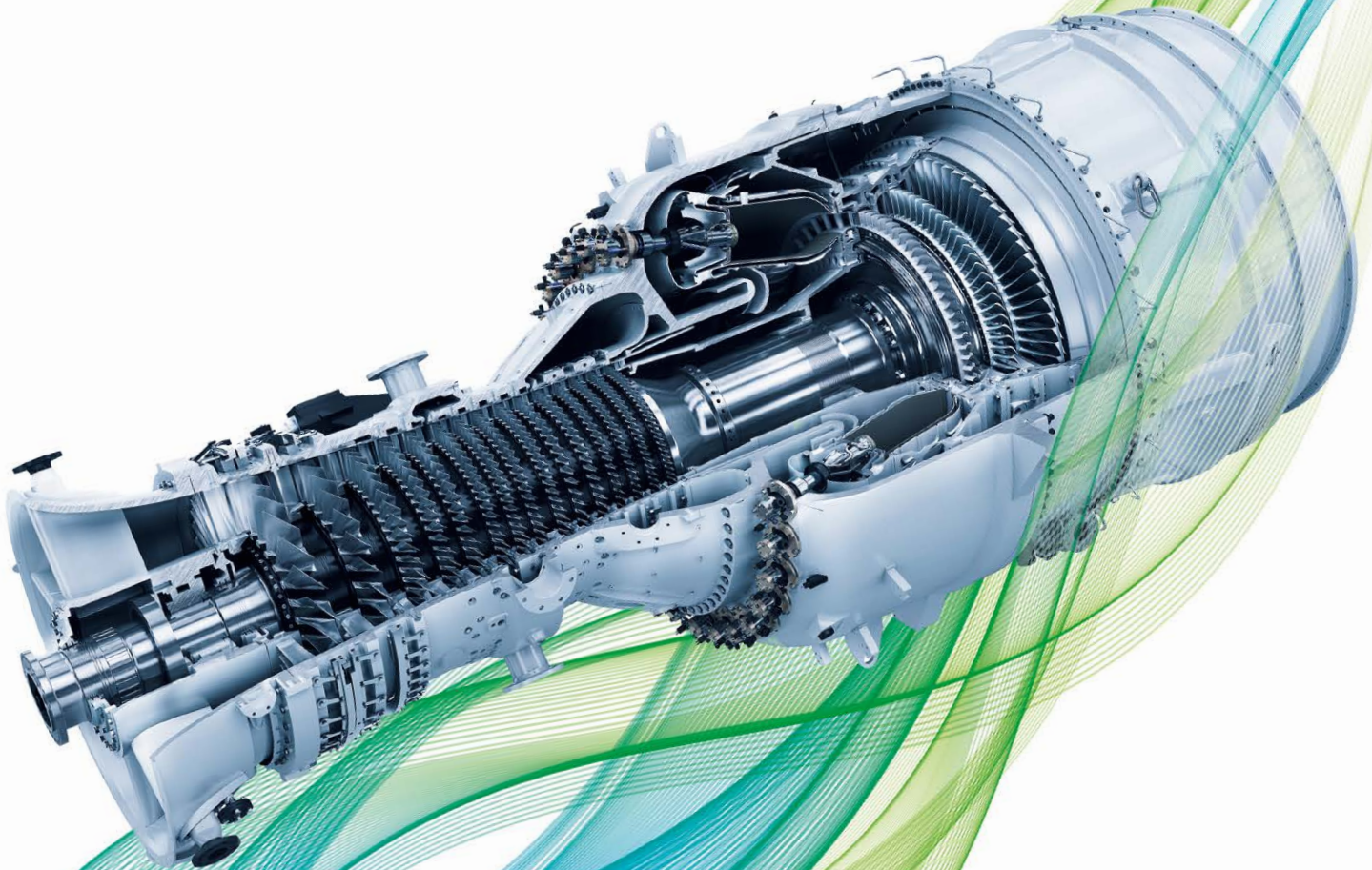




**ETN**  
Global

# ETN GLOBAL R&D RECOMMENDATION REPORT

2026 EDITION



March 2026

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.

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# List of Abbreviations

Acronym	Full name
AI	Artificial Intelligence
ALT	Accelerated Life Testing
AM	Additive Manufacturing
BCCBs	Brayton Cycle Carnot Batteries
BESS	Battery Energy Storage System
BZT	Bethe-Zel'dovich-Thompson vapours
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CBM	Condition-Based Monitoring
CCGTs	Combined-Cycle Gas Turbines
CCPP	Combined Cycle Power Plants
CCUS	Carbon Capture Use or Storage
CFD	Computational Fluid Dynamics
CfDs	Contracts for difference
CH <sub>3</sub> OH	Methanol
CHP	Combined Heat and Power
CI	Combustion Inspection
CID	Clean Industrial Deal
CMC	Ceramic Matrix Composites
COST	European Cooperation in Science and Technology
CSP	Concentrated Solar Power
CPSC	Constant Pressure Sequential Combustion
CV	Computer Vision
DfR	Design for Reliability
DERs	Distributed Energy Resources
DLE	Dry-Low Emission
DME	Dimethyl Ether
DSO	Distribution System Operator
EBCs	Environmental Barrier Coatings
EGR	Exhaust Gas Recirculation
EPA	Efficient Particulate Air
ESBD	Electron Backscatter Diffraction
GDPR	General Data Protection Regulation
GWP	Global Warming Potential
HEFA	Hydro-Processed Esters and Fatty Acids
HGP	Hot Gas Path
HI-CBs	Heat-Integrated Carnot Batteries

Acronym	Full name
HLUM	High-Level Users Meeting
HRSG	Heat-Recovery Steam Generator
HSE	Health, Safety, and Environment
HVAC	Heating, Ventilation, and Air Conditioning
HVO	Hydrotreated Vegetable Oil
IED 2.0	Industry Emissions Directive 2.0
IIoT	Industrial Internet of Things
LAES	Liquid Air Energy Storage
LCF	Low Cycle fatigue
LPBF	Laser Powder Bed Fusion
ML	Machine Learning
NDT	Non-Destructive Testing
NH <sub>3</sub>	Ammonia
NO <sub>x</sub>	Nitrogen dioxide
NZIA	Net Zero Industrial Act
ODS	Oxide Dispersion-Strengthened
OEMs	Original Equipment Manufacturers
OPEX	Operating Expenses
ORCs	Organic Rankine Cycles
OT	Operational Technology
PDC	Pulse Detonation Combustion
PDE	Pulse Detonation Engines
PFHxA	Perfluorohexanoic Acid
PTES	Pumped Thermal Energy Storage
RAM	Reliability, Availability and Maintainability
RDC	Rotating Detonation Combustion
REACH	Registration, Evaluation, and Authorisation of Chemicals
RES	Renewable Energy Sources
RTE	Round-Trip Efficiency
SAF	Sustainable Aviation Fuels
sCO <sub>2</sub>	Supercritical CO <sub>2</sub>
SCR	Selective Catalytic Reduction
SVHC	Substances of Very High Concern
TBC	Thermal Barrier Coating
TMF	Thermo-mechanical fatigue
TIT	Turbine Inlet Temperatures
UHC	Unburned Hydrocarbons

# Executive Summary

ETN Global's 2026 R&D Recommendation Report presents gas turbines and turbomachinery as key "bridging" technologies for the energy transition. They support adequacy, flexibility, and system stability in grids with high shares of variable renewables. They also remain critical for oil & gas operators as well as industrial users that need reliable, high-power rotating equipment. The report aligns with ETN Global's vision: safe, secure, affordable, dispatchable carbon-neutral solutions by 2030, deployed globally by 2050. This report is designed as a living document, updated every two years, to keep R&D aligned with policy goals and operational requirements.

The report begins with market conditions and policy frameworks. It notes a tightening global gas turbine market: rising orders, long lead times, and manufacturing constraints. These trends directly shape what R&D must deliver. Next, the report uses High Level User Meeting (HLUM) 2025 feedback to reflect end user priorities. Finally, it organises recommendations around the ETN Global Technology Wheel: Product Sustainability, Operational Optimisation, Integrated Energy Systems, Energy Efficiency, and Low Carbon Solutions. This report structure aims to encourage action through projects, demonstrations, guidelines, standards, and briefing papers.

Feedback from HLUM shows that operational resilience is now the top concern for end users across utilities, oil & gas, and industry. Three principal barriers to operational resilience are evident.

1. The first is spare-parts availability: lead times for critical hot-section parts are far longer than historical norms. This forces costly inventories and can cause forced outages.
2. The second is ageing fleets: many units run beyond design life, under more cyclic duty, while life-extension options are constrained and new unit lead times remain long.
3. The third is regulatory uncertainty: frameworks for hydrogen, Carbon Capture Use and Storage (CCUS), and capacity mechanisms are fragmented and shifting. Definitions of "hydrogen-readiness" and "low-carbon readiness" are also inconsistent.

The report treats these barriers as primary drivers for R&D. Innovation should reduce unplanned downtime, extend asset life safely, and reduce the cost and uncertainty of decarbonisation decisions.

**Product Sustainability**, sustainability is framed in lifecycle terms. It covers design, manufacturing, operation, repair, and end-of-life. The focus is on maintainability and repairability. Key priorities include more thorough site and shop inspection, improved non-destructive techniques, and stronger borescope interpretation supported by digital tools. It also calls for advanced repair methods for modern high-temperature components, including additive, laser, and weld approaches for single-crystal parts. Repair-specific heat treatments and acceptance criteria are part of this agenda. The report also highlights materials and coatings as both bottlenecks and opportunities. Priorities include Thermal Barrier Coating durability under cycling and corrosion/oxidation behaviour under new conditions, including hydrogen effects and high water-vapour exhaust. It stresses the need for shared, high-quality materials data to support credible lifing models and in-service lifing, especially as operations shift from baseload to cycling. It also notes regulatory pressure and the need to reduce reliance on scarce elements. Both strengthen the case for minimising unnecessary scrappage through improved lifing, repair, and condition assessment.

**Operational Optimisation** shifts the focus from single-point efficiency to reliable flexibility across the operating envelope. Priorities include fast start and ramping, part-load operation with high efficiency and low emissions, robustness to frequent start/stop, reliable overfiring, and fast fuel switching. Digitalisation is presented as a practical enabler. It supports lower operating expenditure, predictive maintenance, and more autonomous operation. The report also notes concerns around data ownership, interoperability, and cyber risk. Reliability, Availability & Maintainability provides a guiding lens: improving reliability through design and testing, enhancing availability via modularity and predictive maintenance, and strengthening maintainability through accessibility, standardisation, and more effective maintenance processes and tools.

**Integrated Energy Systems** explains how turbomachinery fits into a wider energy system under evolving market designs and flexibility needs. Topics include waste-heat recovery and upgrade pathways, and cogeneration/trigeneration as integrated multi-component systems. A key recommendation is to optimise these systems across realistic operating profiles, not just a single design point. The report also highlights hybrid plants, such as Gas Turbine + Battery Energy Storage System, to improve flexibility, provide ancillary services, and strengthen economics in volatile markets. It also covers distributed energy systems where micro gas turbines, cogeneration, and multi-vector district optimisation require scalable control, interoperable platforms, and supportive tariffs and market mechanisms.

**Energy Efficiency** remains important, but the report links it to how plants will actually operate. Future gains must come from part-load performance, transient response, and lower minimum environmental load. These reduce starts/stops and life consumption. The report points to incremental component improvements, such as gas-path optimisation, clearance control, secondary air/cooling system optimisation and air filtration. It also highlights advanced cycles like sCO<sub>2</sub> bottoming cycles and pressure-gain combustion. These offer higher potential but carry higher risk. They require more research on integration, operability, and materials, especially given the unsteady boundary conditions they can impose.

**Low Carbon Solutions** are treated as a portfolio. For hydrogen, the report stresses combustion stability, flashback risk, thermo-acoustics, NO<sub>x</sub> emissions control at high firing temperatures, and uncompromised safety, including leakage, self-ignition, and embrittlement. It also recognises that the business case remains weak at current costs. Limited operational experience is another barrier. The report, therefore, calls for demonstrations that bridge the gap between laboratory conditions and field deployment, building confidence in durability and service life. Other fuels are discussed through practical barriers: variable quality, contaminants, missing standards, and the difficulty of ultra-low emissions across fuels and operating modes. Ammonia is considered to be promising for storage and transport; its technical difficulty lies in NO<sub>x</sub> and toxicity constraints. For Carbon Capture Storage, the report focuses on integration and dispatchability. Key issues include energy penalties, integration with the Heat Recovery Steam Generator, alternative capture routes, and Exhaust Gas Recirculation to raise CO<sub>2</sub> concentration (with operability trade-offs). It also stresses the need to understand transient operation, start-up behaviour, retrofit footprint constraints, and capital expenditure impacts.

Across the report, the message is consistent. Turbomachinery's role in a decarbonising system depends on flexibility, reliability, and future adaptability across fuels, capture options, and operating modes. Technical progress must be matched by enabling frameworks, shared definitions, and market designs that value secure capacity and grid services. The recommendations are designed to trigger collaborative R&D, demonstrations, feasibility studies, and best-practice and standardisation work. ETN Global's role is to provide the framework, connect the community, reduce end user risk, and accelerate deployment at scale.

# 1. Introduction

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The global energy landscape is undergoing a profound transition, driven by the urgent need to decarbonise while maintaining energy security and affordability. This ongoing transformation highlights the persistent challenge known as the energy trilemma—the balance between sustainability, security of supply, and affordability. As renewable energy sources continue to expand, integrating these intermittent resources requires complementary technologies to ensure system stability and reliability.

Gas turbines and turbomachinery technologies remain central to this transition. Their role, however, varies across regions depending on national energy strategies, resource availability, and policy frameworks. These technologies provide critical energy security and support increasing electricity demand, particularly where no scalable alternatives exist for long-term dispatchability. Competitiveness in the energy sector increasingly depends on balancing performance, cost, and environmental impact. For the turbomachinery industry, maintaining competitiveness means advancing technologies that deliver higher efficiency, lower emissions, and operational flexibility while remaining cost-effective.

In this regard, the long-term role of gas turbines and turbomachinery is strengthened by a technological limitation: there is no existing scalable alternative for dispatchable power or energy storage. As analysed in the ETN Global White Paper [\[1\]](#), while battery storage offers several hours of flexibility, hydropower and hydro pumped storage are limited in scope and scale. Gas turbines fill that gap as a dispatchable and affordable solution with the potential of being decarbonised by post-combustion carbon capture and the use of low-carbon or sustainable fuels. Other turbomachinery-based technologies, such as Compressed Air Energy Storage (CAES), Liquid Air Energy Storage (LAES) and Carnot batteries, offer possible avenues of development. Consequently, gas turbines will continue to play a fundamental role in supporting grid stability and enabling the integration of renewable energy sources. Market data confirm this trend. Recently, gas turbine orders have doubled, with long order backlogs, largely driven by utility customers responding to evolving energy demands.

The aim of this report is to assess the current state of technology and provide R&D recommendations that address technical, operational, and market requirements in the context of the energy transition. The analysis draws upon the user requirements gathered during the High-Level Users Meeting (HLUM) [\[2\]](#), leveraging the technical expertise from ETN Global Project Board Members, considering both short-term and long-term innovation needs across the turbomachinery sector.

This report – that builds up on and formally updates its previous edition [\[3\]](#) - is designed as a reference for policymakers to shape effective policies, incentives, and funding calls that accelerate innovation toward a secure, affordable, and sustainable energy system. Equally, it is intended to guide OEMs, suppliers, service providers, universities, and research centres in prioritising technology improvements and aligning R&D with real technical, operational, and market needs.

This report first reviews market conditions and policy frameworks, followed by feedback from the HLUM. It then explores the core technical domains of the ETN Global Technology Wheel: Product Sustainability, Operational Optimisation, Integrated Energy Systems, Energy Efficiency, and Low Carbon Solutions, concluding with key insights and recommendations for future R&D directions.

## 2. Contributors

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### Representatives from the ETN Global Project Board

The ETN Global Project Board is an ETN Global body nominated bi-yearly by the ETN Global 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 Global member community.

The ETN Global Project Board also provides technical and strategic advice to the ETN Global community and leads ETN Global's Working Groups, which cover the most crucial areas of future gas turbine technology development. The Project Board 2024-2026 consists of the following members who have all contributed to this edition of the ETN Global R&D Recommendation Report:



#### Mauro Moretto (Chair)

**Ansaldo Energia, Italy**

**Technical Areas:**

Energy management systems;  
Integrated Energy Storage; MGTs  
Development



#### 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



#### Ward De Paepe (Vice-Chair)

**UMons, Belgium**

**Technical Areas:**

Energy Management Systems;  
Integrated Energy Storage;  
MGTs Development; sCO<sub>2</sub> Cycles



#### Peter Breuhaus

**NORCE, Norway**

**Technical Areas:**

Fundamentals of aero and thermo-  
dynamics; Gas turbine technology  
and design; Power plant monitoring  
and diagnostic systems; Power  
systems and systems integration;  
Process technologies



#### Ludo Bautmans

**Oerlikon, Belgium**

**Technical Areas:**

Additive manufacturing



#### Chris Dagnall

**DNV, United Kingdom**

**Technical Areas:**

Gas turbine performance and  
emissions; Compressor performance;  
Condition monitoring and vibration



**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<sub>2</sub>, ORC, HTHP); Co-generation CHP



**Peter Jansohn (Emeritus Member)**  
**Technical Areas:**  
 Fundamentals of combustion; Gas turbine cycles; Process technologies; Integrated power generation systems; Environmental systems (for exhaust gas clean-up and emission reduction)



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



**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



**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



**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



**Yiguang Li**  
**Cranfield University, United Kingdom**  
**Technical Areas:**  
 Digital twins; advanced instrumentation



**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 (Super-critical Carbon Dioxide Cycles, Organic Rankine Cycles); Micro gas turbines; Techno-economic assessment of power systems; Water & energy nexus



**Andrew Moffat**  
**Solar Turbines, United Kingdom**  
**Technical Areas:**  
 Digital twins; advanced instrumentation, hydrogen induced degradation, lifetime extension

## Representatives from the ETN Global Secretariat

Report Technical Editor



**Giuseppe Tilocca**

**Technical Areas:**

Turbomachinery Aerodynamic Design, Turbomachinery Design and Optimisation tools, CFD, Gas Turbine Market and Innovation, Micro Gas Turbines technology and market, Power to Power Energy Systems

Project Coordinator and point of contact



**Nicolò Cairo**

**Technical Areas:**

Energy policy

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### 3. Market Conditions & Policy Framework

During the last few years Gas turbine markets have tightened sharply, with global orders rising faster than manufacturing capacity. Several OEMs already entered 2024 with substantial accumulated demand, reporting backlogs on the order of 3 to 4 times typical annual orders. The situation intensified in 2025 with industry estimates [4] indicating roughly a 100% increase in orders versus 2024, with oil and gas demand broadly stable whilst utility-driven procurement surged. This demand–supply imbalance has created long lead times – often three to five years and in some cases up to eight years – adding the availability of new units to the pre-existing bottleneck on critical spare parts. The resulting bottlenecks ripple into adjacent markets (e.g., large reciprocating engines and micro gas turbines), while constrained supply and inflationary pressure drive noticeable CAPEX escalation and rapidly increasing gas turbine prices. The market signal is also affecting OEM behaviour, with manufacturers publicly announcing plans to increase gas turbine production capacity [5], [6], [7].

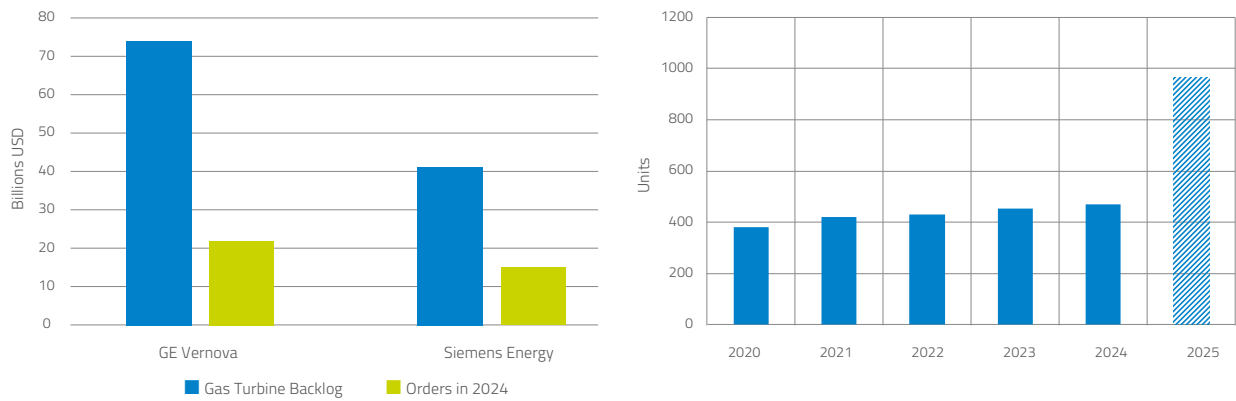


Figure 1: (a) GE Vernova and Siemens Energy orders and backlog in 2024 [8].  
 (b) Evolution of gas turbines order from 2020 to 2025 [4].

## Regional Deployment Patterns

Whilst the Gas Turbine market is surging, largely driven by utility orders, regional patterns vary. As shown in *Figure 2*, most of the gas turbines in Development projects (announced, pre-construction, and Construction) are located in the Asia region (> 300 GW), North America (about 170 GW) and the Middle East (about 140 GW), with Europe following with about 100 GW of capacity in the pipeline. The main regional trends are discussed below.

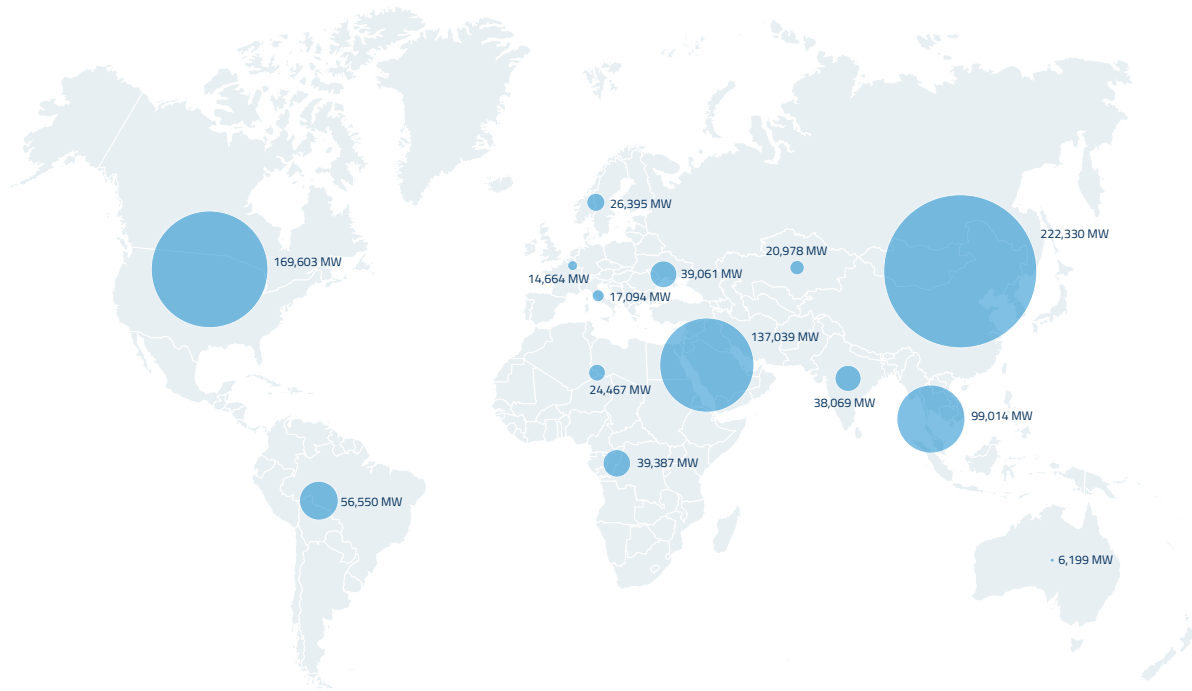


Figure 2: Gas Turbine capacity addition pipeline, (projects announced, in pre-construction, and construction) [\[9\]](#).

### Asia

Asia is the main centre of gravity for new-build gas turbine capacity, largely because electricity demand continues to grow structurally with industrial and economic expansion. Planned additions exceeding 300 GW reflect the need for fast-to-deploy, grid-supporting capacity that can complement rapid renewable build-out while maintaining reliability during monsoon seasons, heat waves, or periods of low wind and solar output. In many Asian systems, gas turbines also serve a dual role: they provide flexible peaking and balancing for variable renewables, and they anchor capacity adequacy in markets where coal retirements, air-quality constraints, and permitting timelines are pushing utilities toward lower-emission thermal options as a transitional step. This combination of load growth and system integration needs explains why procurement is often utility-led and why demand can rise rapidly when reserve margins tighten.

## North America

In the United States, the current wave of announced gas capacity (around 170 GW) is closely linked to large-load growth - particularly data centres and digital infrastructure - which requires flexible and reliable capacity, fast ramping capability, and high availability. This demand profile favours gas turbines because they can be deployed at scale and can provide both energy and essential grid services, especially in regions experiencing transmission congestion or slow interconnection queues for new renewables. In parallel, expansion of LNG export infrastructure [10] reinforces the strategic value of a robust and flexible gas supply chain; this increases the premium on turbines that can operate reliably across varying fuel quality while preserving optionality for future low-carbon fuels.

Scenario	Annual Growth Rate	% of US Electricity (2030)
Low growth	3.7%	4.6%
Moderate Growth	5.0%	5.0%
High Growth	10%	6.8%
Higher Growth	15%	9.1%

Table 1: Increase in electricity consumption of data centres and projected annual growth [11].

## Middle East

The Middle East (around 140 GW of announced capacity in your inputs) is driven by a different set of fundamentals: rapidly growing electricity demand, high summer peaks, and an ongoing shift toward more efficient generation portfolios. Gas turbines - often in combined cycle configurations - are attractive because they can displace older, less efficient oil-fired generation, lower local pollutants, and reduce fuel burn per unit of electricity while retaining the dispatchability required for system security. At the same time, the region is expanding renewables at scale, which raises the need for flexible thermal capacity that can manage ramps and maintain stability without relying on large-scale storage everywhere. This creates a market where the procurement of new gas turbines is not just about adding capacity, but about modernising fleets and improving heat rates, water use strategies, and operational flexibility under adverse ambient conditions.

## Europe

Europe's picture is more about maintaining adequacy and replacing retiring assets than meeting large net load growth, and the policy environment strongly shapes investment decision (see *Figure 3* below). Coal and in some instances nuclear phase-outs (e.g. in Germany), combined with a high and rising share of variable renewables, ensures dispatchable capacity remains valuable - even as annual gas burn can decline in windy or high-hydro years. This is because systems still need dispatchable power for instance during "dunkelflaute" periods (low wind/solar) and during extreme cold snaps and in general to provide grid reliability minimising Loss of Load Expectations. Across Europe, the most visible additions tend to cluster where coal replacement, capacity market signals, and security-of-supply priorities are strongest (including Germany, the United Kingdom, and Poland), rather than being evenly distributed across all member states. In terms of thermal capacity addition and decarbonisation, Germany provides a clear example of policy-enabled capacity preservation and renewal: Germany and the European Commission agreed in principle to allow state support for new gas-fired plants that can later be converted to hydrogen, with first units expected to be operational by 2031, explicitly framed around security of supply while renewables expand. This approach aligns with ETN Global's broader view that gas turbine-based generation maintains a strategic function as renewables grow, evolving toward reliability and balancing roles that protect grid stability. One of Europe's biggest problems related to thermal assets is their profitability: despite the need to

preserve capacity, the actual number of operating hours will inevitably decrease, as highlighted by the Ten-Year Development Plan of ENTSO-e (European Network of Transmission System Operators for Electricity) [12]. Such is the case of Italy whose expected Loss of Load is forecast to skyrocket to about 800h/year if no further measures are deployed [13]. Effectively, as revenue opportunities decrease, these assets will be more on more depending on Capacity Remuneration mechanisms.

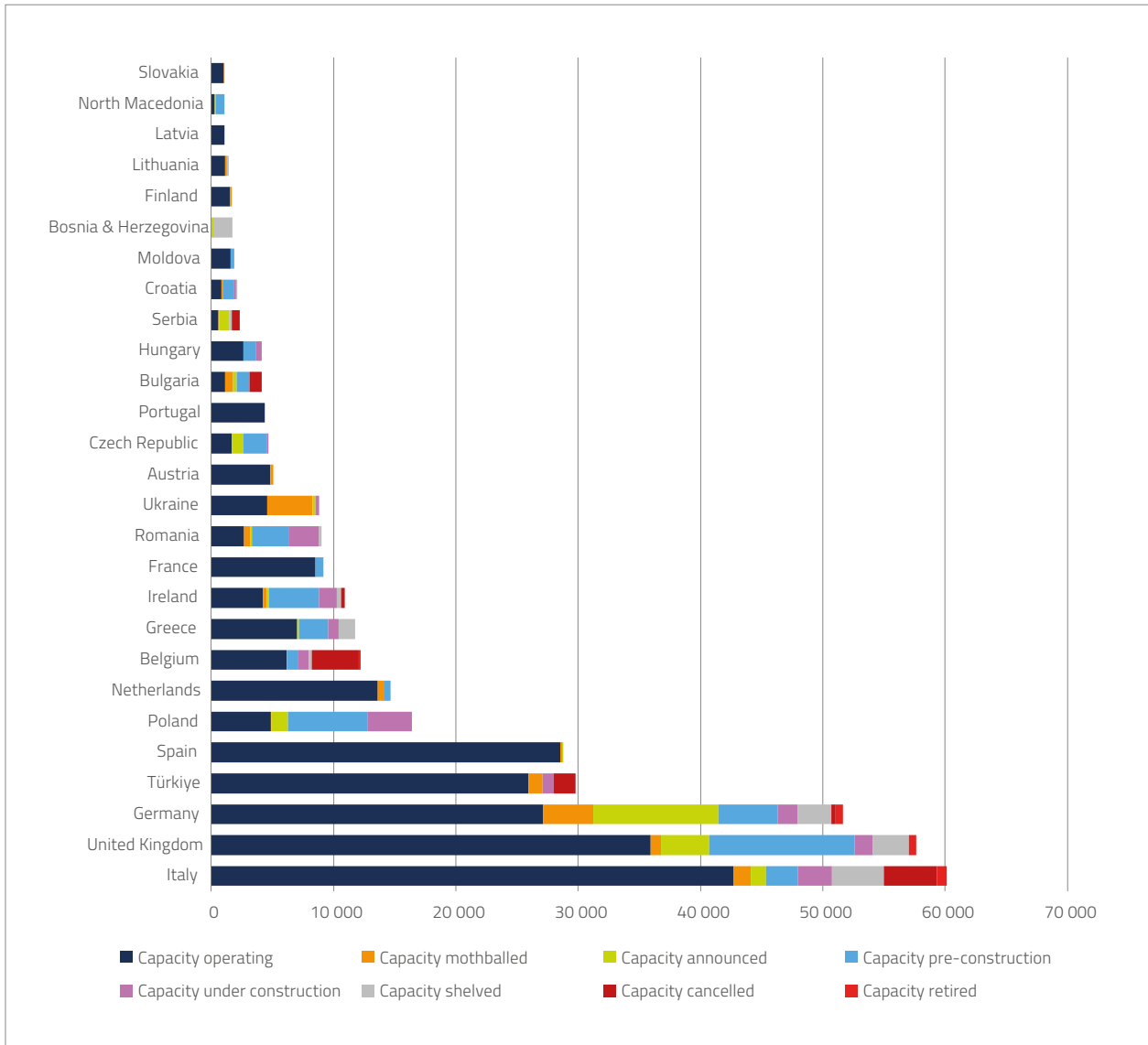


Figure 3: Gas Turbine fleet and new plant projects capacity (Europe) [14].

## Policy

### European Context: Policy-Driven Operation and Decarbonisation

At a time of heightened uncertainty and geopolitical turmoil – when energy is increasingly weaponised – reducing Europe’s vulnerability and dependence on imported energy is central to the Union’s energy security and strategic autonomy. REPowerEU aimed breaking Europe’s structural dependence on Russian fossil fuels without derailing the transition towards cleaner and more sustainable energy sources. The EU replaced a deeply entrenched dependency through a combination of demand reduction, accelerated clean energy investment, diversification of supply routes, improved energy efficiency, and unprecedented EU-level coordination. Recent developments underline the importance of maintaining a diversified set of partners and sources, avoiding the risk of substituting one external dependency with another. This has reinforced the case for stronger EU-wide coordination, planning and infrastructure cooperation – particularly on grids, interconnectors and permitting.

Renewable energy development, driven by the Renewable Energy Directive (stipulating binding target of minimum 42.5% share of Renewable Energy Sources (RES) in the energy mix) is one of the driving forces of the EU energy policy. RES outpaced fossil fuels for power generation in 2025 (with PVs and wind generating 30%, comparing to 29% of EU’s electricity by coal, oil and gas [\[15\]](#)), marking a signification milestone in energy transition. To enable further integration of the RES in the grid and thus safeguarding the security of supply, energy storage, as well as gas turbines will play a key role thanks to the dispatchable energy provision.

Green Deal ambitions are being increasingly met by improved competitiveness, which is translated into the EU policies mainly by (a) Net Zero Industrial Act (NZIA, in force as from June 2024), creating a regulatory framework to boost the competitiveness of the EU industry and technologies crucial for decarbonisation; and (b) Clean Industrial Deal (CID, launched in February 2025), aiming to marry decarbonisation and economic competitiveness. The revised Industrial Emissions Directive (IED 2.0, enacted in August 2024) aims to reduce key air pollutants by up to 40% by 2050.

Looking ahead to 2026, energy remains high on EU’s agenda. The European Commission is finalising the Electrification Strategy (decarbonising transport, industry, and buildings), including a specific Heating and Cooling initiative and the Energy Security Package (accelerating the transition to renewable energy to ensure affordable, stable, and homegrown power), expected to be adopted in early March. In parallel, an Omnibus simplification package for energy product legislation (reducing administrative burdens) is planned for adoption in Q2.

## US: A significant shift from 2023

Since 2023, the energy trilemma and the policy framework have dramatically evolved in the United States. The emphasis on energy transition and low-carbon solutions is being replaced by a shift towards energy security – i.e., the need to satisfy the larger energy demand, also fuelled by the developments of new data centre infrastructure and digital industries [16].

To accelerate the permitting process and the deployment of new gas-fired power plants, the current administration has been reviewing the pre-existing requirements and regulations.

In June 2025, the Environmental Protection Agency (EPA) officially proposed to repeal several standards developed between 2015 and 2024 for gas-fired power plants, namely:

- The New Source Performance Standards for gas-fired power plants from 2015
- Emission guidelines for existing gas-power plants promulgated in 2024,
- The CCS-based standards for new base load stationary combustion turbines [17]

With reference to the carbon capture in power generation, EPA also proposed to repeal the requirement of 90% of capture rate. Such technologies are not considered as the “Best System of Emission Reductions” for such applications, as “[they have] not been adequately demonstrated and because the costs are not reasonable” [18]. The proposal by EPA was also driven by the high capital costs of the onsite capture systems and the pipeline infrastructure, as well as the unlikelihood of deploying such large systems before 2032 [19].

By contrast, the pre-existing 45Q tax credit is set to be in place until 2033, hence generating benefits for the deployment of CCUS. This incentive plays a pivotal role, as it ensures different credit amounts (per Metric Ton of CO<sub>2</sub>) for a wide range of CO<sub>2</sub> sequestration technology [20]. According to Global CCS Institute, the 45Q tax credit will be maintained “for point-source capture at \$85/ton and direct air capture (DAC) at \$180/ton in dedicated geologic storage” [21].

Within this context, the 45Q hydrogen credit will follow a separate timeline, expiring in January 2028. Such a mechanism will allow stakeholders to apply for this incentive scheme, which offers up to 3 US\$ per kilogram [22].

## 4. Feedback from the HLUM

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The High-Level User Meeting (HLUM) is ETN Global's annual strategic forum that gathers key gas turbine and turbomachinery end users from utilities, oil & gas, and industry to discuss their most pressing operational and investment challenges. Its aim is to translate real-world user experience into concrete priorities for technology development, market design, and policy engagement, ensuring that innovation efforts remain aligned with what operators require in the field. By systematically identifying common barriers and emerging requirements, the HLUM provides critical input for setting R&D roadmaps, guiding collaborative projects, and directing resources toward solutions that enhance flexibility, reliability, and long-term competitiveness of turbomachinery assets.

The 2025 HLUM [23] confirmed that operational resilience has become the dominant concern for gas turbine end-users across utilities, oil & gas, and industry. Participants converged on three main barriers hindering this resilience: spare parts availability, ageing fleets, and regulatory uncertainty. Feedback also underlined the need for a more united end user voice to rebalance relationships with OEMs, service providers, and policymakers.

On spare parts availability, users reported that lead times for critical hot-section components have stretched from pre-crisis levels of 4–6 months to typical delays of 9–18 months, with extreme cases exceeding two years. This has forced some operators to immobilise several million euros in strategic inventories, while others face involuntary downtime because OEMs prohibit extending parts beyond prescribed limits but cannot supply replacements on time. To restore flexibility, end users expressed strong interest in condition-based maintenance, more transparent lifetime assessments, and wider use of technologies such as additive manufacturing, which today remain constrained by certification and OEM policies.

For ageing fleets, feedback highlighted a “locked in” situation in which many turbines operate beyond their nominal design life under increasingly cyclic duty, while life extension options and inspection intervals remain tightly controlled by OEMs and new engine lead times often exceed three years. Utilities, oil & gas operators, and industrial users all reported rising planning uncertainty, higher exposure to forced outages, and limited ability to align asset strategies with evolving market and policy trends. Participants therefore prioritised collaborative actions such as regional spare capacity models, shared data on component degradation, and advocacy for market designs that recognise the long-term system value of flexible thermal assets.

On regulatory uncertainty, the meeting revealed broad frustration with fragmented and shifting frameworks for hydrogen, carbon capture, and capacity mechanisms. Users stressed that the lack of harmonised “hydrogen-readiness” and “low-carbon readiness” definitions, combined with uneven national regulations, makes it difficult to justify large retrofit or new build investments with multi-decade horizons. They welcomed ongoing work on common hydrogen-readiness concepts and called for fuel-agnostic, technology-neutral rules that reward firm low-carbon capacity rather than favouring specific solutions.

Finally, participants pointed to several concerns that, while not ranked among the top three barriers, continue to shape expectations for R&D. These include:

- the weak business case for hydrogen and e-fuels at current cost levels,
- persistent doubts about the profitability of thermal assets in electricity markets
- service bottlenecks linked to reduced OEM workforce capacity,
- and internal drive toward cost-reduction policies that discourage investment in turbomachinery despite its critical role in system stability.

Collectively, these insights reinforce the need for R&D and innovation programmes that address both technical challenges and enabling frameworks, ensuring turbomachinery remains a cornerstone of a secure, sustainable, and affordable energy system.

## 5. Product Sustainability

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Product sustainability in the gas turbine sector refers to developing technologies that minimise environmental impact, use resources efficiently, and remain economically viable across the entire lifecycle of the turbine. This includes reducing emissions, improving efficiency, extending the life of critical components, and enabling refurbishment, reuse, and recycling. In this context, research on a circular energy economy is essential, supporting the transition away from a “take-make-dispose” model and ensuring that energy intensive materials, such as high-value assets remain in use for longer, thereby reducing waste, lowering lifecycle costs, and maximising the value extracted from each turbine asset. This section focusses on a few important aspects of product sustainability such as material, life assessment and life extension by repair, where further research will be beneficial.

In recent years, increased order intake for new gas turbines, combined with supply chain disruptions and a shortage of skilled labour, has resulted in significant delivery backlogs. These factors have further exacerbated reliability challenges in newly commissioned units and raised questions about long-term product maintainability and profitability. In some cases, underwriters and reinsurers have expressed uncertainty regarding whether certain risks, associated with advanced turbine designs, are fully understood by manufacturers. As a result, additional exclusions have been introduced for specific engine components until risks are better quantified and effective mitigation strategies are implemented.

Another pressing issue for the operators is single-use capital parts of some engines by design. These engines, inherently on small units, but occasionally to be seen on larger units, have hot-section components designed for only a single operating cycle, typically limited to 24,000 or 32,000 equivalent operating hours. This raises serious questions regarding the long-term sustainability of these engines from the perspective of owners and operators.

Against this backdrop, it is in the collective interest of manufacturers and service providers to rethink existing product and service strategies. Developing viable, sustainable alternatives that address long-term maintenance costs, reparability, and material usage is essential, not only to improve owner and operator confidence but also to restore confidence within the insurance market.

Changes in the operational profile of large-frame gas turbines - from traditional baseload operation to more cyclic, flexible duty in support of renewable generation - can significantly accelerate certain thermal degradation mechanisms. Under frequent starts, stops, and load-following operation, components experience higher thermal gradients and repeated thermal cycling, increasing the risk of thermal fatigue and related damage. Understanding the thermal-fatigue behaviour of key engine components is therefore essential for maintaining system reliability, optimising maintenance intervals, and controlling lifecycle operational costs.

Given the wide range of gas turbine makes and models currently in operation, as well as the continuous introduction of new designs, it is not practical to apply a single sustainability framework across all industrial gas turbines for R&D recommendations. Instead, a segmented approach based on historical operating experience, maintenance practices, and observed service failures is recommended to optimize future operation, maintenance strategies, and overall product sustainability.

Furthermore, advances in materials and manufacturing technologies are enabling alternative and more advanced design concepts for next-generation gas turbines that have yet to be fully developed. These emerging opportunities and associated challenges are also outlined in the following sections.

## Mature B-, E-, and Selected F-Class Units

This group includes relatively mature gas turbines such as most B- and E-class units, including some early version of F-class units—that have been in service for more than two to three decades. Although these engines are less efficient than newer designs, they remain widely deployed across Europe and globally and are predominantly maintained using preventive maintenance strategies. Owing to their well understood failure modes, extensive repair and refurbishment history, and the increasing affordability of advanced monitoring technologies, there is a strong opportunity to further optimize inspection and maintenance approaches for these units.

For example, a 100-MW E-class gas turbine operating under a preventive maintenance regime may require hot gas path inspections every three to four years. However, comparable units operated at base load under a condition-based maintenance strategy have demonstrated the ability to extend hot gas path inspection intervals to approximately five to six years with relatively low risk. This clearly illustrates the potential cost savings achievable through a transition to condition-based maintenance. Owners and operators of mature fleets should therefore actively pursue the evaluation and adoption of condition-based maintenance regimes.

Looking ahead, rotor integrity represents a critical sustainability challenge for these older units. While hot-section components have often been inspected, repaired, or replaced multiple times for these units, comparatively less attention has been given to long-term rotor health. Rotor replacement or overhaul involves substantial cost and extended lead times; typically ranging from 18 to 36 months from contract award, excluding contractual negotiations. Consequently, there is no short-term solution for rotor replacement, making proactive condition assessment and long-term planning essential to manage cost, risk, and availability. Therefore, rotor life assessment and life extension will remain a key element requiring further attention for these units. Any innovative study in this field is highly beneficial for the community and ETN Global has published a rotor life report which can be beneficial for further guidance in this area.

In summary, for these mature engines, extending maintenance intervals and prioritizing rotor life assessment should be considered key focus areas. The deployment of condition-based monitoring systems, now significantly more affordable, can deliver additional operational and financial benefits to owners and operators.

## Advanced F-, H-, and J-Class Units

Advanced F-, H-, and J-class gas turbines operate at the technological limits of current design capabilities, with turbine inlet temperatures typically ranging from 1,400°C to 1,600°C. These units rely extensively on advanced cooling technologies and superior thermal barrier coating (TBC) systems to ensure component durability and acceptable service life. Accordingly, R&D efforts for these platforms should prioritize the development of advanced repair techniques, enhanced on-site inspection capabilities, and improved methods for assessing TBC condition, integrity, and remaining useful life.

Additional R&D focus is required for online monitoring systems deployed on these units, as shown in [Section Condition monitoring and lifing](#).

Extending the normal design life. A large number of gas turbines require frequent replacement of hot-section components by design—typically every 24,000 or 32,000 operating hours. These are so called single engine cycle life hot component parts. This approach is increasingly unsustainable in the medium to long term, particularly in an energy market characterized by strong competition from low-maintenance renewable technologies.

Given the extensive data now available from service-run components, manufacturers and service providers are well positioned to leverage operational feedback to redesign existing components for future gas turbine development. This data-driven approach is essential to advancing product sustainability, reparability, and long-term market competitiveness.

To address this challenge, manufacturers are encouraged to consider redesigning or upgrading hot-section components to achieve operational lifetimes of two or more engine cycle life, incorporating one or two repair and recoating intervals. Such a balanced approach would significantly reduce reliance on scarce and costly exotic materials whilst improving the overall economic attractiveness of gas turbines for owners and operators.

For the majority of modern gas turbine models, the Combustion Inspection (CI) and Hot Gas Path (HGP) inspection intervals are now scheduled at the same operating duration. Additionally, several OEMs have extended major maintenance intervals to around 40,000 equivalent operating hours, depending on operating profile and component technology. This is encouraging and improves the competitiveness of the gas turbine in the energy market.

## Operational flexibility

Operational flexibility has become a key requirement for gas turbines operating in the power sector, driven by the increasing need to support and back up renewable generation. Frequent rapid start-ups and fast load changes significantly increase thermal and mechanical cycling, which in turn accelerates thermal fatigue cracking in structural and critical components. Therefore, targeted research in this area is essential to improve product lifetime in such harsh operating conditions. In particular, a deeper understanding of operational limits, damage accumulation, and margin reduction under thermal cycling is required to extend the life operation.

## Areas to be considered for improved sustainability

Significant research and development efforts are still required to address gas turbine operational risks, maintenance strategies, and component integrity to ensure competitiveness. Key areas of focus include:

- Advanced repair and refurbishment: innovative repair techniques and refurbishment strategies to extend component life and reduce downtime.
- Turbine materials and coatings: development of advanced alloys and thermal barrier coatings to improve durability and high-temperature performance.
- Condition-based monitoring integrated with life models: enhanced monitoring systems that provide actionable insights and link real-time condition data to turbine life-consumption models.

These topics are discussed in more detail in the following sections.

### Advanced repair

#### Inspection

Inspection can be considered in the following two categories:

- a) Site inspection of gas turbines: including borescope inspection, visual inspection, and other non-destructive testing (NDT) techniques.
- b) In-shop inspection of gas turbine components: performed on ex-serviced parts and during various stages of repair.

Enhancements in extended borescope inspection can provide valuable insights for decision-making regarding operational life extension, without requiring full turbine disassembly. Conventional borescope inspections and reports often do not provide sufficient information on the actual condition of the engine. Future work should leverage digitalization and AI-based analysis to compare current borescope data with historical inspection records, enabling more informed decisions on extended operation of the units. Additionally, advanced on-site NDT techniques should be developed to assess the condition of downstream gas turbine components in situ, reducing the need for full disassembly.

For modern engines with complex geometries and cooled rotating and stationary components, advanced defect detection techniques are essential. These techniques help identify both operational and inherent manufacturing defects that may be missed during in-shop inspections, ensuring component integrity and reliability during repair processes.

## Repair

Traditional repair processes for gas turbine components such as coating stripping, inspection, weld-braze repair, and coating replacement remain essential for maintaining durability and restoring service life. These approaches are well established and widely applied for B and E class turbines, as well as some earlier F-class components. However, their effectiveness becomes increasingly limited when applied to high-temperature components manufactured from advanced materials, particularly single-crystal superalloys used in modern gas turbines, with much higher turbine inlet temperature and more complex hot component design.

Advanced repair technologies, including additive manufacturing, welding techniques, such as laser-based repair, offer significant potential for restoring complex parts with high gamma prime volume fraction. At present, repairs to these components are largely restricted to blade tip build-up and platform restoration. Substantial R&D effort is still required to reliably extend these repair methods to the wider aerofoil. During repair, these materials are highly susceptible to cracking and recrystallization. Carefully controlled pre-heat treatments are required to minimize residual stresses and reduce cracking risk during the repair. Post-repair heat treatments, such as solution heat treatment and aging, are necessary to restore microstructure, mechanical properties, and creep resistance. It should be noted that the full solution heat treatments applied during original manufacture are generally not feasible during repair; therefore, repair-specific heat treatment processes must be developed to prevent recrystallization in critical regions. *Figure 4* shows the results of the Electron Backscatter Diffraction (EBSD) work on the development of welding for single crystal blades.

An additional R&D challenge relates to recrystallization acceptance criteria. While original manufacturing qualification limits typically impose restrictions on recrystallized grains within aerofoils, further research is needed to assess whether limited recrystallization in less critical regions—such as pressure and suction surfaces away from leading and trailing edges - may be acceptable. Addressing this question could significantly expand reparability while maintaining safe and reliable operation.

## Coating

Advanced coating systems are essential to achieving the required service life of high-temperature gas turbine components. As turbine inlet temperatures continue to increase and intervals between overhauls are extended, TBCs have become increasingly critical for protecting hot-section components. These systems are applied over oxidation (and corrosion) resistant MCrAlY bond coats, which provide the necessary environmental protection. Ongoing R&D efforts focus on optimizing coating chemistry, adhesion, and durability, while addressing key challenges associated with applying TBCs to components containing hundreds of small and/or fan-shaped cooling holes.

Applying advanced TBC systems to newly manufactured turbine aerofoils, after casting but prior to drilling cooling holes, is generally more feasible and controllable. However, during repair processes, significant effort is required to effectively mask and demask complex cooling hole geometries, representing a key technical challenge that warrants further development. Emerging solutions, including laser ablation, vision-based processing, and advanced coating application techniques, show promise but require further maturation for application to complex, cooled components. In addition, maintaining robust process continuity and repeatability during thermal spray application and cooling hole regeneration is critical to consistently achieving the required coating quality. This can be supported through the use of spray monitoring and process control systems for thermal spray processes.

Particular attention should be given to internal coatings. In recent years, the application of internal coatings within the cooling cavities of advanced turbine blades has, in some designs, been replaced by a no-internal-coating approach. While this may simplify manufacturing, it can have significant in-service implications, particularly with respect to hot corrosion and oxidation resistance. Most base alloys of advanced turbine blades have low levels of

chromium and provide little hot corrosion protection. The absence of internal protective coatings may accelerate base material degradation within cooling passages, potentially reducing component life and increasing the risk of premature failure.

### Repair summary

The successful repair and reuse of complex gas turbine components require integrated expertise across materials science, inspection, manufacturing, and turbine design and life analysis. When correctly applied, these capabilities enable advanced components to be safely returned to service beyond their nominal design life, while maintaining structural integrity and reliability.

Component-specific qualification and a full repair development cycle are essential, with particular emphasis on restoring material and coating properties and accurately controlling wall thickness in cooled parts. The use of advanced measurement tools, such as white-light scanning, provides effective dimensional control and supports informed repair decisions. When executed correctly, these approaches significantly reduce unnecessary scrapping of capital-intensive components and deliver meaningful environmental sustainability benefits.

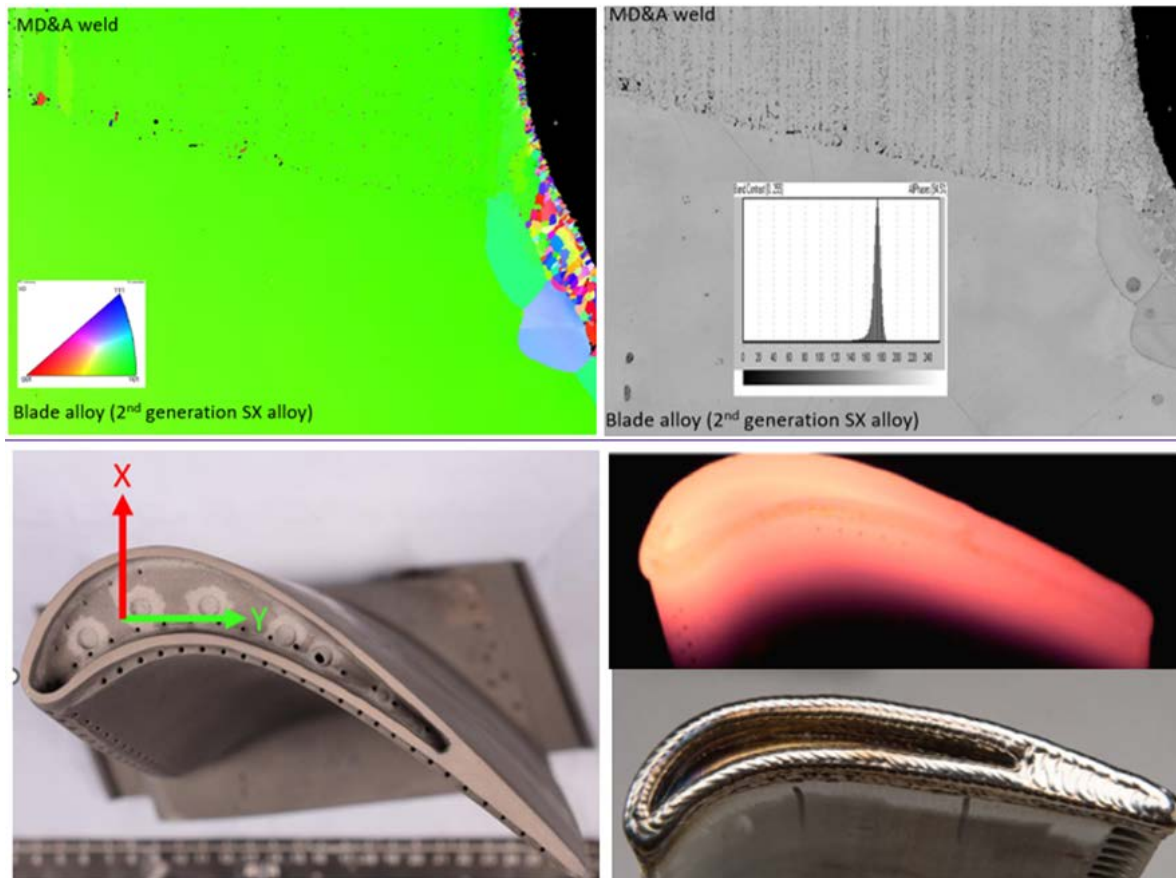


Figure 4: Advance weld repair development of single crystal blade, assessing the recrystallisation of the blade tip after welding by EBSD.

## Materials

The ever-increasing requirements for more efficient turbines and reduced CO<sub>2</sub> 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 can be subjected to operating gas temperatures of 1600°C and future targets aim at 1800°C. The hot gas path parts of the turbine highly rely on advanced cooling design and TBC systems. Additionally, the rising international ambitions towards emissions reduction, efficiency gains and renewables integration are reshaping for flexible operation requirements. This trend will further impact the operational life of the gas turbine components.

The blades and vanes of a gas turbine with frequent start cycles should be replaced at much shorter intervals than are traditionally implemented. 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.

### Improved alloys

Most modern alloys are designed to sustain long creep life. However, for the future market demand (i.e. with fuel and start/load flexibility), alloys with higher thermal fatigue, oxidation resistance, with acceptable creep life would be more favourable. Another important factor is manufacturing relatively large and complex turbine blades and vanes. The alloy selection should also consider the need for future repair and refurbishments.

Significant research has been conducted on the development of advanced single-crystal blade alloys, driven primarily by the need for higher turbine inlet temperatures for aviation. While these alloys have proven highly effective for aero engines, they have also been adopted for some larger industrial gas turbine components. However, comparatively limited research has been carried out on their oxidation behaviour under lower-temperature (400–600°C), high-stress (~600 MPa or higher) operating conditions typical of certain areas around the blade root internal cavity. As illustrated in *Figure 5* and *Figure 4*, preferential oxidation of the  $\gamma'$  phase can lead to cracking in highly stressed regions of single-crystal blades at relatively low temperatures. This fast-growing cracking mechanism has affected several aero and industrial engines in recent years and represents an important area for further investigation.

### Materials data

Reliable life analysis of gas turbine components requires access to comprehensive and validated materials data covering a wide range of properties, including creep, fatigue, thermo-mechanical fatigue (TMF), oxidation behaviour, coating degradation, crack growth, and environmental effects. These properties must be available over the relevant temperature, stress, and time regimes, and for both base materials and coating systems, to enable reliable life modelling and prediction of remaining useful life under real operating conditions.

In practice, a major limitation in life assessment and in-service lifing applications is the lack of accessible, high-quality materials data, particularly for some advanced alloys, coatings, and repaired materials. Much of the existing data is proprietary, incomplete, or not representative of current operating regimes such as flexible operation (i.e. when creep-fatigue interaction and crack growth are the major lifing limiting factors). Without suitable materials data, life models cannot be properly validated, significantly increasing uncertainty in life predictions and limiting the reliability of condition-based and online life assessment systems.

To address this gap (for specific superalloys or properties), it is recommended to initiate multi-disciplinary, collaborative research programs, with participation from OEMs, operators, research institutes, and international partners. Similar approaches were successfully implemented in the past through European Cooperation in Science and Technology (COST) programs, which generated widely shared materials databases and fundamental understanding. Reviving such coordinated efforts—potentially with global collaboration—would enable the systematic generation and validation of critical materials data used for the lifing of gas turbine.

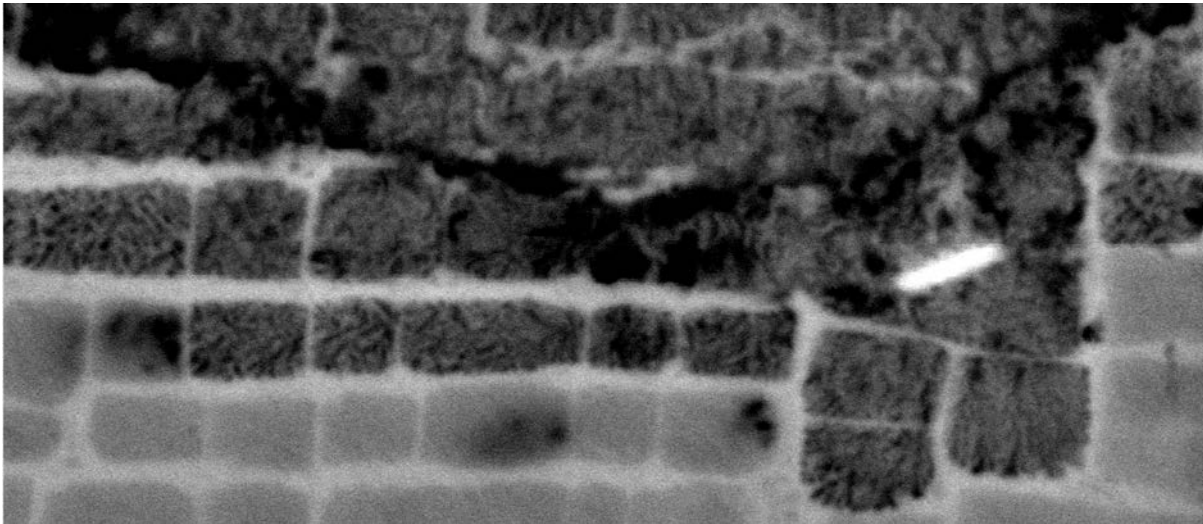


Figure 5: Preferential oxidation of the gamma prime at a low temperature and highly stressed region of second-generation single crystal blade leading to blade cracking.

### 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)

Further research should focus on improving the durability of TBCs for gas turbines subjected to high numbers of start–stop cycles, as cyclic operation is a primary driver for coating spallation life. In parallel, the development of advanced non-destructive inspection techniques for TBC condition assessment is essential to better evaluate the residual life of service-exposed components. Many existing TBC systems exhibit limited spallation resistance in contaminated environments due to accelerated oxidation and corrosion of the bond coat; therefore, coatings with improved tolerance to moderate hot gas path contamination would provide significant industry benefits.

### Additive manufacturing

Additive manufacturing (AM) techniques are being actively explored by OEMs, third-party suppliers, and operators for both the manufacture of new gas turbine components and the repair of in-service parts. AM enables the production of complex geometries and novel material compositions that are not achievable using conventional subtractive manufacturing methods, offering opportunities for cost reduction, performance enhancement, and design innovation.

A key advantage of AM is its potential to produce oxide dispersion-strengthened (ODS) alloys, which offer improved high-temperature strength and creep resistance. While ODS alloys were extensively studied in the 1960s and 1970s, their commercial application was limited by challenges in achieving uniform oxide dispersion. Modern AM technologies are expected to overcome these limitations, enabling the development of the new generation of superalloys tailored for gas turbine applications. In addition, AM may allow the manufacture of complex through-wall cooled components that are impractical with traditional investment casting, opening opportunities to design alloys with improved oxidation, and thermal fatigue resistance.

Further research is required to develop robust non-destructive inspection techniques for additively manufactured components and to qualify AM-based repair processes for advanced turbine parts. When properly developed and validated, additive manufacturing has significant potential to both manufacture next-generation components and extend the service life of existing gas turbine hardware.

### **Reduced usage of strategic and environmentally-damaging elements**

European legislation on the Registration, Evaluation, and Authorisation of Chemicals (REACH), in force since 2007, has significant implications for gas turbine materials and manufacturing. Several elements commonly used in structural alloys and coatings such as hexavalent chromium, nickel (including fine nickel oxide particles), and other base or alloying elements are classified as Substances of Very High Concern (SVHC) due to health risks. Compliance requires careful evaluation of materials throughout component manufacture, operation, and repair, including monitoring corrosion by-products that may release hazardous substances.

Gas turbine alloys also contain strategically important and scarce elements such as Co, Mo, Ta, W, and Re. Minimising unnecessary replacement of components through accurate assessment of service life and repairability not only reduces environmental impact but also provides significant cost benefits for stakeholders.

### **Condition monitoring and lifing**

Condition-based monitoring (CBM), combined with AI-driven analytics and integrated lifing systems, offers significant benefits for gas turbine operation. By continuously tracking key operating parameters—such as temperatures, pressures, vibrations, and fuel flow—CBM enables operators to identify early signs of wear, degradation, or abnormal behaviour. This predictive approach reduces unplanned downtime, optimizes maintenance schedules, and extends the operational life of high-value components, ultimately improving reliability and reducing operating costs. See condition monitoring recommendation in Section [Condition Monitoring](#).

### **Reliability of available online monitoring systems**

Although most modern engines, such as F-, H- and J class units are equipped with monitoring systems incorporating diagnostic and prognostic functions, field experience has shown that critical anomalies are not always detected or adequately reported prior to catastrophic failures. This gap underscores the need for a comprehensive review of monitoring system effectiveness, including data quality, signal interpretation, alert logic, and failure prediction methodologies. While all major OEMs – and, in some cases, non-OEM providers – offer advanced online monitoring solutions, there is limited evidence that the effectiveness, robustness, and response of these systems have been independently validated. Focused research and development in this area, including independent performance assessments of currently deployed monitoring systems, would provide significant value to owners and operators as well as feedback to manufacturers to improve the system.

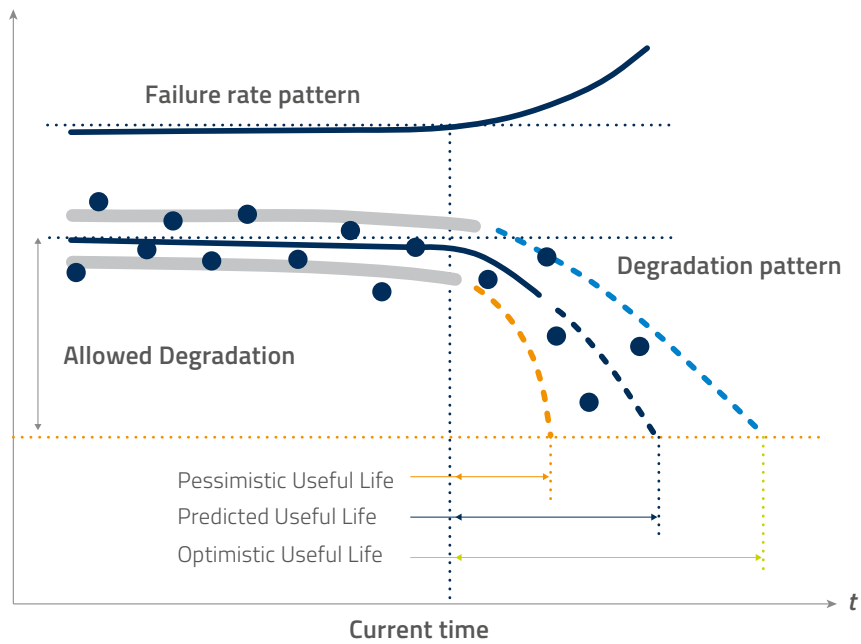


Figure 6: Degradation and prognostic model.

### Hydrogen Capability and Impacts

Transitioning gas turbines to high-hydrogen fuels requires careful evaluation of materials selection, degradation mechanisms, and component life. Key challenges include changes in heat transfer characteristics of the combustion gas and its effect on the hot gas path durability.

Hydrogen-induced alloy embrittlement and weld sensitivity prior to combustion, and the effects of high water-vapour content after combustion, which can accelerate oxidation, hot corrosion, and thermal barrier coating (TBC) spallation are the issues still to be understood well. Combined effects of water vapour and trace contaminants (e.g., Na, S, Cl) on alloys and coatings remain poorly understood. Targeted research is needed to identify hydrogen-compatible superalloys, coatings, and welding processes, quantify life-limiting degradation mechanisms, and develop strategies to maintain durability and safe operation under 100% hydrogen or high-hydrogen fuel conditions.

## 6. Operational Optimisation

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As power systems progressively rely on more on variable renewable generation, gas-turbine-based plants are increasingly dispatched for flexibility rather than steady baseload, which exposes them to frequent start–stop cycles, deeper part-load operation, faster ramps, and more stringent grid-service requirements. This operational shift drives higher thermal and mechanical transients, faster degradation, and tighter emissions–performance constraints, so “running the plant” is no longer a matter of meeting setpoints it becomes a continuous optimisation problem across competing objectives that include maximisation of revenue streams and minimisation of operational expenses and risks.

In this context, operational optimisation means systematically selecting and executing the best operating decisions at plant and fleet level, across scheduling, start-up/shutdown, loading, fuel switching, and maintenance planning, using models and data to quantify trade-offs. The goal is to maximise value (availability, revenue from energy and ancillary services, and efficiency where it matters) while minimising penalties (life consumption, forced outages, OPEX, and emissions) under real constraints such as grid codes, ambient conditions, fuel quality, hardware limits, and cybersecure connectivity.

Operational optimisation therefore sits at the intersection of controls, digitalisation, and asset health: it relies on high-fidelity performance and lifing models, validated instrumentation, and plant-wide coordination (gas turbine–steam cycle–auxiliaries–storage, where applicable). As plants become more connected and data-driven, the optimisation stack must also be designed to operate safely and securely within industrial cybersecurity frameworks commonly used in Operational Technology (OT) environments.

This chapter focuses specifically on R&D topics that enable better operational decisions and execution—improving flexibility, part-load performance, cycling reliability, overfiring capability, and fuel-switching—while providing the digital and control foundations (digital twins, advanced/autonomous control, condition-based operation) required to optimise across the full operating envelope. Where decarbonisation or low-carbon fuels are discussed here in an operational context (e.g., hydrogen co-firing, fast fuel switching, new constraints on operability), the detailed technology pathways and system impacts are treated in the dedicated low-carbon solutions section and should be cross-referenced accordingly.

Effectively, open cycle gas turbines or combined cycle power plants are likely to provide a significant proportion of flexible back-up in the medium term. The role of CCGTs has already shifted from baseload to load cycling in many countries. This trend is expected to continue, with gas turbine power plants further moving from the energy market to the service market. Therefore, the design of new power plants and retrofits of existing power plants will need to consider multi-discipline optimization of the designs, operations and maintenance of the power plants. Emerging technologies, such as use of low carbon fuels and hydrogen fuel to achieve zero or near-zero CO<sub>2</sub> emissions, digitalization, Artificial Intelligence, remote and autonomous control and condition monitoring, etc. will be important technologies supporting the optimization of gas turbine power plant operations.

*Figure 7* below shows a Siemens' view of the future Hydrogen GT Power Plant where wind turbines and solar panels produce power to the grid and also using their excess energy to generate hydrogen which can be used by gas turbines during periods of RES shortage. Such complicated power plant operations could be enabled and optimized by the application of digital twins.

This chapter focuses specifically on R&D topics that enable better operational decisions and execution - improving flexibility, part-load performance, cycling reliability, overfiring capability, and fuel-switching, - while providing the digital and control foundations (digital twins, advanced/autonomous control, condition-based operation) required to optimise across the full operating domain.



Figure 7: Siemens Energy Hydrogen GT Power Plant. © Siemens Energy.

The following areas have been identified as active R&D topics related to gas turbine-based power plant operations.

## Operation Flexibility

### Fast response capability

One of the key demands in power generation in the future energy market is the capability to react quickly to load changes as required by the grid. As a 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, small gas turbines: from cold standstill to full load in 5 minutes) while minimising the impact on component life consumption and emissions.

The capability of responding to quick load changes may be achieved by either novel designs of gas turbine power plants, or hybridisation with a variety of energy storage systems, such as mechanical storage (flywheels, compressed air), electrochemical storage (batteries), thermal storage (molten salt in solar thermal plants), electrical storage (Supercapacitors, Superconducting Magnetic Energy Storage) with the consideration of the impact of fast response on engine life consumption and ancillary components.

### Part-Load Operations with High Efficiency

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 contribute in the future toward grid balancing, the number of operating hours at partial load and frequent load changes are expected to increase. This will require efficiency improvements, the reduction of the emission of CO and unburned hydrocarbons (UHC), and improved low cycle fatigue (LCF) life.

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 energy storages 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 shutdowns, therefore potentially reducing LCF life consumption supported by digital twin technology.

## **Frequent start-up and shutdown at high 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. Sometimes such operations may also cause failure of low-value components that consequently results in significant downtime.

In order 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. Condition based assessments may be beneficial in this regard, helping to understand the state of key engine components during service and reducing conservatism compared with design.

Additionally, the integration of energy storage systems could provide solutions of power-to-X-to-power with the benefits of reduced number of start-ups and shutdowns. Furthermore, optimization of power plant operations, for example during start-up and shut-down, could also minimize engine life consumption and ensure high reliability.

## **Over-firing operations with high reliability**

Gas turbines are already expected to be able to overfire to support grid code and related schemes. The increased temperature within the hot section of the gas turbines increases the risk of degradation (e.g. creep, oxidation and fatigue) for key engine components. Overfiring can also play a role at increasing power on a hot day or reducing the requirement for spinning reserve.

Developments in condition-based assessments, supported by digital twins, are required in order to mitigate the increased risk of failure due to the additional load on the turbines. Consideration should also be given to the increase in NOx with the developments to maintain low emission. Integration with alternative energy storage solutions could also be developed to support the additional power requirements.

## **Quick switching of fuels**

Many gas turbines are currently able to switch between liquid and gaseous fuels. However, with the demand for fuel flexibility in power generations and the development of alternative fuels, such as natural gas, bio-fuels, hydrogen, methanol, the ability to switch between different fuels in a short period of time, will be an increasing challenge. R&D research may focus on combustor technology, turbine and boiler adaptation, fuel handling and storage, control systems, grid and system integration, digitalization, and new materials, with the consideration of safety, economics, and reliability.

## Power Plant Retrofit for Net Zero Emissions

As most existing power plants use fossil fuels for power generations, it is necessary to replace or retrofit these power plants to achieve the target of net zero emissions by 2050.

The focus of the R&D research on the retrofit of existing fossil fuel power plants may be decarbonisation CCUS switching fossil fuels to low-carbon or hydrogen fuels, integration with renewables and energy storages, non-carbon emissions control (NO<sub>x</sub>, SO<sub>x</sub>, solid particles, etc), efficiency improvement, digital optimization, autonomous operations and repurposing. R&D research aims to explore more technical solutions and economic approaches to achieve such a transition will be valuable. This research shares some common interests with the Low Carbon Solutions described in [Chapter 9](#).

## Reliability, Availability, and Maintainability

Gas turbine operators are constantly focused on delivering their products to customers. A high level of reliability, availability and maintainability (RAM) for gas turbine power plants allows ambitious forecasts to be reached without disruptions. These R&D requirements are generally specific to different classes of gas turbines and so are discussed more generally in this section.

**Reliability** - is a design feature and is defined as the probability of a system to perform its intended function satisfactorily in a defined environment for a specified period of time. The R&D activities to improve gas turbine power plant reliability could focus on exploring new techniques, such as design for reliability (DfR) (failure mode and effects analysis, redundancy design, life analysis, design margin analysis, etc.), accelerated life testing (ALT), research on new materials and process (new surface treatments and manufacturing process), data analytics and predictive modelling (reliability modelling, predictive maintenance, field data analysis), root cause analysis and corrective actions, reliability standards or benchmarking, tools and processes to document and share lessons learned from past failures. Identification of persistent problems across different users can help to target R&D for a swift resolution of reliability issues.

**Availability** - is an operational feature and is defined as the probability of a system being available/operational. The R&D activities to improve the availability of gas turbine power plants should focus on developing new technologies in the areas of designs for availability (modular designs, more swappable components, design for maintainability), redundancy and fault tolerance, accelerated failure testing and maintenance simulations, predictive maintenance and prognostics, applications of digital twins, automated maintenance process, spare parts optimization, root cause analysis, degradations and failures analysis, advanced lifing methods, human error and human factor studies.

**Maintainability** - is defined as the probability that equipment will be retained in, or restored to, a specified condition within a specified period of time. It is measured by maintenance workload and mean time to repair. The R&D activities could focus on the improvement of designing systems, component design, and processes that minimize the time, cost, and complexity of performing maintenance. In other words, they may include design for maintainability (modular designs, easy-to-access designs, standardised components and tools, etc.), maintainability modelling, diagnostics and remote condition monitoring, human factors and ergonomics, maintenance procedure optimization, advanced tools and technologies (augmented/virtual reality, robotic maintenance systems, digital twins, additive manufacturing, new TBC, etc.), root cause analysis and corrective actions, spares and logistics optimisation.

## Digitalisation for Operations

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). Remote monitoring and online machine monitoring are not new concepts, but for some the advantages of IIoT are not immediately obvious. Additionally, there are 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 for power plant operations.

### Advanced Control and Autonomous Operations

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, life consumption analysis, and the reduction of CAPEX and OPEX.

The continuously increasing share of RES 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 have to be reduced while improving reliability, flexibility and lifetime.

R&D is required to address the optimization of entire plants with reduced CAPEX and OPEX without the compromise of performance, efficiency, emissions control and reliability by replacing the traditional open cycle gas turbine power plants and gas turbine combined cycle power plants with emerging technologies such as novel power plants based on different cycle configurations, burning renewable fuels (hydrogen, methanol, etc) and using a variety of different working fluids (organic fluids, supercritical CO<sub>2</sub>, etc). When aligned with cost models, such research could improve the capability and provide essential information to support decision making.

Further improvement could be realised by automatic tuning systems, e.g., 'self-learning' or 'self-adapting' control systems for optimization of plant operations based on advanced digital twins and artificial intelligence technologies. This is important for the power plants to adapt to changing operating scenario quickly, such as fuel changes (H<sub>2</sub> or other low-carbon fuels), plant degradations or failures, and market variations (change of power demands, fuel prices, electricity prices).

Emerging future demand of the technology could be the autonomous control and operations of power plants for further reduction of operating costs, fewer staff demand, better reliability, improved safety, and optimal performance.

### Condition Monitoring techniques

When deployed as part of an integrated diagnostic and prognostic system, the value of CBM is further enhanced. Diagnostic algorithms can identify the root cause of detected anomalies, while prognostic models predict the remaining useful life of critical components under real operating conditions. This allows operators to make informed, data-driven decisions on maintenance, repair, and component replacement, improving asset utilization and operational safety.

Integrated lifing systems, combining historical operational data, AI driven data analysis, and component life models, provide a comprehensive framework for managing the life cycle of gas turbines. These systems enable not only optimized scheduling of inspections and repairs but also support decision-making for life extension programs. By linking CBM, diagnostics, and prognostics, operators can maximize component reuse, reduce unnecessary part scrapping, and support long-term sustainability objectives. This process further assists the enhanced repair requirements or improved designs for extended operation of the turbines.

## Development of Digital Twins

Digital Twins (see *Figure 8* 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. *Figure 9* shows an example of the classification of the maturity level of a digital twin system starting with a static representation (e.g., for reporting purposes), and ending in a digital twin for dynamic predictions of the physical entities to support designs, manufacturing, operations, predictive or preventive maintenance, disposal, etc. of the systems.

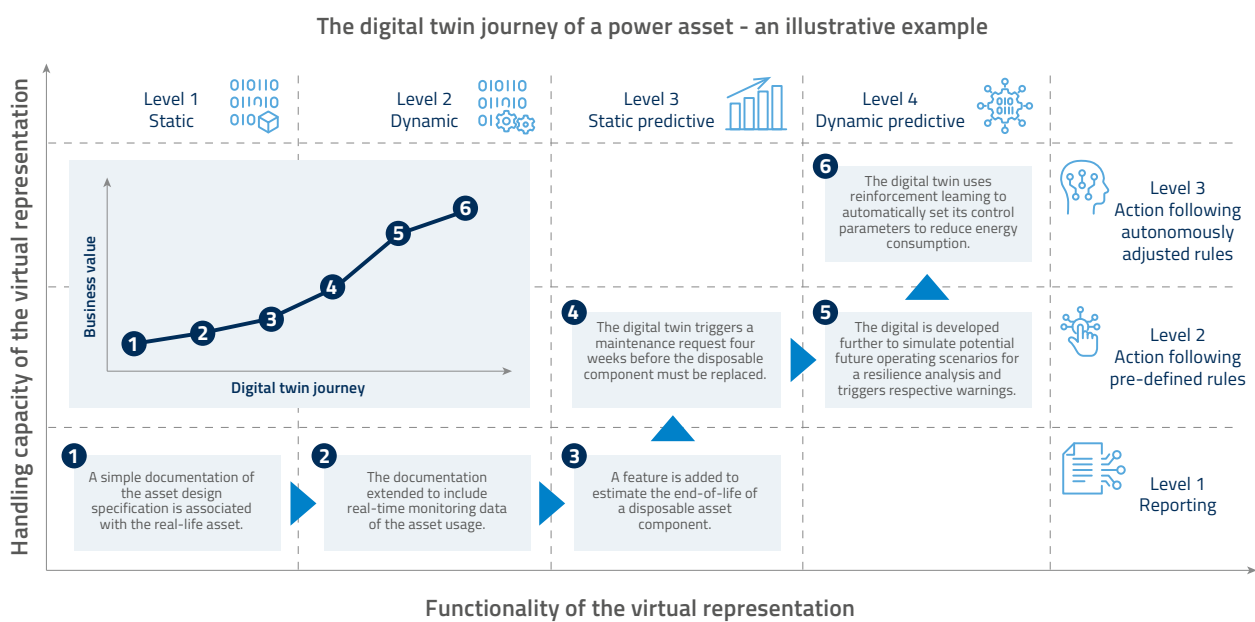


Figure 8: The digital twin journey of a power asset. © Siemens Energy.

Within such a digital twin ecosystem, individual digital twins can be configured for specific use cases. Using different 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 users 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.

R&D research activities on digital twin technology may also focus on the development of service capabilities, such as the power system designs or retrofit for effective integration of RES, optimal operations to compromise the conflicting demands of performance, economy, life consumption and sustainability, autonomous control of power plants, condition monitoring and lifing to support condition-based maintenance, etc. They share some common interests in condition monitoring and lifing mentioned in [Chapter 5](#) regarding CBM. Activities on digital twin standardisation to enable compatibility across different systems, potentially through an ISO standard, would potentially provide benefits to users operating a diverse fleet of gas turbines.

## Lifecycle Management

Lifecycle management refers to the process of managing the entire life span of a product, system, or project—from its initial conception to its end-of-life or disposal—in a structured and efficient way.

The R&D activities would focus on the development of digitalisation technology to improve reliability, efficiency, safety, sustainability, and cost-effectiveness of power plants across the whole life span, from design, commissioning, operation, maintenance, modernization, and decommissioning. The research may have a strong emphasis on lifecycle analysis, covering new plant designs and retrofit of existing power plants for net zero emissions, optimal operations, AI-driven condition monitoring and predictive maintenance, integration with renewables, combined life consumption due to creep, fatigue and oxidation, and decommissioning technologies with the considerations of sustainability and resilience.

## Big Data Management

Turbomachinery equipment, such as in power plants, produce large amounts of data during their lifetimes. Timely insights into these data help 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 and effective communications among different people 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, transfer, 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, system compatibility, enable consistent and robust access control and security to ensure data integrity, reliability, and availability.

## Cybersecurity

Gas turbines and turbomachinery equipment 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, and the hardware solutions develop to comply with this standard 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.

## Applications of Artificial Intelligence (AI)

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

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.

## 7. Integrated Energy Systems

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The transition toward a decarbonised and resilient energy system demands a comprehensive rethinking of electricity market structures, investment mechanisms, and system flexibility. A recent regulatory development within the European Union (European Electricity Market Design Reform [\[24\]](#)) reflects this urgency, emphasizing the integration of renewable energy sources, the enhancement of cross-border interconnectivity, and the deployment of advanced market instruments to stabilize prices and support long-term investments.

EU is reinforcing its approach to flexibility needs assessment. Member States are now required to regularly evaluate their electricity systems' flexibility requirements over a 5 to 10 year horizon. These assessments consider seasonal and hourly variations, the integration of variable renewables, and the role of non-fossil flexibility resources such as energy storage, demand response, and digitalisation. Coordination between transmission and distribution system operators, supported by ENTSO-E and the EU DSO Entity, ensures consistency and alignment with EU-wide climate targets.

On the market instruments' side, it is important to mention that the implementation of two-way contracts for difference (CfDs) aims to provide direct price support for new power-generating facilities. These contracts offer financial stability to investors while ensuring that excess revenues are redistributed to consumers, thereby aligning economic incentives with climate objectives. The design of such schemes must preserve market efficiency, avoid distortions, and promote competition through transparent bidding processes.

Together, these measures form a cohesive framework for **energy systems integration**, enabling the Union to meet its 2030 and 2050 climate goals while maintaining security of supply and market stability.

To operationalize this vision, integrated energy systems must leverage a diverse set of technologies and configurations. The following sections review four key areas of technical integration:

- Waste Heat utilisation and recovery from Gas Turbines – improving energy efficiency through thermal integration and heat upgrade.
- Cogeneration and Trigenation Systems – optimising energy use in industrial and urban environments.
- Energy storage – to compensate the variable nature of RES and optimise the integration of Gas turbines in energy systems.
- Distributed Energy Systems – exploiting district-level co-optimisation of energy resources.

### Waste-Heat Utilisation and Recovery from Gas Turbines

Waste heat recovery can be categorised into two categories: direct and indirect recovery.

Direct recovery involves the direct reintroduction of the waste heat in the cycle, leading to improved performance and efficiency (this topic is further discussed in the Chapter on [Energy Efficiency](#)). Alternatively, this mismatch in temperatures can be addressed by reintroducing the waste heat in a different form, such as humidification (See Section [Humidification](#)) or a chemical pathway.

Chemical recuperation covers the use of the waste heat in different fuel preparation cycles, ranging from preheating the fuel to use in biogas/syngas production. Although valuable for specific projects, this option is not applicable to general frameworks. Moreover, due to the integration of different processes, this limits the flexibility of the power cycles.

Indirect recovery involves the valorisation of remaining thermal energy through the production of a secondary product. Several examples that are well embedded in the current industry can be found: e.g., production of process heat/steam or for heating purposes (see section on [cogeneration](#)), production of cold through absorption chillers or production of fresh water in desalination plants. Generally, these applications are only profitable if the demand for the secondary product is sufficiently high and constant (e.g., heat-driven operation of gas turbines in cogeneration).

The recent development of high-temperature heat pumps offers interesting opportunities for waste heat recovery in gas turbines. Especially, the recovery of waste heat using heat pumps provides the unique feature to upgrade the waste heat. The mature vapour compression technology offers solutions that provide heat up to 250°C, whilst the reversed Brayton Cycle heat pump, currently under development, allows for even higher temperatures (400°C). However, as the Coefficient of Performance (COP) of most of these cycles depends on maximal temperature as well as temperature lift, comparing these solutions is challenging.

Heat pump R&D should focus on raising achievable delivery temperatures (from 50–120°C sources to 200–250°C and beyond, including >250°C and mid-grade steam around 300°C) whilst simultaneously reducing capital cost through simpler, more robust system designs and validated component performance. Priority needs include piloting and demonstrating 2–3 MW high efficiency concepts—such as steam generating heat pumps, open cycles, and advanced/complex cycles - paired with deeper insight into internal energy flows (e.g., Sankey-based analysis integrated with irreversible thermodynamics) to unlock improved heat integration and recovery strategies. R&D must also address safe and controllable heat recovery from challenging industrial streams (high temperature/volume, corrosive or fouling media, and hot solids/particles), broaden and optimise heat transfer media options (water/steam, oils, salts, gases, solids), and prove operability, flexibility, and efficiency in real process environments, with clear verification of energy savings and performance at pilot and demonstration scale.

Today, COP and efficiency are often reported at different source/sink temperatures and with inconsistent system boundaries, which prevents robust benchmarking and slows down scale-up decisions; an analogue to the well-defined domestic heat-pump test conditions is needed for industrial high-temperature applications as well. A priority R&D need is to establish a unified, high-temperature heat-pump assessment and integration framework that enables both consistent reporting of performance across clearly defined boundary conditions and standardization of systems and components. In parallel, targeted component-level advances are required: for reverse-Brayton heat pumps, improved turbomachinery and high-effectiveness, low- $\Delta P$  heat exchangers are key levers to raise COP, while vapor-compression approaches need accelerated transition to low-Global Warming Potential working fluids and compatible components in response to EU F-gas constraints (EU Regulation 2024/573), alongside cycle and component development to reach higher output temperatures with acceptable CAPEX and reliability.

Another option is the integration of Carnot batteries, also referred to as Pumped Thermal Energy Storage (PTES), and particularly Brayton Cycle Carnot Batteries (BCCBs). These are developed as geographically independent large-scale energy storage solutions based on reversible thermodynamic cycles. While originally envisioned as electricity-only alternatives to PHES and CAES, their moderate round-trip efficiencies and relatively high capital costs limit competitiveness for short-duration storage, positioning them instead for long-duration applications (tens of hours) coupled to variable renewable generation. The state of the art is increasingly shifting toward Heat-Integrated Carnot Batteries (HI-CBs), where rejected heat is valorised within industrial processes. By simultaneously delivering electricity, process heat, and potentially cooling, these systems act as multi-energy hubs, improving overall exergy efficiency, increasing asset utilization, and enhancing economic viability in industrial settings with significant thermal demand.

## Cogeneration and Trigeneration

In contrast to the above-mentioned use of waste heat, there are changing priorities for energy generation in cogeneration and trigeneration from the focus on optimizing power generation to also providing thermal energy for heating and/or cooling as demanded. Whilst cogeneration and trigeneration were usually seen as an option in context of a power plant, recent research points towards cogeneration plants being an integral part of larger process ([25], [26], [27], [28], [29]). This results in an increased overall complexity when optimizing a plant and its operational optimisation due the various component characteristics and operational profiles which need to be matched. The review of recent publications as well as the consideration of on ongoing activities indicate the following needs for further research and development:

- Evaluation and optimisation of processes in nearly all cases considers the optimisation for a single operating point. This neglects the need to cover a wider range of operating conditions especially when systems are integrated with other fluctuating renewables or connected to grids with varying demand profiles.
- When considering turbomachines in connection with other components, for example in the context of renewable fuel production of bio processes, different operational characteristics need to be connected which might in turn result in the need to consider buffer elements (i.e. storage) for matching.
- The consideration and integration with processes and local plants are expected to also result in the need for certain “auxiliaries” which often seem not to be considered in research and simulation activities. Components for efficient operation of a plant and safety-relevant components usually add to the complexity of an installation and might impact the estimated plant efficiency.

As a result of these three bullet points it is recommended that further research and development activities focus on simulations and optimisations considering various operational conditions, replacing the single point optimisation by one considering realistic operational profiles and characteristics of the components. The integration of uncertainty is another topic to be covered in this context. Uncertainties might result for changing boundary conditions, accuracy of available information and data and the expected development of markets. The optimisation can contribute to real integral performance and efficiency evaluation for a typical operational period (e.g. one year) while the inclusion of uncertainties contributes to the estimation of its economic viability as well as helping to identify and dimension potentially needed buffer capacities to match various component characteristics.

Other aspects to be considered are measures contributing to resilience and safety during operation as well as secured energy supply. These are also expected to result in adjustments of the plant and its layout as well as impacting the design of components. Especially, the consideration of thermal energy storage at higher temperature levels and/or the integration of heat pumps should be evaluated to decouple thermal and electrical demand and to further contribute to increased overall efficiency. However, this might be also subject to the business case of each application/plant.

## Energy Storage

Energy storage technologies are playing an increasingly vital role in achieving grid stability and flexibility, particularly as renewable generation grows. Whilst electrochemical batteries are effective for short-duration energy storage, their limited discharge time restricts their role in large-scale applications. In the short term, integrating batteries with gas turbines provides several advantages—enhancing operational flexibility, improving start-up response, and reducing emissions during transient operation. For long-term energy storage, power-to-gas technologies offer a promising pathway, converting surplus renewable electricity into hydrogen or synthetic fuels that can be stored seasonally and later used in gas turbines or other energy systems. Alongside thermo-mechanical concepts such as Compressed Air Energy Storage (CAES), Liquid Air Energy Storage (LAES), and Carnot batteries, these approaches together form a robust portfolio for delivering flexibility, reliability, and decarbonization across future energy networks.

### Power to gas

The power to gas technology, with specific focus on hydrogen, is discussed in Section [Hydrogen](#).

### Compressed air energy storage (CAES)

Current CAES development is best understood as a family of thermomechanical storage cycles whose achievable efficiency, cost, and siting feasibility are jointly governed by (i) the treatment of compression heat (diabatic vs adiabatic vs. near-isothermal concepts) and (ii) the air storage medium and facility design (salt caverns, engineered/rock caverns, vessels) [\[30\]](#). Recent reviews frame CAES as a credible grid-scale LDES pathway and they emphasise an industry trend toward larger plant sizes, higher efficiency, decreasing reliance on fuel-fired reheat and strengthening thermal integration and heat management. In parallel, coupling CAES with renewable-heavy systems is increasingly treated as a primary use case driver, shifting attention from pure energy shifting to operational flexibility and system adequacy contributions over long durations.

The dominant technical bottlenecks sit at the interfaces: thermodynamic integration (heat capture/storage/reuse), subsurface (or engineered) air storage engineering, and validated performance/cost representation for investors and planners. R&D should therefore concentrate on (1) high-fidelity thermal management development (high-temperature materials and containment, exchanger effectiveness under cycling, loss mechanisms and degradation under realistic duty profiles) to close the gap between conceptual adiabatic/high-efficiency cycles and bankable plant performance. In parallel, development of standardised, transparent, techno-economic and operational models that can be used consistently across “routes” and storage options; which are essential to reduce soft costs and to support procurement, permitting, and interconnection decisions on an equal footing with other LDES technologies.

### Liquified air energy storage (LAES)

LAES is a thermomechanical storage option that converts electrical energy (and, in some configurations, thermal energy) into cryogenic stored inventory, then regenerates power through expansion and associated power-recovery processes [\[31\]](#). Current designs integrate air liquefaction, cryogenic storage, heat exchange, and turbomachinery into a dedicated storage plant, with performance primarily governed by the degree of cold/heat recovery and overall thermal integration across charge and discharge. The design space spans standalone configurations and integrated/hybrid layouts that incorporate thermal energy storage and/or exploit available hot/cold streams to improve efficiency and overall value, with the technical frontier largely defined by how well these integrations are optimised and validated under realistic operation.

Key gaps relate less to component availability and to closing the delta between conceptual performance and bankable, duty-cycle robust plant operation at scale. R&D should prioritise plant-wide thermodynamic integration and thermal reservoir engineering: improved internal cold recycle and heat recovery, reduced exergy destruction in cold-box/heat-exchanger networks, and scalable hot/cold storage concepts that preserve useful temperature levels over relevant storage times. In parallel, develop dynamic models and controls that explicitly address transient, cycling, and part-load behaviour (renewable-following duty cycles), and validate these with representative operating profiles rather than design-point assumptions. To support investment decisions and procurement comparability, the establishment of harmonised techno-economic assessment (standardised cost breakdowns, consistent assumptions, and comparable metrics across standalone vs integrated/hybrid configurations), coupled with measurement-backed analysis would be beneficial.

## Carnot batteries

Carnot batteries, also referred to as Pumped Thermal Energy Storage (PTES), and particularly Brayton Cycle Carnot Batteries (BCCBs), are being developed as geographically independent large-scale energy storage solutions based on reversible thermodynamic cycles. While originally envisioned as electricity-only alternatives to PHEs and CAES, their moderate round-trip efficiencies and relatively high capital costs limit competitiveness for short-duration storage, positioning them instead for long-duration applications (tens of hours) coupled to variable renewable generation. The state of the art is increasingly shifting toward Heat-Integrated Carnot Batteries (HI-CBs), where rejected heat is valorised within industrial processes. By simultaneously delivering electricity, process heat, and potentially cooling, these systems act as multi-energy hubs, improving overall exergy efficiency, increasing asset utilization, and enhancing economic viability in industrial settings with significant thermal demand.

Research should focus on thermodynamic and operational integration of Brayton-based Carnot batteries with gas turbines, including hybrid configurations using exhaust heat, shared turbomachinery concepts, and coordinated pressure and temperature matching. Priority topics include dynamic modelling, transient control, and system optimization to enable flexible operation under renewable-driven load variations while maintaining high efficiency. Such integration can improve plant performance, reduce fuel use, and enable dispatchable low-carbon power with embedded long-duration storage.

The integration of Gas Turbines Power Plants with utility scale Battery Energy Storage System (BESS) offers a pathway to improving flexibility, resilience, and adequacy of electricity grids in the face of rising shares of renewables and more variable demand. The technology complements the strengths of both: the dispatchable high-power output of GT and the rapid response, energy shifting and grid stabilization of BESS.

The integration of GTs and BESS can be designed as a hybrid system with centralised control architectures that manage both generation and storage assets behind a unified electrical interconnection point. This configuration allows for real-time optimization of energy flows, directing electricity either to the grid or to storage.

Effectively integrating BESS with gas turbines creates a hybrid resource that pairs sub-second battery response with sustained thermal generation, enabling enhanced flexibility and higher-value grid support. The battery can inject/absorb power rapidly to cover fast load changes, smooth operating transitions, and expand effective ramp rates (including mitigating combined-cycle steam-turbine lag), which reduces turbine wear and supports deeper, steadier part-load operation by absorbing excess generation instead of forcing shutdowns or inefficient cycling.

This operating mode improves the plant's ability to deliver ancillary services - frequency response and regulation, reserve products (including "bridging" spinning reserve while the GT starts and, in some concepts, providing reserve with the turbine offline), and voltage support - while also lowering fuel burn, starts/fast-starts, and maintenance burden by keeping the GT closer to steadier and efficient operating points and using the battery for short transients [\[32\]](#). Co-location can further reduce costs through shared interconnection and site infrastructure, and, for some reserve

use cases, enables smaller battery energy sizing than a standalone storage plant providing the full-service duration alone. From an R&D perspective, these technical capabilities translate into economic optimisation opportunities (stacking ancillary-service revenues and time-shifting energy where market rules allow) alongside environmental benefits from reduced runtime and less inefficient part-load operation, with additional system value in resiliency/adequacy for renewable variability, extreme events, and islanded grids—especially where rapid response is needed but long-duration support must ultimately be sustained by fuel-based generation.

R&D should prioritise developing and validating advanced control, modelling, and assurance methods for hybrid gas-turbine-plus-battery plants so they can reliably deliver their full flexibility and ancillary-service value without increasing operational risk. This includes designing a robust hybrid control system that coordinates dispatch while minimising fuel burn and managing battery state-of-charge and degradation and establishing commissioning/test protocols that verify seamless joint operation with no adverse impact on normal gas-turbine behaviour. In parallel, research should close valuation and representation gaps by improving production-cost/dispatch models that correctly capture gas-turbine heat-rate behaviour across the operating range and quantify system-level benefits of hybrid operation, supporting credible planning and market participation. Finally, targeted testing and data collection should characterise battery behaviour under abnormal conditions and strengthen integrated safety and cybersecurity practices for co-located installations, enabling scalable, low-risk deployment and clearer pathways for market and capacity-rule alignment.

## **Final R&D and policy recommendation**

EU regulatory developments (RfG amendments, market design reforms, increasing recognition of storage and flexibility needs) are moving in a favourable direction, but some technical, regulatory, and economic barriers remain. Research and demonstration work should focus on control systems, economic modelling, grid-code updates, and ensuring that hybrid plants are explicitly accommodated in codes, markets and investment planning.

Other research should focus on thermodynamic and operational integration of Brayton-based Carnot batteries with gas turbines, including hybrid configurations using exhaust heat, shared turbomachinery concepts, and coordinated pressure and temperature matching. Priority topics include dynamic modelling, transient control, and system optimization to enable flexible operation under renewable-driven load variations while maintaining high efficiency. Such integration can improve plant performance, reduce fuel use, and enable dispatchable low-carbon power with embedded long-duration storage.

## Distributed Energy Systems

The integration of distributed energy resources (DERs) – including micro-CHP systems, residential thermal storage, rooftop solar, residential battery storage, heat pumps and flexible demand, represents a transformative shift in energy system architecture.

Unlike centralized generation, DERs require advanced coordination across grid layers, digital infrastructure, and market mechanisms. Recent EU policy trends, including the Electricity Market Design Reform (Regulation EU 2024/1747), increasingly emphasize the role of prosumers (i.e., active energy consumers who both consume and produce energy), local energy communities, and active distribution networks. Innovations in smart inverters, peer-to-peer trading platforms, and AI-based grid management are enabling real-time optimization and resilience at the edge of the grid. However, challenges remain in harmonizing grid codes, ensuring cybersecurity, and managing data interoperability across diverse systems.

Among DER technologies, micro gas turbines in CHP configurations are gaining renewed attention for their compactness, fuel flexibility, and ability to deliver heat, power, and cooling in a distributed manner ((IWG5), 2024) [\[33\]](#). These systems must evolve toward dual-fuel capabilities and renewable fuel compatibility, while maintaining operational flexibility and integration with smart control systems.

Further R&D and policy efforts toward integration of distributed energy resources are addressed to scalable control architectures for multi-agent systems, dynamic tariff models that reflect locational and temporal value, and integrated planning tools that combine DER forecasting with grid reinforcement strategies. Pilot projects should also explore the co-optimization of energy, heat, and mobility at the district level, leveraging digital twins and interoperable platforms to validate techno-economic performance under realistic operating conditions.

## 8. Energy Efficiency

Energy efficient operation is critical to minimize fuel consumption and CO<sub>2</sub> emissions. In this context, the latest generation of large heavy duty gas turbines are able to 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 poses 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<sub>x</sub>H<sub>y</sub>, H<sub>2</sub>, or NH<sub>3</sub>). 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.

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 in order 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.

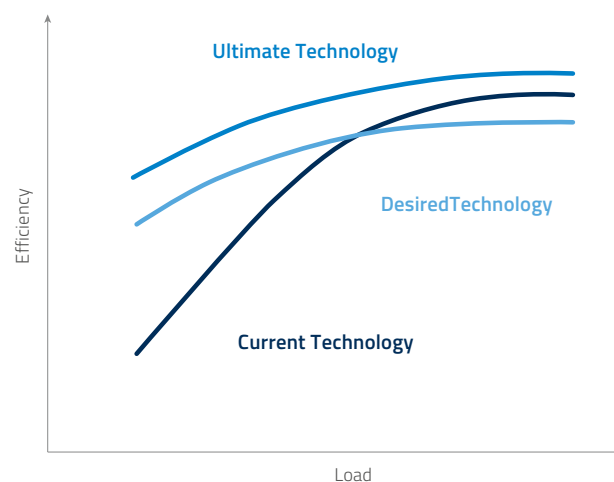


Figure 9: Gas turbine efficiency versus load.

## Main thermodynamic cycle and component improvement

Most contemporary gas turbines run on simple open cycle with relatively few engines making use of compressor intercooling, reheat 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<sub>2</sub> bottoming cycles [34]) 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 are able to 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 a gas turbine vs. load (see *Figure 9*).

### 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 in order 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.

## Air filtration

The main role of a highly efficient air filtration system is to keep the engine clean by preventing the introduction of contaminants into the gas turbine air intake. Achieving a high level of engine cleanliness helps maintain engine efficiency and integrity and reduces or even eliminates the need for water washes which generate avoidable downtime. The ultimate target for the filtration system is to keep the engine in clean condition with the lowest possible pressure drop across the system to maintain the highest possible efficiency and available power output from the gas turbine.

The increased implementation of EPA (Efficient Particulate Air) filters in gas turbine applications has ensured a step change in cleanliness for applications where such filters are installed and new compact EPA filter products with large filter surface area can enable upgrades of legacy fleet of air intakes without introducing unacceptable levels of pressure drop across the system.

However, there is a need to improve the ability to predict operational filter performance and life before implementation in the field. The air filters used for gas turbine applications have historically been tested in accordance with the standards for general HVAC filters and the challenges the filters are exposed to in the field are very different from the ones used in the lab tests. ETN Global has made key contributions to the development of ISO 29461 - Part 4 "Test methods for static filter systems in coastal and offshore environments" with the purpose of closing some of the gap between the current filter element characterization conditions (e.g.: ISO 29641 – Part 1) and the site environment. Part 4 focuses on the effect of humidity and alkali such as salt changing its structure with humidity, and the work on the standard revealed that current test methods are not mature enough for inclusion of soot, volatile hydrocarbons and oily vapor challenges which are experienced in the field. Hence, further work is needed to be able to develop suitable test methods to determine the impact on filter performance when exposed to soot, volatile hydrocarbons and oily vapours. There is also a need for a more representative test standard for pulse jet systems typically used in very dusty environments.

The contribution of EPA filtration in reducing the carbon footprint of gas turbines in operation is significant, but it is challenging to document a direct and universal link between filter grade and CO<sub>2</sub> emission for all applications. Further research is therefore desirable to better quantify the savings for different gas turbine technologies, environments, filter arrangements, and filter grades.

Water repellence is a key attribute for gas turbine air intake filters and R&D developments are needed to maintain or even improve this capability with more environmentally friendly solutions than the use of Perfluorohexanoic Acid (PFHxA) (C6 PFA) which is used in many of the current products.

Even the best intake air filters will not be able to keep the gas turbine clean if the ductwork or other components between the filters and the gas turbine allows unfiltered air to enter the airstream and there is a need for better methods for condition monitoring and inspection. The widely used practice of relying on differential pressure over the air filters to determine performance and end of useful filter life in the field has severe shortcomings; it will generally not be able to detect leakages of unfiltered air entering the airstream between the filter elements and the gas turbine and heavy rainfall or operation under high ambient humidity conditions (including fog) may induce filter washings that release filtered particles into the gas turbine, but "improves"(lowers) the differential pressure.

## Bottoming cycles and advanced cycles

Gas-turbine exhaust contains substantial residual thermal energy that can be recovered and converted into additional electricity through bottoming cycles, improving overall plant efficiency and reducing the specific emissions of power generation. The conventional approach is the steam Rankine cycle, implemented as a heat-recovery steam generator (HRSG) feeding a steam turbine, which is mature, bankable, and well suited to a wide range of exhaust conditions.

Contemporary HRSGs producing steam at three pressure levels and incorporating reheat are able to recover as much energy as it is technically feasible, bounded by the minimum stack temperature that would trigger condensation problems in the flue gas stream. From a second law perspective (i.e., exergy destruction), supercritical high-pressure evaporators could reduce this irreversibility, but the cost associated 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<sub>2</sub>) should also be explored for bottoming cycles, in particular 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 up new opportunities for compact, lower capacity combined cycle power plants with enhanced efficiency as compared to simple cycle gas turbines.

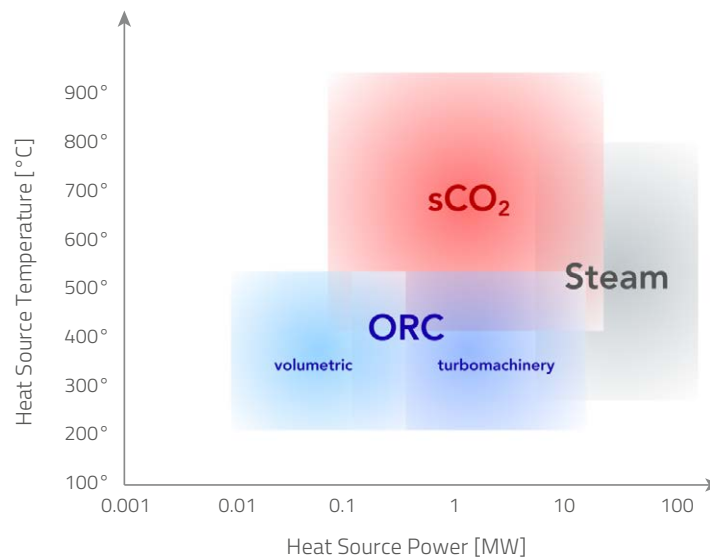


Figure 10: Comparison of thermodynamic power cycles by heat source temperature and power capacity.

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 [\[35\]](#) [\[36\]](#)). 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 are able to 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 [\[37\]](#)). Increasing overall generation efficiency and reducing CO<sub>2</sub> 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.

## Humidification

Humidification includes the injection of steam, or heated water or the use of saturation towers to humidify the working fluid. Humidification leads to higher power output, specific power output, as well as efficiency. However, to be highly effective, this should be combined with a recuperated cycle, leading to the challenges listed above. Most recent efforts were performed by Mitsubishi-Hitachi, leading to the 20 MWe demonstrated [38]. Unfortunately, the project was abandoned several years ago. Remaining obstacles, besides the issues above related to recuperated cycles, are compressor-turbine imbalance, cost of water, possible combustion instabilities, and issues related to corrosion due to the higher water content. Nevertheless, due to its higher specific power and the absence of a bottoming cycle, humidification shows high potential for flexible, efficient power production.

## Supercritical CO<sub>2</sub> 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 sCO<sub>2</sub> 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<sub>2</sub> 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 oxy-firing [39]. 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<sub>2</sub> 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<sub>2</sub> 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 expensive alloys is to be minimised. The corrosion potential of CO<sub>2</sub> 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<sub>x</sub> 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 kW<sub>e</sub> 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) [40]. 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. Low Carbon Solutions (Decarbonisation)

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The need to reduce CO<sub>2</sub> emissions is growing, while pressure from policy and regulation is intensifying. The EU Taxonomy Regulation sets certain emission standards (“performance thresholds”) for CO<sub>2</sub> emissions which need to be met for companies, project promoters and users to 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. This underpins the strategic importance of the gas turbine industry maintaining its commitment to ongoing R&D into the development of low-carbon options and cost-effective carbon capture and storage (CCS) for both new designs and retrofit to existing units. Development activities have increased significantly in recent years and have been supported by corresponding EU funding programs. These funding programs were mainly focused on the use of hydrogen or ammonia as fuels, while other topics, such as renewable liquid fuels and CCS, were less within the scope of the calls.

Reducing CO<sub>2</sub> emissions (tCO<sub>2</sub>/MWh<sub>e</sub>) from gas turbines can be achieved through efficiency improvements, especially during part-load operation, process hybridisation, the use of renewable and low-carbon fuels, or the integration of CO<sub>2</sub> capture technologies. The first two points are addressed under the Chapters on [Integrated Energy Systems](#) and [Energy Efficiency](#), while the latter topics are covered in this section.

### Additional Emission Limits

In addition to CO<sub>2</sub> emissions, NO<sub>x</sub> and CO emissions will continue to be relevant for the operation of gas turbines and power plants in the future. However, there are currently no specific emission limits for NO<sub>x</sub> and CO defined for most renewable liquid and gaseous fuels. For conventional fuels NO<sub>x</sub> emission levels from gas turbine engines of 25 ppm NO<sub>x</sub> (about 50 mg/Nm<sup>3</sup>) (corrected to 15 %vol. O<sub>2</sub>) is still accepted as industry standard (for gaseous fuel firing), though projects increasingly adopt 15 ppm (about 30 mg/Nm<sup>3</sup>) NO<sub>x</sub> as an emission target, and even single digit ppm NO<sub>x</sub> levels are requested in certain regions. For liquid fuel operation, 42 ppm (about 84 mg/Nm<sup>3</sup>) NO<sub>x</sub> 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/Nm<sup>3</sup> for Large Combustion Plants (LCP) with more than 50 MW<sub>th</sub> input). Legislation for CO emissions has been less stringent (e.g., in the IED less than 100 mg/Nm<sup>3</sup> CO is required), but in some cases CO emission limits (at base load) have been set as low as those for NO<sub>x</sub> (about 25 ppm). The IED makes reference to a number of Best Available Techniques Reference (BREF) documents for various industry sectors setting expectations for further reduction in NO<sub>x</sub> and CO for both existing and new plants. Currently, enough operational experience with renewable and low carbon fuels is missing to be able to define a technical reference specifically for these fuels. But this will be needed if the usage of these fuels is increasing.

### 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<sub>x</sub> (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<sub>x</sub> 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.

## Hydrogen

Gaseous and liquid fuels will remain indispensable in the long term as vectors of power generation and reserve energy, even in future decarbonised energy systems. Gas turbines will remain one of the most relevant solutions for converting these fuels into electricity. While today gas turbines mainly run on natural gas or heating oil, they have already proven high fuel flexibility in niche applications. New is the large variety of renewable fuels currently under discussion, which need to be taken into account.

However, GT OEMs are increasing the fuel flexibility of their gas turbines. They currently offer solutions that account for future hydrogen use and can be easily adapted for hydrogen (i.e., “H<sub>2</sub>-ready”), through the design of new combustors capable of running on 100% hydrogen by 2030. In this way, the transition from natural gas to alternative fuels, such as hydrogen, can occur gradually while maintaining complete fuel flexibility. With this approach, gas turbines and combined cycle power plants represent a sustainable investment and a critical instrument for delivering a CO<sub>2</sub>-neutral energy system, where gas turbines become the technology of choice for backing up intermittent RES.

With large installed capacities of wind and solar PV, storing intermittently produced surplus electricity is a significant challenge. Storage via hydrogen production from water electrolysis and subsequent re-electrification (power-to-gas-to-power) is one option under consideration. Moreover, it is foreseeable that not every country can cover its 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<sub>2</sub> content in natural gas, especially in decentralised small gas grids or dedicated hydrogen grids. In addition, some countries have started setting up a hydrogen network, which will be realised in part by completely switching from natural gas to hydrogen.

This approach demands increasing hydrogen combustion capabilities of modern gas turbines up to 100%, which involves addressing issues such as combustion performance and control (e.g., flame stability, flashback, combustor cooling, and thermo-acoustics), NO<sub>x</sub> 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 this end, ETN Global members recently launched an industry-funded initiative titled “Assessment of Pressure Generation by Small Hydrogen Clouds in GT Enclosures”. By studying the Computational Fluid Dynamics (CFD) dispersion and explosion modelling, and carrying out an experimental validation, this collaborative project aims at determining whether ISO 21789-1 needs updating to account for hydrogen use in Gas Turbine (GT) Enclosures [\[41\]](#).

Combustion of fuel gas mixtures with high hydrogen concentrations (>50% vol.) in conventional systems tends to result in higher NO<sub>x</sub> emissions. It requires significant changes to the design of fuel-air mixing and combustor systems to avoid this [\[42\]](#). This issue is crucial 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<sub>x</sub> emissions. In that case, issues related to safe combustion performance (e.g., flame stability, flashback, combustor cooling, or thermo-acoustics) must be addressed while maintaining low NO<sub>x</sub> emissions.

As alternatives to conventional lean premix combustion, which localises heat release in a distinct flame front, other combustion technologies that target spatially distributed heat release offer potential advantages, such as low NO<sub>x</sub> emissions, even when the premixing quality of fuel & air is imperfect or not applied at all. For this reason, other combustion technologies are being considered, such as micro-mix combustion (i.e., the fuel gas is burned in a large number of small, short diffusion or partially premixed flames) or jet-stabilised combustion (i.e., fuel and air are injected with high velocity without swirl into the combustion chamber) creating a more volumetric heat release providing more favourable conditions to avoid thermo-acoustic feedback loops which can cause catastrophic

pressure fluctuations. Other 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.

To guarantee complete operational flexibility, a modern combustion system should ultimately be able to handle the entire range of fuel changes, from 100% natural gas to 100% hydrogen at all operating points (i.e., from extended minimum environmental load to peaking, ramping, and fast start-up). 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. A detailed status description can be found in the [ETN Global Hydrogen Gas Turbine report \[43\]](#). One major obstacle at the moment is a lack of operational experience to build trust in the new technologies and to gain insight into durability and service life. Unlike natural gas, hydrogen remains expensive, and large hydrogen supplies are rare. Thus, in addition to further development at the component level, demonstration projects that provide operational experience in real applications are needed to bridge the gap between development and application.

In addition to the technical challenges, regulatory and economic issues are increasingly becoming the focus of discussions. There is a discrepancy between the current availability of hydrogen and the investment decisions that need to be made now to build new power plants. One solution is to plan and build so-called “H2-ready” power plants, i.e., plants designed for fossil fuels with a view to later conversion to hydrogen. The terms “H2-ready” and “H2-readiness” are now widely used. However, there is no uniform definition of what exactly this means. For this reason, ETN Global members are working to develop a definition of “H2-readiness” that is accepted by both users and manufacturers. This common definition is intended to create clarity in the dialogue with users, manufacturers, and political decision-makers.

Because of the expected high costs of hydrogen, the question arises of how power plants can be operated economically with hydrogen in the future, particularly against the backdrop of the further expansion of renewable energies. ETN Global members are currently developing guidelines for sensible market strategies to ensure stable, long-term, sustainable framework conditions for an economically viable and sustainable energy supply.

## Other renewable fuels

In addition to hydrogen, other liquid or gaseous renewable fuels will play an important role in the future energy system. Which fuels are used for a particular application depends, in some cases, on regional availability. It is therefore to be expected that the requirements for fuel flexibility will continue to increase in the future, particularly in the decentralised sector.

The broad fuel-spectrum capability of gas turbines is closely coupled with operational challenges, including flame stability and emissions compliance. These challenges can be exacerbated if flexible fuel-switch-over procedures are considered.

Typically, achieving ultra-high efficiency requires very narrow fuel specifications, whereas using fuels with fluctuating quality or different fuels generally requires trade-offs, resulting in slightly lower performance and possibly a redesign of key components to achieve a fuel-flexible gas turbine.

The specific research topics that need to be addressed in this respect are given below.

## Biogas and biomass derived gaseous fuels

While most gas turbines will run on natural gas and hydrogen, their fuel flexibility and robustness also allow the use of a wide range 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<sub>2</sub> mixtures from biomass or wood gasification – can be considered CO<sub>2</sub>-neutral (depending on the origin of biomass) and thus can play a role in future power generation scenarios. Co-firing 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. It 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<sub>x</sub> 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 applications of such fuels are currently missing, there is a need to develop appropriate standards and norms.

## 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 alcohols, dimethyl ether (DME), or Fischer-Tropsch products. Other liquid fuels, such as pyrolysis oils, can be produced in pyrolysis processes of various types of biomass, while hydro-processed esters and fatty acids (HEFA) and hydrotreated vegetable oil (HVO) can be produced by chemical refinement of biobased products like vegetable oil. All these liquid fuels have a high energy density per unit mass and per unit volume. Still, 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 are not yet fully characterised.

Biomass-based fuels of this kind will likely have limited supply, therefore narrowing their use to decentralised and peaking applications, which would also limit the transportation needs and allow higher rates of net-CO<sub>2</sub> reduction. Additional properties need to be considered for these fuels, such as S/N/Cl content, acidity, and corrosivity. The composition of the fuel is affected by the type and quality of biomass and can vary over time. Therefore, robust combustion systems are necessary to allow for a broad fuel spectrum.

Liquid-fuel operation of gas turbines is especially important for mobile applications (i.e., gas turbine propulsion systems on land/sea/air) that – due to their typically very dynamic operating modes with steep and frequent load ramps – pose additional challenges. Power-to-Liquid fuels can offer new possibilities as their physical and chemical properties can be tailored for specific applications. The co-optimisation of fuel and combustor design can potentially lead to lower emissions and higher combustion stability. But synthetic liquid fuels – like methanol (CH<sub>3</sub>OH) and Sustainable Aviation Fuels (SAF) – each have their specific advantages and disadvantages with respect to their emission characteristics and thus require customised combustion techniques to meet lowest emissions (e.g., NO<sub>x</sub>, CO, soot, etc.) without jeopardising performance (i.e., efficiency, power rating, safe operation, or load variation).

While the first tests of industrial gas turbines using biomass-based fuels, such as HVO, show promising results, even for retrofitting existing plants. Nevertheless, the large variety of different liquid fuels pose a significant challenge to reach very low NO<sub>x</sub> emission limits (less than 42 ppm or 90 mg/Nm<sup>3</sup>) for liquid fuel operation of gas turbines 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 include liquid fuel atomisation/evaporation and pre-mixing with air for homogeneous gas-phase combustion as a prerequisite for low NO<sub>x</sub> formation. Combustion performance and flame stability should not be compromised, either with or without the addition of water/steam, and a combined minimum level of emissions (e.g., NO<sub>x</sub>, CO, or particulates) must be targeted. "Trade-offs" between gas and particle emissions should be avoided due to the complexity of regulatory frameworks and potential adverse health effects. Because particulate emissions are typically very low, reliably measuring them at these levels remains challenging. Feasible monitoring strategies will be essential to support the development of future evaluation standards and maintain public acceptance.

## Non-carbon fuel (e.g. ammonia)

The combustion characteristics of ammonia ( $\text{NH}_3$ ) differ significantly from those of conventional hydrocarbon and hydrogen fuels, including reduced flame speed (fuel conversion rate). 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. There are two ways to do so: 1) direct usage of ammonia as fuel, or 2) reconvert ammonia to nitrogen/hydrogen mixtures via thermal/catalytic cracking. One of the main drawbacks of using ammonia for combustion is the potential for high  $\text{NO}_x$  emissions due to the fuel-bound nitrogen in  $\text{NH}_3$ . This issue is severe if pure ammonia is burnt, and it persists in the cracked gases if any residual ammonia is present. Special low- $\text{NO}_x$  combustion processes need to be explored to minimise the conversion of fuel-bound nitrogen. One of such concepts is staged combustion for direct combustion of  $\text{NH}_3$  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 to the architecture of the gas turbine combustion system and thus require substantial R&D before they can be considered for commercial gas turbine products. New manufacturing techniques (e.g., laser metal forming or additive manufacturing) have recently opened routes for burner and combustor designs, enabling cost-competitive manufacturing of these new combustion technologies. Another option for direct use as fuel is to dope the fuel with a more reactive molecule, such as hydrogen, which can conveniently be obtained from (partial) cracking of ammonia.

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 was previously investigated in the EU-funded project FLEXnCONFU [\[44\]](#), which aimed at developing 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 was developed and coupled with a micro gas turbine modified to burn ammonia. Such a solution was successfully demonstrated at the laboratories of the University of Genoa in Savona, Italy.

## CCUS

Carbon Capture Use or Storage (CCUS) is possible decarbonization strategy for Gas Turbine based energy conversion systems (Power, Heat, compressors etc.). The application of CO<sub>2</sub> capture approaches may be post-combustion, with the capture unit located on the gas turbine exhaust or pre-combustion, where the CO<sub>2</sub> is largely removed after catalytic reformation of natural gas leaving a hydrogen-rich fuel gas. Options to enhancement to post combustion capture include the combination with exhaust gas recirculation (EGR); or by using oxy-combustion where the CO<sub>2</sub> is more readily separated from steam in the exhaust gas stream.

The integration of CO<sub>2</sub> capture into renewable fuel-based power generation (e.g., biofuel) could result in negative CO<sub>2</sub> emissions and might be an interesting option when considering emission trading as part of the business plan.

### Integration of post-combustion CO<sub>2</sub> capture technologies with gas turbines

The decarbonisation of gas turbines using CO<sub>2</sub> 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<sub>2</sub> capture process. Selecting the most suitable capture technologies and optimising their integration with gas turbine systems while maintaining plant dispatchability and 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<sub>2</sub> 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<sub>2</sub> separation membranes) to increase exhaust gas CO<sub>2</sub> concentration. This approach can reduce the size, thermal energy usage, and costs of the capture plant and it can potentially reduce NO<sub>x</sub> emissions and solvent degradation (i.e., in the case of CO<sub>2</sub> absorption process). As EGR can lead to more complex gas turbine configurations and significant changes to combustion and hot gas path environments, the research needs to consider benefits versus additional challenges such as the effects operability, materials, and component lives.

Some 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 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.

## 10. Conclusion

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Gas turbines and wider turbomachinery will remain essential for power-system adequacy and flexibility in a renewables-dominated grid, because they can provide dispatchable capacity and grid services where scalable long-duration alternatives are still limited, and because market signals (surging orders and long backlogs) confirm sustained demand.

End-user priorities have shifted from incremental performance gains to operational resilience, with spare parts availability, ageing fleets under more cyclic duty, and regulatory uncertainty emerging as the most immediate constraints on reliable operations, investment decisions, and effective decarbonisation pathways.

The central R&D challenge is no longer just “highest efficiency at baseload,” but delivering cost-effective, reliable and profitable turbomachinery that can operate flexibly, integrate into diverse energy systems, and progressively decarbonise through fuel flexibility and carbon capture - without compromising safety, maintainability, or emissions compliance across a wider operating envelope.

To achieve this, R&D must address technology, operations and enabling frameworks together (standards, certification, data governance, and market design), because technical readiness alone will not unlock deployment if supply chains, qualification routes, and policy definitions remain fragmented.

Further work should focus on converting today’s constraints into bankable, scalable solutions.

- strengthen operational resilience by reducing exposure to spare-part shortages through wider adoption of condition-based maintenance, improved online/offline inspection capability, and more transparent, data-driven lifetime assessment and repair qualification routes (including additive manufacturing where feasible).
- make flexibility a design requirement: advanced start/stop robustness, cycling-resistant components and coatings, and validated lifing models for transient operation, supported by digital twins, diagnostics/prognostics and advanced control.
- de-risk decarbonisation pathways that preserve dispatchability by progressing fuel flexibility (hydrogen and other sustainable fuels) with clear safety and durability evidence, and by maturing CCS integration and dispatchability - including heat integration, footprint constraints for retrofits, and operability during dynamic duty.
- Align enabling conditions with technology: harmonise readiness definitions and standards, improve data interoperability and enable contemplation of hybrid configurations (e.g., combined cycle plus storage) by explicitly accommodating them in grid codes and market frameworks.

Delivering this roadmap will require coordinated action across operators, OEMs, suppliers, researchers and policymakers so that turbomachinery remains a dependable, affordable and progressively carbon-neutral pillar of the energy system through 2030 and beyond.

# 11. ETN Global Support Schemes: Projects and Working Groups

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ETN Global facilitates and assists in the development process of any project initiatives that are brought to the ETN Global platform by our members. The ETN Global 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 Global'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:

# ACT2Flex

## ACT2Flex: Flexible, Sustainable, and Digitally-Enabled Solutions for Industrial Process Transformation (2026-2030)

Energy-intensive industries lie at the core of the European economy, ensuring the production of valuable products. However, their environmental footprint remains high, as they account for more than 25% of final energy consumption and are responsible for a significant share of greenhouse gas emissions. The increasing penetration of Renewable Energy Sources creates unique opportunities for decarbonisation, but also introduces strong variability in energy supply, to which existing industrial plants are currently unable to adequately respond.

Through its novel Systemic Flexibility Solution, it combines targeted process redesign, hybrid energy integration, storage, and advanced digital tools such as Digital Twins and Artificial Intelligence, allowing process industries to adapt their operation in real time according to the availability and price of renewable energy. In this way, flexibility and adaptability are enhanced, and resilience against fluctuations in energy markets is increased. The project also introduces certification instruments like Digital Flexibility Passports and Flexibility Balanced Scorecards, while embedding skills, governance, and human-centric practices aligned with Industry 5.0.

Validation of ACT2Flex solutions is carried out through two large-scale flagship pilot applications under real industrial conditions. The first pilot is implemented in the titanium dioxide chemical production industry of KRONOS EUROPE in Belgium. It focuses on converting energy-intensive continuous processes into batch operation, supported by using electric boilers and innovative energy storage systems. The second pilot (metallurgy) is implemented in Greece, at the facilities of ElvalHalcor, where a hybrid heating system is applied, combining microwave assisted plasma burners, induction heating, and electromagnetic stirring, enabling dynamic management depending on raw material quality.

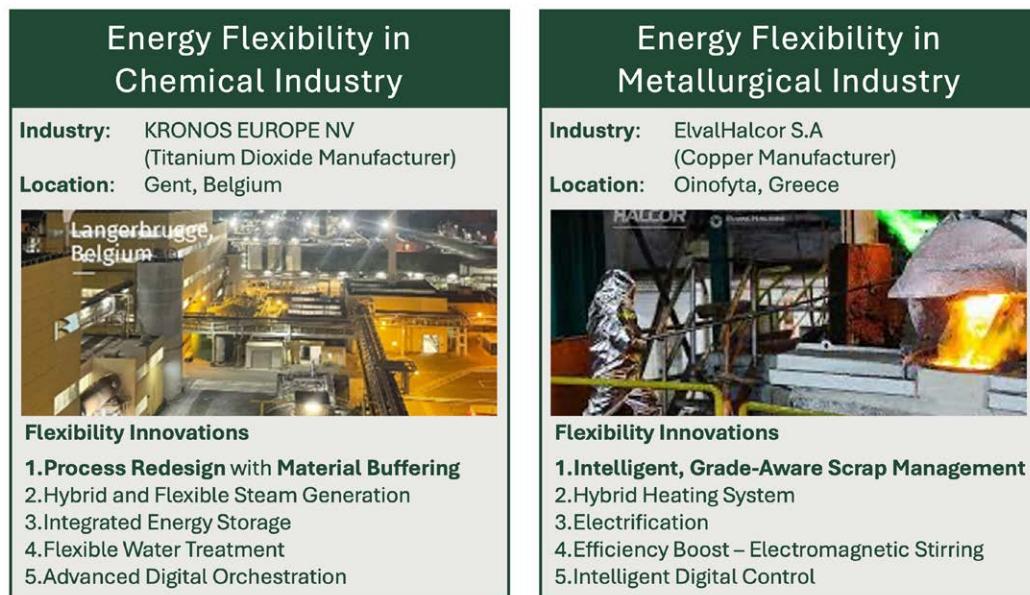


Figure 11: Demo sites in ACT2Flex project.

The project involves 16 partners from 6 countries.

With a total duration of 48 months, ACT2Flex aspires to become a “blueprint” for the future of the European process industry. It delivers a step change in industrial flexibility by transforming energy-intensive industries into renewable-responsive, digitally orchestrated production systems, strengthening the energy autonomy and competitiveness of the European industry.

This project receives funding from the European Union’s Horizon Innovation Action programme under grant agreement N° 101294465. ETN Global, as partner, is the Work Package Leader for dissemination, communication and strategic links.



## ASTERIX-CAESar: Air-Based Solar Thermal Electricity for Efficient Renewable Energy Integration & Compressed Air Energy Storage (2023-2027)

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<sub>th</sub> demonstration-scale prototype in a relevant environment.

The ASTERIX-CAESar project reaches 2026, entering the second half of its timeline with the objective of developing a novel, high-efficiency solar thermal power plant concept featuring an integrated electricity storage solution. The project combines air-based central receiver Concentrated Solar Power (CSP) with Compressed Air Energy Storage (CAES) to maximize conversion efficiency and optimize power grid energy management, enabling new operational strategies and business models.

The hybrid concept ushers in a futuristic era of adaptive renewable power plants, producing not only electricity but also thermal energy for reverse osmosis desalination and the decarbonization of medium-temperature (<200 °C) industrial processes. The thermodynamic evaluation of the concept highlights key results, including a Round-Trip Efficiency (RTE) of 43.1% - comparable to conventional diabatic CAES - while achieving zero emissions. Furthermore, the electricity production-to-consumption ratio reaches 107.8%, thanks to the combined contributions of grid-stored electricity and dispatchable solar power.

Within the project, the concept is being analysed through techno-economic optimization for specific use cases. Preliminary results already demonstrate the high potential of the concept under scenarios with strong solar irradiation and high electricity price spreads (e.g., Chile and Spain), particularly for large-scale plants based on underground caverns. The project plans to use an open-source tool, allowing the developed models to be run by anyone without license costs.

In addition, the concept will be validated with a demonstration-scale prototype in a relevant environment (TRL 6-7), which is currently being implemented.

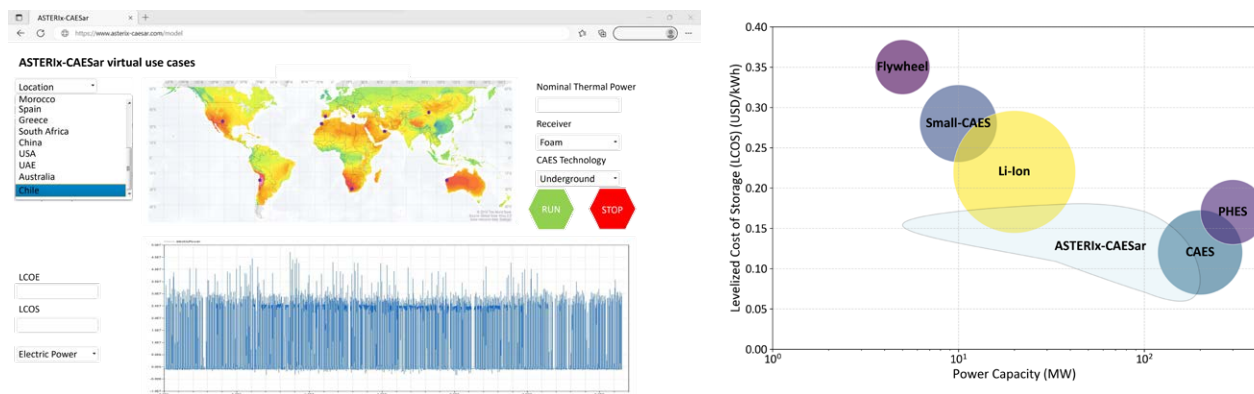


Figure 12: (a) Design of virtual use cases graphical user interface (not yet launched).

(b) Preliminary techno-economic results of ASTERIX-CAESar in comparison with other storage technologies.

ETN Global, as partner, is the Work Package Leader for 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° 101122231. | UK participant in Horizon Europe Project ASTERIX-CAESAR is supported by UKRI grant number 10097908 (Bluebox Energy). | This work has received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI).

[www.asterix-caesar.eu](http://www.asterix-caesar.eu)



## FLEX4H<sub>2</sub>: Flexibility for hydrogen (2023-2026)

FLEX4H<sub>2</sub> (Flexibility for Hydrogen) aims to develop a highly fuelflexible, lowemission combustion system for Hclass gas turbines, capable of operating with 0–100% hydrogen at low emissions and without diluents. A central focus is enabling retrofitready solutions to accelerate decarbonization of existing assets.

The project builds on Ansaldo Energia’s Constant Pressure Sequential Combustion system, featuring a twostage architecture combining flamepropagation and autoignition stabilization. This design supports stable operation across all hydrogen blends, reduces emissions, and enables independent stage control—crucial for handling hydrogen’s higher reactivity and ensuring stability at high firing temperatures. Coordinated by Ansaldo Energia, the project involves nine partners across six countries.

Through an integrated experimental and modelling approach, FLEX4H<sub>2</sub> has delivered a set of important findings and technological advancements:

- Fullscale highpressure testing has demonstrated stable combustor operation with natural gas, hydrogen, and all intermediate blends, reaching TRL6 readiness.
- Scaled, optically accessible highpressure tests have characterized hydrogen autoignition flame behaviour, providing essential data for validating simulations and supporting combustor design optimization.
- Advanced numerical modelling has been used to investigate flame stabilization, ignition delays, and mixing characteristics under hydrogenrich conditions. These models integrate directly with experimental results to refine sequential combustion performance.
- Thermoacoustic behaviour has been mapped through simulations and test campaigns, refining the understanding of the impact of hydrogen on auto-ignition driven combustion and developing solutions to ensure stable operation even at 100% hydrogen.

FLEX4H<sub>2</sub> is establishing a robust pathway toward 100% hydrogencapable gas turbines; its results offer a practical, retrofitable route to decarbonizing dispatchable power generation in alignment with European climate goals.

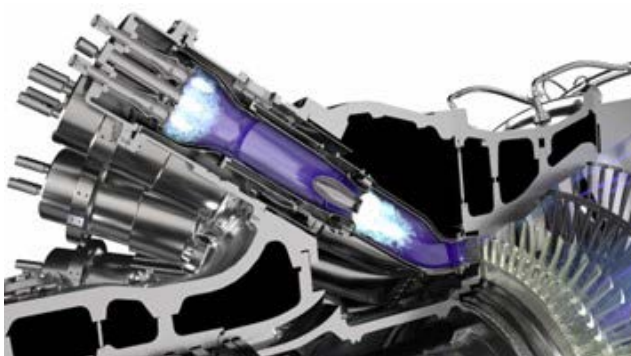


Figure 13: Constant Pressure Sequential Combustion (CPSC) system, consisting of two combustion stages in series, enabling outstanding fuel flexibility.

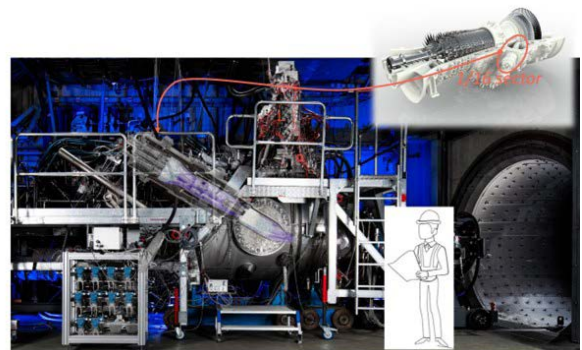


Figure 14: High Pressure rig for full-scale validation of the GT36 (H-class) can combustors.

ETN Global, as partner, is the Work Package Leader for dissemination, communication and exploitation.



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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](http://www.flex4h2.eu)

## HyPowerGT: Demonstrating A Hydrogen-Powered Gas-Turbine Engine Fuelled With Up To 100% H<sub>2</sub> (2024-2027)

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<sub>2</sub>) capable of handling mixtures of natural gas and hydrogen with concentrations up to 100% H<sub>2</sub>. The combustion technology has been successfully validated at TRL5 (early 2021) retrofitted on a 13 MWe industrial gas turbine (Baker Hughes NovaLT 12). The new technology will be further developed and demonstrated at TRL7 on a 16.9 MWe gas-turbine engine (Baker Hughes NovaLT 16) towards the end of the project.

Direct numerical simulations of H<sub>2</sub>/air flames at industry relevant conditions performed and an improved turbulent burning rate scaling law for premixed hydrogen/air flames at high-pressure conditions is proposed. The flame response of the burner to acoustics was measured experimentally at ZHAW and damper development is ongoing. An open-source methodology for FEM geometry inclusion into network models was defined and validated.

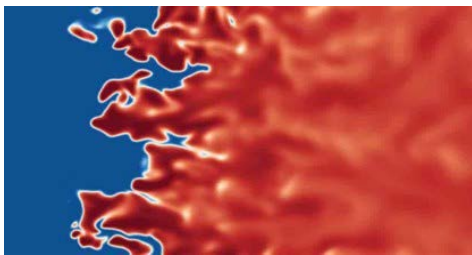


Figure 15: Direct Numerical Simulation (DNS) of a hydrogen/air flame (Andrea Gruber, SINTEF).

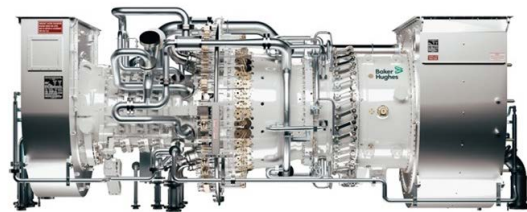


Figure 16: Baker Hughes NovaLT™ 16. NovaLT™ is a trademark of Baker Hughes and its affiliates. All right reserved.

The first highlight of the HyPowerGT project is the successful conclusion of the TRL6 test campaign at Sesta Labs in the fall of 2025. The DLE H<sub>2</sub> technology was demonstrated in a full-scale combustor test. Two prototype burners were tested, and the results are well aligned with the project KPIs in terms of dynamic stability (combustion instabilities), static stability (flashback) and NOX emissions for any mixture of natural gas and H<sub>2</sub>.

The HSE (Health, safety, and environment) guidelines, dealing with risks introduced by retrofitting the DLE hydrogen technology on existing GT assets and including safety plans for all experimental activity and the FMECA analysis, are finalised. Numerical simulations of ignition events in the exhaust system of the NovaLT™ 16 under emergency scenarios where unburnt hydrogen is released were performed.

The work on the roadmap for hydrogen gas turbines throughout the European energy transition (2030-2050) was initiated and the structure is defined. The replication scenarios pertaining the upstream and industrial systems for the technoeconomic analysis have been defined.

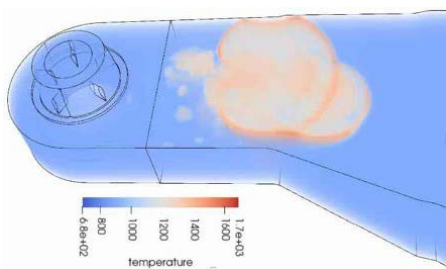


Figure 17: Forced ignition in the exhaust system for an emergency hydrogen release (Thierry Poinot, CERFACS).

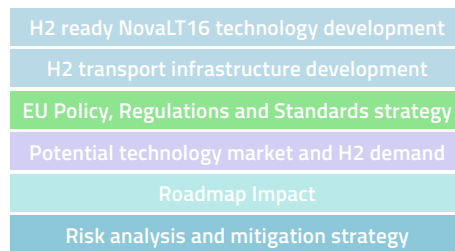


Figure 18: Structure of the hydrogen gas turbine roadmap (Matteo Robino, Snam).

ETN Global, as partner, is Work Package Leader for dissemination, communication and exploitation activities.



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This project is supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research N° 101136656.

[www.hypowergt.eu](http://www.hypowergt.eu)



## InsigH<sub>2</sub>t (Scientific insights into H<sub>2</sub> combustion under elevated pressure conditions) (2024-2027)


InsigH<sub>2</sub>t aims to advance the current scientific understanding regarding the effect of pressure on the turbulent burning rate, thermoacoustic response, and emissions performance of premixed hydrogen flames under relevant gas-turbines operating conditions. By leveraging science-based predictive capabilities, InsigH<sub>2</sub>t aims to accelerate the deployment of clean, reliable, and efficient hydrogen-fired gas turbines.

ETN Global, as partner, is the Work Package Leader for dissemination, communication and exploitation activities.



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This project is supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research N° 101192349.

[www.insigh2t.eu](http://www.insigh2t.eu)



## ISOP (Innovation in Supercritical CO<sub>2</sub> Power generation systems) (2023-2026)

The ISOP project aims to explore sCO<sub>2</sub>-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<sub>2</sub> 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 Global is associated partner of this project and will host one doctoral candidate. Another doctoral candidate will be seconded to ETN Global.

*Relevant results being generated:*

Unlike many R&D projects defined by a single technical target, ISOP is designed around a different kind of impact: training people who can turn sCO<sub>2</sub> research into industrial reality. The added value of this MSCA Doctoral Network lies in the fact that doctoral research is co-created and co-supervised by academia and industry, keeping research questions grounded in practical needs.

ISOP has recruited a total of 17 doctoral candidates, whose research is tightly connected to industry through secondments and extended stays, enabling early-career researchers to gain first-hand experience. In this respect, a key strength of ISOP is the breadth of its industrial ecosystem, spanning multiple segments of the sCO<sub>2</sub> value chain, from OEM, turbomachinery expertise and heat exchanger technologies to engineering & deployment actors, with ETN Global amplifying dissemination and community outreach.

To date, ISOP's training activities has included four workshops and two winter schools, designed to build complementary skills that sCO<sub>2</sub> technology needs to mature, such as (i) system-level understanding and optimisation methodologies (including the emerging role of AI tools), (ii) component design and high-fidelity CFD approaches for turbomachinery, (iii) materials, coatings and manufacturing routes relevant to high-performance energy systems, and (iv) innovation and commercialisation topics such as IPR management and regulatory/economic context.

While training is ISOP's primary output, the project is already producing tangible results. In this regard, the project has been featured in a dedicated ETN Global webinar episode, and research contributions have been presented at leading conferences, including ASME Turbo Expo and major European sCO<sub>2</sub> and ORC seminars. First journal publications are also emerging, such as state-of-the-art reviews on windage effects in turbines and on control strategies for sCO<sub>2</sub> power systems, early examples of how ISOP is simultaneously building knowledge and building talent for the sector.

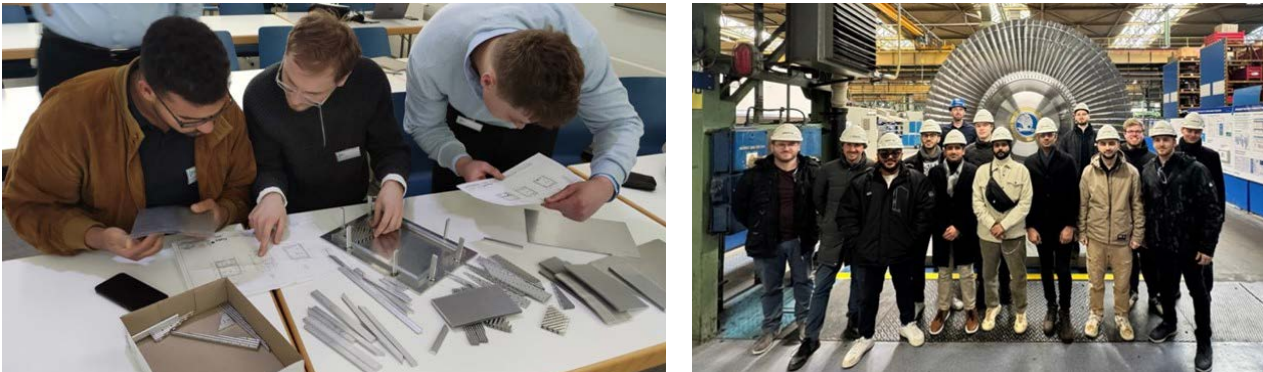


Figure 19: (a) Practical activity on manufacturing of Heat Exchangers. (b) Technical Visit at Doosan Skoda Power.

ETN Global is one of the beneficiaries, hosting one of the Doctoral Candidates and offering a secondment opportunity to another one.

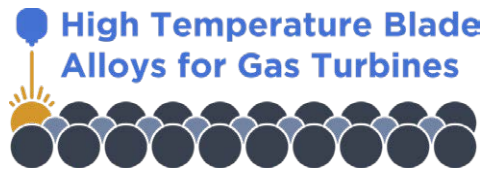


Funded by  
the European Union

This project 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](http://www.isopco2.eu)

## ETN Global High Temperature Blade Alloys for Gas Turbines (2025-2027)



ETN Global's Additive Manufacturing Working Group launched a new joint industry-led project, aiming at identifying and validating 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.

## ETN Global Assessment of Pressure Generation by Small Hydrogen Clouds in Gas Turbine Enclosure (2025-2026)



### Assessment of Pressure Generation by Small Hydrogen Clouds in Gas Turbine Enclosure

This project – launched by ETN Global's Hydrogen and other Alternative Fuels Working Group – addresses a gap in current gas turbine enclosure standards when operating with hydrogen or hydrogen blends. This initiative – carried out by DNV– gives the opportunity to shape future safety guidelines, de-risk hydrogen adoption, and reduce long-term compliance costs. The project includes 1) CFD modelling of hydrogen and blend dispersion and explosion behaviour; and 2) experimental validation through large-scale testing.

## Working Groups

ETN Global 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 Global website](#).

### Additive Manufacturing

The objective of ETN Global's Additive Manufacturing (AM) 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.

### Air Filtration

The objective of ETN Global's Air Filtration Working Group (WG) is to provide users with a single point of reference for state-of-the-art filtration technology and to address air filtration issues through projects of common interest. ETN Global represents the WG members in the ISO Technical Committee 142 – "Cleaning equipment for air and other gases" – and is actively involved in drafting ISO 29461 – "Air intake filter systems for rotary machinery – Test methods". This WG is focusing on harmonising testing procedures for static and pulse filter systems, and on establishing a best-practice reference for air intake maintenance and inspection.

### Carbon Capture Utilisation and Storage

ETN Global's Carbon Capture Utilisation and Storage Working Group aims to assess the status of CCS solutions and document their advantages and challenges. It provides guidelines on R&D priorities to accelerate CCS deployment, and it explores opportunities for cross-industry collaboration to drive innovation and cost-effective CCS implementation.

### Digital Solutions and Diagnostics

The objective ETN Global's Digital Solutions and Diagnostics Working Group is to promote the development and deployment of digital solutions for gas turbine and rotating machinery operations. The WG works towards creating a network, improving awareness, promoting the implementation and expansion of existing Digital Solutions and technologies, and producing documents relevant to the gas turbines and rotating machinery industry. Under the current scope, digital solutions include instrumentation for operation and maintenance, machine learning/AI, development of digital twins, data management, cybersecurity, and sensors for instrumentation for GT development.

## Energy Integration System

ETN Global's Energy Integration System Working Group aims to explore market opportunities and solutions, and review the technology readiness level of individual components, the GT system and its integration into decentralised and multi-vector sustainable energy systems, as well as its interfaces and interaction with other system components. Moreover the group aims to evaluate the technical and economic feasibility of integrating GTs with advanced control and energy management systems and address challenges of intermittent renewable energy with gas turbine solutions.

## Gas Turbines Life Assessment & Extension

ETN Global's Gas Turbines Life Assessment & Extension Working Group aims to address the challenges associated with extending the life of gas turbine components, with a focus on critical parts such as hot gas path components, rotors, and compressors.

## Hydrogen and other Alternative Fuels

The aim of ETN Global's 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 readiness, urgency and positioning, and gas turbine safety.

## Supercritical CO<sub>2</sub>

ETN Global's Supercritical CO<sub>2</sub> Working Group aims to develop, enable and optimise the use of supercritical CO<sub>2</sub> 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<sub>2</sub> as working fluid for power generation, and creating a database of European open test beds.

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**ETN**  
Global

**Energy & Turbomachinery Network  
(abbrev. ETN Global) 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

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