safely returned to service after the end of nominal design life. This process reduces the unnecessary scrapping of capital-intensive parts and significantly benefits environmental sustainability.

12. Reliability, Availability and Maintenance

Gas turbine operators are constantly focused on delivering their production to customers. A high rate of reliability allows ambitious forecasts to be reached without disruptions that would otherwise generate time loss, team and organisation efforts, and loss of production revenue. High availability is a key driver to maintain and potentially increase production (e.g., electricity, heat, steam, or oil and gas) with a given asset. The ultimate goal for gas turbine operators would be a maintenance-free gas turbine, knowing that this would increase the asset availability and decrease operational expenditures. Another factor which can potentially impact the unit operation is compatibility with environmental regulations and emission control. This aspect of operation will be under further scrutiny for gas turbines using conventional fuels. Therefore, gas turbine reliability when operated with alternative fuels such as hydrogen will be crucial in the transition to net-zero.

High reliability, availability, and maintenance (RAM) values are of paramount importance to the gas turbine user communities because it impacts their day-to-day operations. 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, monitoring and data acquisition systems, data evaluation algorithms, procedures to detect faults and an understanding of asset integrity. Beyond the expected improvements in accuracy, further developments are needed to take advantage of the advance in the digitalisation of power plants and to make these tools easier to operate and directly usable by an operator or pool of operators.

Gas turbine reliability will also be improved with more robust instrumentation having not only 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. Directly associated instrumentation for control and protection should be maintained and calibrated in line with the gas turbine maintenance interval to avoid unnecessary additional outages.

Other areas which would further help the community and need further attention are understanding the reliability of advance gas turbines which are designed to their limit, understanding the reliability of the older fleet of gas turbines (i.e., new or matured engines) under flexible operation (e.g., high start cycles or fast load change), and determining the impact of alternative fuel on the availability and reliability of the units [26].

Availability

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

Key developments should improve the capability of the gas turbine and its associated systems to sustain harsh environments (i.e., gas and liquid fuels with high sulphur content, offshore and coastal locations with wet and salty conditions) as well as flexible operating regime. Materials, inspection, and repair technology improvements should also play a role. This includes tailoring the repair and coating to a specific operation regime. For instance, advanced nano coating (or similar) on compressor air foils which produces extremely smooth surface finish would reduce fouling and thus the need for operational interruptions, such as shut down for a compressor wash. Inlet air filtration system addressing industrial conditions like hydrocarbon vapours or soot would improve air intake filter performance and enable longer service time between maintenance at high efficiency.

Finally, improved availability forecasts considering 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 shutdowns [27].

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% reparable and reusable components.

Modelling and algorithms for predictive analysis (e.g., thermal engine or sub-system performance) require further improvement to provide the complete set of benefits that operators expect from the developments in condition monitoring and remaining useful life evaluation. The integration of different digital tools provides opportunities enabling the adoption of condition-based maintenance. Complementary to this approach, further model improvements are needed in investigate risk-based maintenance, which considers the probability and the economic consequences of the potential failure modes. Combining 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 due to large scale adoption of the developed best practices. Besides, technology and methodology transfer from other industries considered to be best in class (e.g., nuclear, aviation, etc.) can provide large benefits to the gas turbine sector.

Recent improvements in remote systems and access have also accelerated the need for remote assistance implementation. While it may not become common practice at each site in the long term, several activities have benefited from the faster response or cost reduction opportunities. A balanced approach to operational data access and processing (on site or remotely) would further help to improve the reliability of the system.

Up to date training of the operational and maintenance team in the power plant would further improve the unit availability and reliability.

13. 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, the 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. Additionally, there are also concerns regarding 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. The following suggested topics are aimed at answering the concerns of end users and highlighting the benefits of digital technology.

Development of Digital Twins

Digital Twins *(see Figure 9 below)* are virtual representations of real-life entities like processes (e.g., sourcing, logistics, or construction) and assets (e.g., turbines, power plants, or power grids). The virtual representation comprises at least a simple data model, but it may also include complex simulation capabilities. It will be updated on the time scale of the aspired use case and has no limitation in terms of data sources. Therefore, it can cover the entire life cycle of the entity.

The target state of a digital twin, configured on the basis of standardised information or data packages, so called data products, depends on the considered use case. The classification of the maturity level starts with a static representation (e.g., for reporting purposes), and ends in a digital twin for dynamic prediction to support predictive or preventive maintenance enabling autonomous operation.

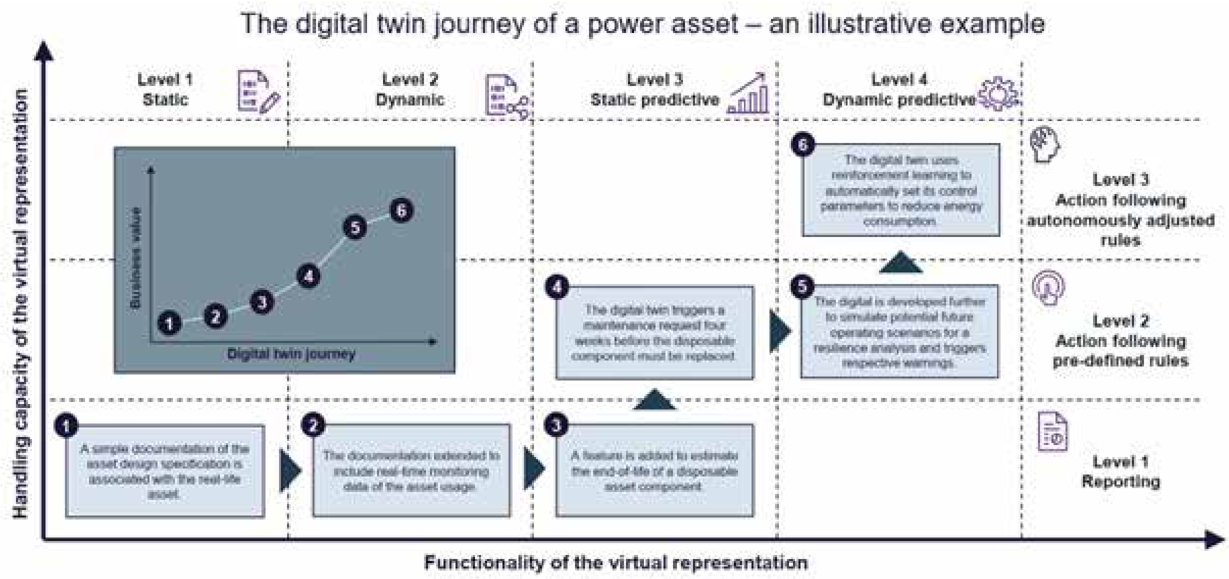


Figure 9: The digital twin journey of a power asset
© Siemens Energy

Within such a digital twin ecosystem, individual digital twins can be configured for specific use cases with or without simulation capabilities. Using the different existing data sources within a standardised digital twin ecosystem architecture, the scope starts from a simple asset, such as a piece of equipment, via the plant level up to whole energy-systems covering the complex grid level including all aspects of energy production, storage, transmission, and consumption. When smart simulation capabilities are included, the user can optimise microgrids and energy consumption, foresee reliability risks and support the vision of an autonomous operation of energy assets up to whole energy systems.

Data Management

Turbomachinery equipment, such as in power plants, produce large amounts of data during their lifetimes. Timely insights into these data sets help to ensure safe, reliable, and efficient operation of the power systems. As one investigates adoption of digital solutions to improve overall performance, reliability, and transform the way things work, there will be a growing necessity to access other data sources to deliver these solutions.

There is also an increasing expectation for interoperability and data sharing across technologies as the industry and energy systems become more connected and further integration is anticipated – data is one of the common denominators here and so a common approach to data management is key to facilitate and ensure proper data governance.

As the requirements for energy systems, including turbomachinery, continue to evolve, the complexity of the associated data lifecycle will also increase accordingly. Further effort is required to develop and evaluate solutions for data acquisition, storage, sharing, provisioning, and processing for advanced analytics and interface at increasing scale and speed. More importantly, it is essential to continue to invest in methodologies and techniques to address data quality, enable consistent and robust access control and security to ensure data integrity, reliability, and availability.

Cyber Security

Turbines are often operated as part of critical infrastructure and are subject to current and future cyberattacks. The energy industry is currently facing significant risks worldwide. Therefore, cybersecurity activities must be aligned with local laws and regulations. To fulfil these legal requirements, cybersecurity standards, such as the ISO 27000 family for information security management systems in general and IEC 62443 for industrial cybersecurity, define and provide proven and state-of-the-art best practices. Leveraging an international standard for industrial cybersecurity, such as the leading IEC 62443 standard for products and solutions, supports interoperability, reduces operational costs, and fosters standardisation. 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.

Machine Learning / AI

The energy domain across its full value chain from design, manufacturing, operation, maintenance and repair has been dominated by classical approaches. Historically, physics-based methods and computer simulations have been state-of-the-art. The ever-increasing amount of data and Huang's law, making vast computational resources available, laid the grounds for the development of a third pillar: Artificial Intelligence (AI) and Machine Learning (ML).

Here, some fields will be of special interest, considering the current needs to transform energy systems with a focus on reliability, sustainability, safety, and affordability. Among them, computer vision, time series analysis for anomaly detection and forecasting, federated ML, and edge ML.

Advanced computer vision (CV) technologies will be an integral part of solutions for autonomous operation, monitoring, anomaly detection for (predictive) maintenance, automatic quality, and wear inspection after operation and many more. In combination with IoT, CV will also be used to feed digital twins in many ways. The entire field will largely contribute to safety by minimising incidents and to the qualitative and quantitative assessment of defects, leading to scalable, cost-effective surveillance solutions. The same will be true for unmanned operation and hierarchical autonomous data acquisition strategies.

In the field of time series analysis, anomaly detection and forecasting will be in focus. Anomaly detection may be addressed in the time domain or across different sensors, so missing data or incomplete sets of sensors for varying instrumentation of assets must be considered. Forecasting with data-driven models will be required for the cost-effective utilisation of new developments, e.g., for storage solution optimisation like wear and aging models for electrolysers. More applications arise in forecasting of power consumption and demand from the grid, requiring novel approaches in this field of time series analytics.

Since the energy domain is part of the critical infrastructure, federated and edge ML will be of high importance as well, as any asset needs to operate at a maximum level of autonomy. Resilience and redundancy will only be achievable with edge-based services. Consequently, ML solutions must be deployed on-site and independent of cloud-based computational resources, for example. And while edge computing capabilities are limited, resource demanding models need adaption.

Finally, an increasing concern about data privacy and specific local regulations such as the General Data Protection Regulation (GDPR) in the EU, requires special caution when it comes to the development of models using data from different sources. Data owners may have concerns sharing data with the vendors of ML models, e.g., technical barriers, commercial competition, or for legal reasons. Federated ML has been developed to address these concerns with their distributed learning approach, updating models locally and aggregated globally without the need for centralised data storage. Federated and edge ML are tightly connected and must be further developed as they directly add to the resilience and reliability of the energy system as a critical infrastructure.

14. Sensors & Instrumentation

Sensors play a fundamental role in the control of industrial machineries and processes. Gas turbines require sensors that are highly accurate, fast responding and temperature resistant. In order to maintain safe and reliable operation, a large number of machine parameters have to be continuously monitored.

Sensor 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 consequently CO_2 emissions while bringing economic benefits. The incoming transition to low-carbon fuels will require specific sensors to guarantee safe and reliable operation of the plants. Low-carbon gas turbine operation will involve significant fuel flexibility of the new fleet and, importantly, of the modified installed fleet. As well as core combustor adaptation, fuel delivery modifications or the installation of Carbon Capture and Storage will be required in many cases along with SCR systems for NO_x abatement.

Future IEA low-carbon energy scenarios predict that approximately half of all CCUS systems will be retrofitted to existing CCGTs. Therefore, future gas turbine use in low carbon grids will likely be integrated with significant additional process equipment. This makes plant start, stop, and ramp up/down much more complex and adds to the needs and opportunities for plant optimisation and condition monitoring. It also makes plant options for Grid Auxiliary Services significantly more complex. This inevitably complicates plant control strategies and increases the demand for reliably delivered and actionable data.

The ETN community has been consulted in terms of suggested instrumentation capability gaps that could inform R&D requirements. We have noted the excellent work of EVI-GTI (https://evi-gti.eu) and PIWG (https://piwg.org) who have defined required gas turbine instrumentation developments for many years, and we include development themes from their work within these recommendations.

Sensors and instrumentation developments should focus on the following areas.

Instrumentation for operation and maintenance optimisation

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 gas turbine component health and life consumption. This embedding of sensors into hot structures applies only to technologies that can survive the environment, one candidate being sapphire based Fabry-Pérot optical sensors. The use of additive manufacturing to embed instrumentation (e.g., temperature, pressure) in components and locations previously remote or requiring extrapolation is a discussed topic although commercial realisation has not yet been achieved. The potential benefits are those of safer reduced margin operation, improved performance, and enhanced condition monitoring. Aero engine applications may lead these developments.

Artificial Neural Network (ANN) sensors may provide opportunities for combustion optimisation and control with initial work on reciprocating engines potentially being extended to gas turbines.

Fiber optic sensors offer an opportunity for the distributed measurement of temperature or strain. Solutions based on Fiber Bragg grating technology need validation for high-temperature (i.e., 700°C) applications in industrial environments.

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. Acoustic (microphone) techniques are an alternative route for development. Software development to address actionable data is a major opportunity with enhanced autotune systems worthy of further development.

Non-intrusive temperature measurement capability for flashback detection (in combustor) and turbine blade metal temperature has potential for extending the safe operation of advanced flex-fuel combustion systems – and its further development has merit.

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 understanding of firing temperatures and therefore control of the machine. This would enable operation closer to the gas turbine design values, with benefits for efficiency and maintenance intervals. Instrumentation for gas path temperature measurement that has lower temperature accuracy drift in service than traditional thermocouples would deliver overall cost benefits for powerplant.

Downstream of the gas turbine, more accurate emission sensing techniques such as Fourier Transform Infrared (FTIR) spectrometry create new opportunities for the on-line analysis of exhaust gas composition.

Power plant 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 to reduce the cost and time for repairs.

Gas turbine compressor optimisation by operating with a reduced surge margin is an opportunity for performance improvement in power, efficiency, and start/ramp. To benefit from this, high frequency, high sensitivity, stage level pressure measurement systems should be further developed and implemented.

Fuel delivery instrumentation improvements to enable real time tracking of fuel composition would help manage core combustion and emissions better in a market in which fuel specification is now wider and more uncertain. In a hydrogen or ammonia fuel blend, if the hydrogen or ammonia proportion of the blend with natural gas is fluctuating, using sensors to detect the level of the secondary fuel in the blend would be important. Cracking some fraction of the ammonia, or at least vaporising it to burn it as a gas and monitoring the phase or liquid fraction of the fuel would be important also. Making sure the catalyst 'cracker' is behaving as intended by monitoring could also be important. A fuel tolerant combustor can be devised, but the GT control needs to know what is being delivered in the moment. The fuel delivery system having to handle such a wide range of fuels, MWI, liquids, and gases is also challenging and needs sensors to inform the control system. This tends to be under-appreciated with the focus on combustion and emissions. This is particularly true with the potential introduction of hydrogen into natural gas, where it will be important to have fast response gas quality measurement that can determine the hydrogen composition in the blend and be able to feed that information into a GT control system to avoid instabilities and NO_x emissions. This could also apply to ammonia or ammonia/hydrogen/nitrogen blends (i.e., if ammonia is cracked before the GT).

Use of higher temperature electronics for >175°C module packaging presents an opportunity for smaller systems and more localised electronics. This could be a translation of aero engine technology to power generation applications.

Enhanced leak detection instrumentation, both for methane (natural gas) and hydrogen, inside and outside the GT enclosure (e.g., fuel delivery system) is of interest. There is an increased emphasis on reducing methane emissions given its high global warming potential, and so being able to quickly identify and rectify leaks is essential (in addition to the safety risk and cost of wasting fuel into the atmosphere). There is also quite a bit of work to be done yet on hydrogen gas detection sensors. This would also apply to ammonia with a very high safety need for detection in this case due to its toxicity.

Downstream of the gas turbine, more accurate emission sensing techniques such as Fourier Transform Infrared (FTIR) spectrometry create new opportunities for the on-line analysis of exhaust gas composition. High fidelity/reliability, multiple species, and quick response continuous emissions monitoring systems (CEMS), capable of non-standard gas detection such as hydrogen, ammonia, N_2O, and formaldehyde among others will provide the compliance assurance required to meet new environmental regulations.

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. The innovation would enable automated imaging of key components during scheduled shutdowns and then use of imaging software to monitor and predict degradation.

Ion species particulate sensors could inform on degradation and, as a result, maintenance planning.

Sensors and instrumentation for GT development

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

Development of flow path history coatings (which are distinct from thermal paint) continues and can be extended, potentially delivering REACH benefits and more detailed data.

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.

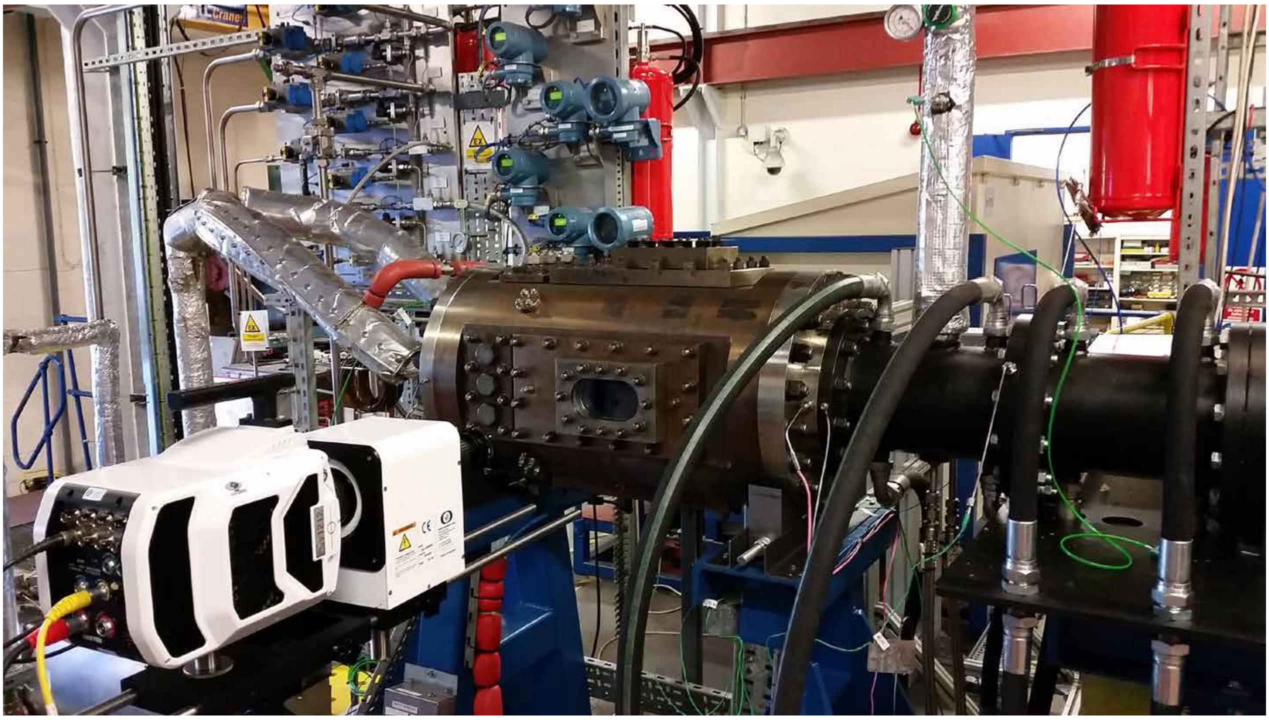


Figure 10: High Pressure Optical Combustor with High Speed Chemiluminescence at Cardiff University Gas Turbine Research Centre (GTRC)
© Cardiff University

Flame detection instrumentation (in combustor) requires further development, particularly with a wide enough optical range to be used for both natural gas flames and hydrogen flames (and blends). This could also apply to ammonia flames as well with a different optical signature.

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 and fast-response entropy probes will help the design of turbomachinery with higher efficiencies and wider operating ranges.

Enhanced tip clearance and tip timing capability based on technologies including Eddy current, capacitive sensing, and optical pressure sensing (potentially in combination) could provide gas turbine performance improvement.

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 significant interest in the 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 and lower cost than for hard wired solutions.

15. Condition Monitoring and Lifing

Plant cycling together with quick start-ups and rapid load changes result in less predictable effects of aging and degradation than in continuous operating conditions. Significantly changing 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 gas turbine operators. While the plant operators mainly require information on the status of the plant (i.e., operational state and possible ramp rates for starts, stops and load changes), the engineers and planners require detailed information from condition monitoring. Therefore, condition monitoring is a central tool to estimate operating hours until the next service, remaining useful life of components as well as required service activities and spare parts. It contributes to avoiding unexpected outages and reducing outage durations by allowing advanced detailed resource planning and identification and ordering of required spare parts. In case of advanced alloys and coatings being used by gas turbines (GTs) and heat recovery steam generators (HRSGs), condition monitoring supports the early detection of TBC spalling/blade hot-spots and the need for repair/refurbishment. Condition monitoring is therefore a necessary tool to ensure increased reliability, availability, and maintenance planning of GT plants.

For the power generation and oil and gas industries, high reliability and low operational costs are more critical than ever to stay competitive. Condition monitoring is a crucial technology to support the move from traditional time-scheduled or preventive maintenance to more advanced condition-based or predictive maintenance for both new and existing assets, particularly as the GTs are operated in varying and often hostile environments.

Specific topics for R&D activities for condition monitoring are as follows.

Integrated condition monitoring

There are many different condition monitoring techniques available in industry, such as visual inspections, vibration monitoring, debris and oil system monitoring, gas path diagnostics, acoustic monitoring, and life monitoring, amongst others. Each technique has a unique capability, however none of them can monitor all potential gas turbine faults or degradations. The inclusion and application of these technologies might significantly expand the coverage of engine health monitoring and improve the capabilities of condition monitoring systems. The quality and reliability of the condition monitoring systems could also be improved through integration as the same gas turbine fault/degradations could be monitored or detected by more than one method. Further research should target the development of integrated condition monitoring systems that include different condition monitoring methods. Data fusion could be applied to analyse the prediction results from different condition monitoring methods and provide a comprehensive view of gas turbine health.

Real-time and online condition monitoring

Real-time and online condition monitoring for gas turbine power plants is another area which requires further R&D activities. It is also closely connected to advanced data analysis tools due to big data (high sampling rate) and the associated fast processing requirements. Currently, condition monitoring and diagnostic systems rely on data from steady state operations as a base for analysis. Given the growing share of RES requiring balancing by conventional power generation technologies, the transient operations of gas turbines for rapid response to varying power demands will increase. The increasing importance of internet usage makes the online applications of condition monitoring even more necessary. Therefore, further R&D focus should be put on the development of real-time and online condition monitoring tools. This should also include fast data processing (e.g., to distinguish transients from normal fluctuations of measured values), transfer of big data, super-fast diagnostics, and online applications to achieve accurate, reliable and accessible results. Results of such development could also be used for the determination of consumed life and remaining useful life of the plants and/or its sub-systems.

Prognostic predictions of gas turbine degradation

Prognostic predictions of gas turbine faults/degradations are technologies to estimate how the engine degradation would develop into the future based on all the relevant historical data of the gas turbine engine. Every gas turbine engine would degrade at a different rate because the gas turbine health is affected by many variables, such as ambient and environmental conditions, operating conditions, design, and manufacturing quality of the engines, etc. The conventional time-scheduled maintenance could either miss unexpected failures or require maintenance of the engines when they are still in a healthy condition. To move from time-scheduled maintenance to condition-based maintenance, effective prognostic predictions (*see Figure 11 below*) to forecast gas turbine degradation well in advance is crucial. Further R&D research should focus on the development of prognostic condition monitoring technologies that are able to forecast gas turbine degradation or faults into the future. Such technologies are essential for condition-based maintenance and has a significant potential to improve plant availability and reduce maintenance costs.

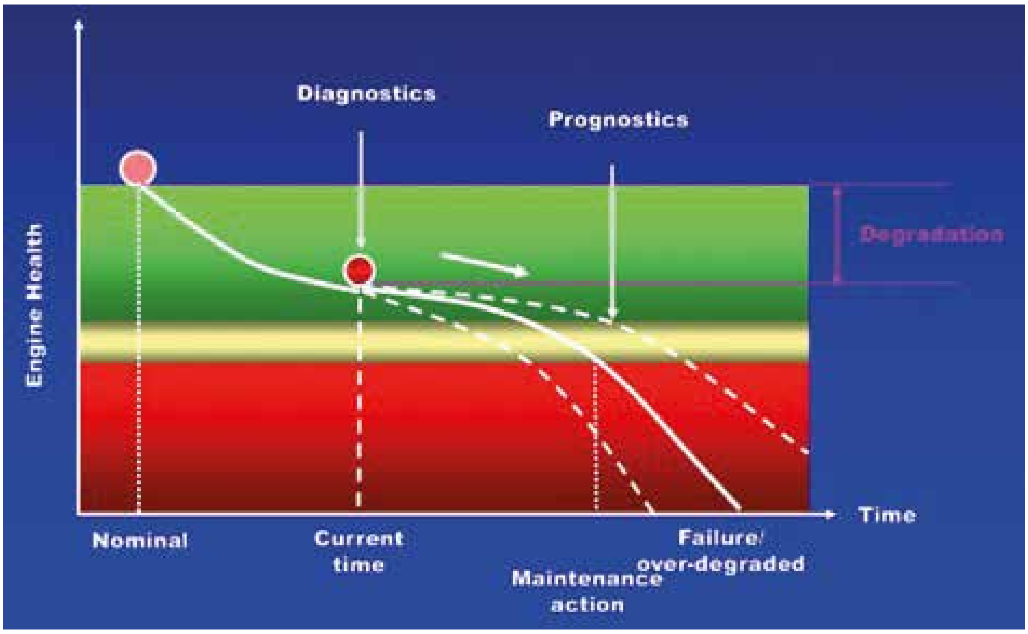


Figure 11: Diagnostic and prognostic predictions

Digital twins for condition monitoring

Gas turbine digital twins are digital representations of real gas turbine systems. For condition monitoring, gas turbine digital twins could potentially provide information of performance, operations, degradations, maintenance, etc. The R&D activities to develop digital twins based on models for gas turbine power plants could significantly improve the observability of the system health and provide enhanced support to operational decision making, condition monitoring, life consumption monitoring, overhaul, and maintenance. For example, this approach could be used in a situation where base load gas turbine power plants may be shifted to peaking units. Beside operational performance (i.e., efficiency, emissions, etc), gas turbine life will be consumed faster and become an important issue in the future. Most of the OEMs limit gas turbine rotor life to 3000-5000 start/stops. Lifetime extension beyond these numbers will become a challenge especially for non-OEMs (i.e., service providers). Digital twins of gas turbine power plants could provide crucial health information of the critical components of the machines and support life extension programs.

Monitoring of life consumption and Remaining Useful Life predictions

The life consumption of gas turbine power plants is affected by many factors. For example, high ambient temperature, polluted environment, high loading, severe engine degradation, and frequent starts and shutdowns will consume the remaining engine life more quickly. R&D activities to develop and implement the technologies for the prediction of life consumption and Remaining Useful Life (RUL) in terms of creep, low cycle fatigue and oxidation of life-limiting components (e.g., high-pressure turbine rotor blades) would significantly enhance condition monitoring capability, ensure safe operations of gas turbine engines and support condition-based maintenance. In particular, when moving from conventional natural gas fuel to low or zero carbon fuels such as hydrogen or biofuels, variations in fuel composition or online switching from one type of fuel to another might lead to operational issues and faster life consumption. This would be due to combustion instability, increased engine degradation and life consumption that need to be monitored and addressed.

Monitoring of critical performance parameters based on measurement data

Due to technology limitations, some important performance parameters of gas turbine engines, such as firing temperature or TIT, air/gas flow rates and the efficiencies of major gas path components (i.e., compressors, combustor, turbines) that should be monitored cannot be directly measured. By monitoring these parameters, the varying thermodynamic condition of degraded gas turbine engines could be determined. R&D activities to develop and implement technologies to accurately predict those critical unmeasurable performance parameters based on available gas path measurements are recommended. The developed capability could enhance condition monitoring, reduce operational risk, and support decision making for safer operations and more effective maintenance.

Artificial Intelligence applied to condition monitoring

Certain Artificial Intelligence (AI) technologies, such as ANN, have been studied and used in gas turbine condition monitoring. However, recent developments of Artificial Intelligence (AI) technology in various areas, such as chatbot, voice assistance, autonomous vehicles, facial recognition, gaming, navigation, etc. has demonstrated a surprisingly huge potential of capabilities. This indicates a great potential of AI to solve engineering problems. R&D activities to apply advanced AI technology, particularly Machine Learning, to condition monitoring of gas turbine power plants could result in very capable condition monitoring tools or digital twins. These tools could be trained using available data, information and knowledge of performance, vibration, visual inspections, acoustic monitoring, oil and debris monitoring, human knowledge and experience, operation and maintenance history, etc. When applied correctly, it could lead to intelligent diagnostic and prognostic predictions of faults/degradations and remaining useful life of gas turbine engines.

16. 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 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 or modelling tools & procedures
- Demonstration projects

Ongoing and future projects

HyPowerGT (2024-2027)

Demonstrating A Hydrogen-Powered Gas-Turbine Engine Fuelled With Up To 100% H_2

The HyPowerGT project aims at moving technological frontiers to enable gas turbines to operate on hydrogen without dilution. The core technology is a novel dry-low emission combustion technology (DLE H_2) capable of handling mixtures of natural gas and hydrogen with concentrations up to 100% H_2. The combustion technology has been successfully validated at TRL5 (early 2021) retrofitted on a 13 MWe industrial gas turbine (Baker Hughes NovaLT12). The new technology will be further developed and demonstrated at TRL7 on a 16.9 MWe gas-turbine engine (Baker Hughes NovaLT16) towards the end of the project.

ETN, as partner, oversees dissemination, communication, and exploitation activities.

Co-funded by the European Union

Clean Hydrogen Partnership

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

This project is supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research N° 101136656 and the Swiss Federal Department of Economic Affairs, Education and Research, State Secretariat for Education, Research and Innovation (SERI).

ASTERIx-CAESar (2023-2027)

Air-Based Solar Thermal Electricity For Efficient Renewable Energy Integration & Compressed Air Energy Storage

This project focuses on the development of a novel high-efficiency solar thermal power plant concept with an integrated electricity storage solution. The project combines air-based central receiver Concentrated Solar Power (CSP) and Compressed Air Energy Storage (CAES) to maximise conversion efficiency and power grid energy management, enabling a new operation strategy and business model. The hybrid concept initiates a futuristic era with adaptive renewable power plants, producing both electrical and thermal energy, including process heat supply and reverse osmosis desalination. Targeting a TRL of 6-7, the ASTERIx-CAESar concept will be validated with a 480 kW_{th} demonstration-scale prototype in a relevant environment.

ETN, as partner, oversees dissemination, communication, and exploitation activities.

Co-funded by the European Union

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 101122231.
www.asterix-caesar.eu

FLEX4H2 (2023-2026)

Flexibility for hydrogen

FLEX4H2 aims to design, develop, and validate a safe, efficient, and highly fuel-flexible combustion system capable of operating with any concentration of hydrogen blend up to 100% H_2. Crucially, this objective will be pursued at the most challenging hydrogen combustion conditions, i.e., at H-Class operating temperatures, required for highest cycle efficiency, while still meeting emission targets without the use of diluents. The design of the combustor will be based on Ansaldo Energia's Constant Pressure Sequential Combustion (CPSC) technology and will be demonstrated in a stepwise approach at full gas turbine operating conditions (TRL6).

ETN, as partner, oversees dissemination, communication, and exploitation activities.

Co-funded by the European Union

Clean Hydrogen Partnership

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

This project is supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research (N° 101101427), and the Swiss Federal Department of Economic Affairs, Education and Research, State Secretariat for Education, Research and Innovation (SERI). www.flex4h2.eu

ISOP (2023-2026)

Innovation in Supercritical CO_2 Power generation systems

The ISOP project aims to explore sCO_2-based power generation system technology and its potential through further research & development. By providing specialised training for 17 doctoral researchers to help establish the backbone of sCO_2 technology, the objective is to become a major contributor to the 2050 net-zero emissions target and lead to a crucial change in thermal energy power cycles.

ETN is a beneficiary of this project and will host one doctoral candidate (DC). Another DC will be seconded to ETN.

ISOP has received funding from the European Union's Horizon Europe research and innovation programme, Marie-Sklodowska-Curie Actions (DN-ID), under Grant Agreement N° 101073266.
www.isopco2.eu

CO2OLHEAT (2021-2025)

Supercritical CO_2 power cycles demonstration in operational environment locally valorising industrial waste heat

CO2OLHEAT's ambition is to support the EU's energy efficiency targets and GHG emissions reduction. This translates into the project's main objective – to unlock the potential of unused industrial waste heat and transform it into power. The development of innovative and cutting-edge sCO_2 technologies will be used to design and demonstrate in a real industrial environment an EU first-of-a-kind sCO_2 plant.

ETN is CO2OLHEAT project coordinator and is also in charge of dissemination, communication and exploitation activities.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 101022831.
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.

ETN is ROBINSON project coordinator and is also in charge of dissemination, communication and exploitation activities.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 957752.
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 when needed. This will enable the design and operation of an integrated power plant layout that can unlock additional combined-cycle power plant flexibility.

ETN, as partner, oversees dissemination, communication, and exploitation activities.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 884157.
www.flexnconfu.eu

ETN Additive Manufacturing (L-PBF) machines evaluation (2021-2024)

ETN enabled an industry-led consortium to carry out a study of Additive Manufacturing (AM) machine producers (i.e., machine OEMs). The study intends to investigate similarities and differences between execution and results when several AM producers were asked to perform the same build, all using the same powder feedstock as basis.

More information on this project can be found on the ETN website.

ETN High Temperature Gas Turbine Blade alloy for Additive Manufacturing (2023-2025)

The Additive Manufacturing Working Group is launching a new joint industry-led project titled "High temperature turbine blade alloy for additive manufacturing". The project will seek to identify and validate a high temperature alloy for manufacturing using the laser powder bed fusion (LPBF) process. The target alloy will have material characteristics and temperature capabilities upwards of 1000°C suitable for stage 1 turbine blade application.

The project will aim to identify candidate material(s) and develop it from TRL 3 up to TRL 4. This will include LPBF process development, key material property evaluation and capability demonstration using LPBF by manufacturing a select turbine blade geometry.

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 inlet 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 and other Alternative Fuels

The aim of the Hydrogen and other Alternative Fuels Working Group is to share technical knowledge and experience to progress towards the overall objective of safe and flexible low-carbon solutions for hydrogen and other sustainable fuels, such as ammonia. Through research collaboration and sharing of best practises from an operational and maintenance perspective, to the Working Group will accelerate the development and implementation of economically viable decarbonisation solutions for retrofit and new, advanced technologies, in line with the user community's needs. The activities of this Working Group are implemented through four taskforces on hydrogen combustion, alternative fuels, CCS solutions, and gas turbine safety.

Supercritical CO_2

ETN's Supercritical CO_2 Working Group 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 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.

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 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 and improve the integration of gas turbine systems into decentralised and multi-vector energy systems.

Gas Turbines Life Assessment & Extension

The Gas Turbine Life Assessment and Extension Working Group aims to address the challenges associated with extending the life of gas turbine components, with a specific focus on critical parts such as hot gas path components, rotors, and compressors.

17. References

[1] ENTSO-E // ENTSOG TYNDP 2022 Scenario Report – Version April 2022

[2] See Chapter 16 on ETN Support Schemes: Projects and Working Groups

[3] IEA (2020), Natural Gas-Fired Power, IEA, Paris https://www.iea.org/reports/natural-gas-fired-power

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

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

[6] More details can be found in Chapter 5 of this Report on Extended Fuel Spectrum.

[7] Source: IEA WEO 2022

[8] More details can be found in Chapter 8 of this Report on Advanced Cycles.

[9] More details can be found in Chapter 8 of this Report on Advanced Cycles.

[10] For more details about the way towards hydrogen gas turbines please refer to the ETN report "Hydrogen Gas Turbines" and ETN summary on "Addressing the Combustion Challenges of Hydrogen Challenges of Hydrogen Addition to Natural Gas".

[11] More details can be found in Chapter 2 of this Report on Market Conditions & Policy Framework

[12] See more details in a recent review paper of the ETN Working Group on Hydrogen.

[13] For more information on manufacturing techniques, see Chapter 10 Materials of this Report.

[14] M. Pathak, R. Slade, P.R. Shukla, J. Skea, R. Pichs-Madruga, D. Ürge-Vorsatz,2022: Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.002

[15] For more details, see efficiency in Chapter 4 on High Efficiency Power Generation in Chapter 8 on Advanced Cycles, and Chapter 9 on Decentralisation.

[16] More details are to be found in Chapter 5 on Extended Fuel Spectrum.

[17] More details are to be found in Chapter 5 on Extended Fuel Spectrum of this report.

[18] See https://netpower.com/technology/

[19] See https://www.cleanenergysystems.com/oxy-fuel-turbines

[20] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, REPowerEU Plan, 18.05.2022 COM (2022) 230 final

[21] More details can be found in Chapter 2 of this Report on Market Conditions & Policy Framework

[22] 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.

[23] More details can be found in Chapter 7 of this Report on Decarbonisation.

[24] "Thermal Energy Harvesting, The Path to Tapping into a Large CO2-free European Power Source", 2022, Knowledge Center on Organic Rankine Cycle Technology.

[25] More details on hydrogen are covered by the ETN "Hydrogen Gas Turbines" Report and the ETN "Hydrogen Deployment in Centralised Power Generation Report".

[26] More information can be found in Chapter 13 on Digitalisation, Chapter 14 on Sensors & Instrumentation, and Chapter 15 on Condition Monitoring and Lifing.

[27] More information can be found in Chapter 10 on Materials, Chapter 13 on Digitalisation, and Chapter 14 on Sensors & Instrumentation.

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