The role of turbomachinery in the energy transition

A position paper of the AG Turbo

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Content

Foreword

The structures of energy supply are subject to major changes worldwide, which are necessary to realise the energy transition and the international climate protection goals. Turbomachinery is an essential component of today's energy supply. More than two thirds of the world's electricity is generated by steam turbines, usually in coal-fired, nuclear or combined cycle power plants, and increasingly by gas turbines. In addition to electricity generation, turbomachinery is a central component in various industrial processes, and modern, efficient air travel would not be possible without turbomachinery.

While the introduction of the first turbomachinery dates back well over 100 years, the corresponding technology has developed continuously over the decades. Today, turbomachinery construction is a high-tech sector. State-of-the-art turbomachinery requires high-performance materials due to the extreme thermomechanical stresses and extremely precise manufacturing methods for production. The complex planning and design requires state-of-the-art computer technologies. A major driver for further developments in recent years, in addition to continuous increases in efficiency, has been new requirements in terms of operational flexibility resulting from the increasing integration of fluctuating, renewable energy sources into the energy market.

In order to achieve the climate targets, the expansion of renewable energy sources must be continued. In addition, the demand for electricity will continue to rise due to the decarbonisation of other sectors such as transport (electromobility), housing (heat pumps) and industry. In order to ensure a reliable and affordable energy supply in the long term, the fluctuating renewable energies must be supplemented by flexible storage technologies and the corresponding infrastructure, which can compensate for both short-term and seasonal fluctuations in electricity production from water, wind or sun. For many of these storage technologies, but also for the infrastructure, e.g. to distribute hydrogen or other green energy sources to appropriate consumers, new types of turbomachinery optimised for these applications will be needed.

Within the framework of the AG Turbo, numerous research projects for the further development of turbomachinery technology have been carried out for over 35 years. In the process, research results from different areas such as gas turbine or compressor development could also be integrated into the development of state-of-the-art steam turbines. This synergetic use of public funding was and is only possible because AG Turbo offers a unique network that enables industrial companies and research institutions to work together in a closely coordinated manner on pre-competitive topics. AG Turbo would like to continue using this network in the future to master the new challenges and thus support a successful energy transition in Germany. Turbo technology is indispensable for a stable power supply and thus for maintaining and expanding our prosperity.

1 Climate protection policy development

Human-driven climate change. There is now no doubt about the immense impact that human economic activity has on our environment and the global climate. The term anthropocene was created as a name for a new geochronological epoch, namely the age in which humans have become one of the most important factors influencing biological, geological and atmospheric processes on Earth. Crutzen and Stoermer [1] create it in 2000 to describe an epoch that is predominantly characterised by the influence of human activity on the natural world and the Earth system. For example, the industrial application of the Haber-Bosch process to produce synthetic fertiliser from atmospheric nitrogen has been shown to have significantly altered the global N_2 cycle since the last relevant geological events 2.5 billion years ago.

In its sixth Assessment Report [2] the Intergovernmental Panel on Climate Change (IPCC), established in 1988, confirmed the observed anthropogenic increase in global temperature, with the mean value over the years 2010-2019 being 1.09°C higher than the reference mean value of the years 1850-1900. A comparison with the mean value measured up to 2022 shows that this has increased by a further 0.16°C and consequently the total increase has reached 1.25°C. At the same time, a constant increase in atmospheric CO_2 concentration to the current value of 415 ppm has been observed over the last six decades. [3], see Figure 1-11. The cause of this is known to be industrial processes on which the human economy is currently based. The combustion of coal for the purpose of energy and heat generation is a major factor.

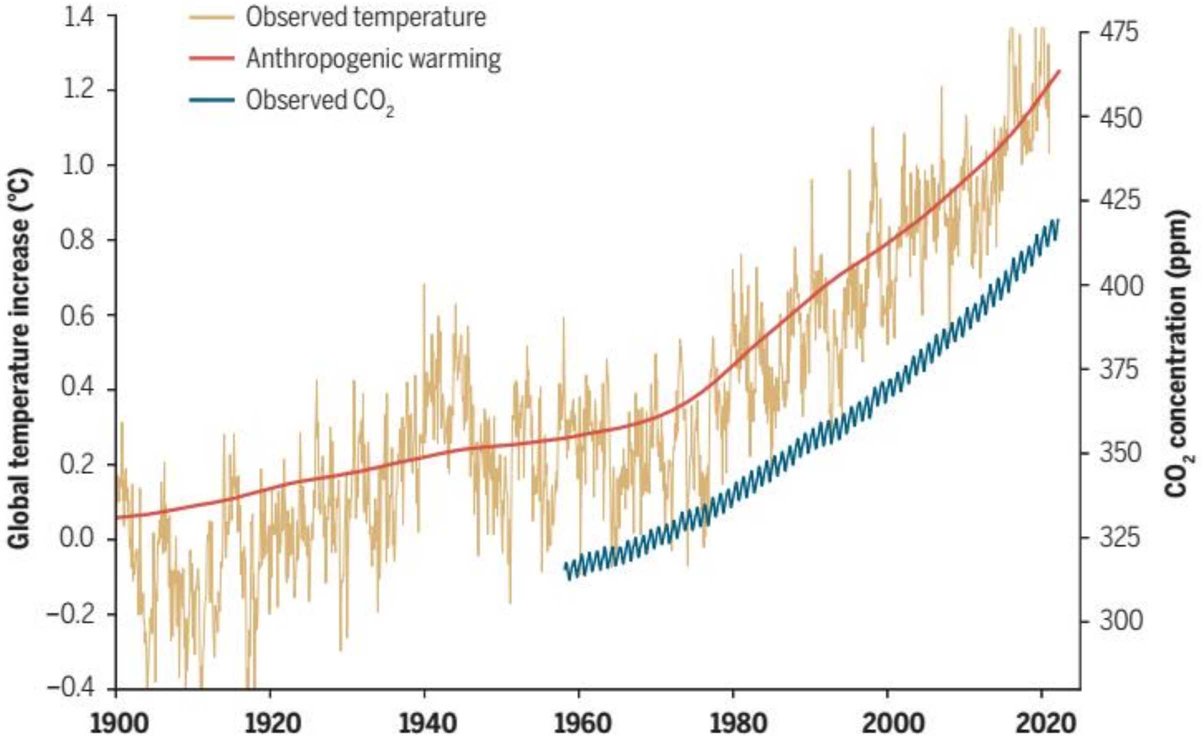


Figure 1- : Correlation between observed increase in global temperature and increase in atmospheric CO_2 concentration [3]

Causes and consequences of CO_2 emissions. In total, about 555,000 megatonnes of coal have been extracted and burned by human activity since 1750, resulting in the highest atmospheric CO_2 concentrations by far in the last 800,000 years. [4]. Already in the early 1990s, the urgent need for global corrective action to avert the catastrophic consequences of anthropogenic climate change became clear. With this motivation, the United Nations formed a framework for the necessary political as well as legal actions. This was done by drafting a global agreement on climate protection, which led to the ratification of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and the establishment of the COP (Conference of the Parties of the United Nations Framework Convention on Climate Change).

Europe-political directive. At COP 21 in Paris in December 2015, the so-called "Paris Agreement" was adopted, which entered into force in November 2016. It set out the future commitment of European partner states to limit the global temperature increase to well below 2.0°C above pre-industrial levels, with a clear ambition of a limit of 1.5°C. [5].

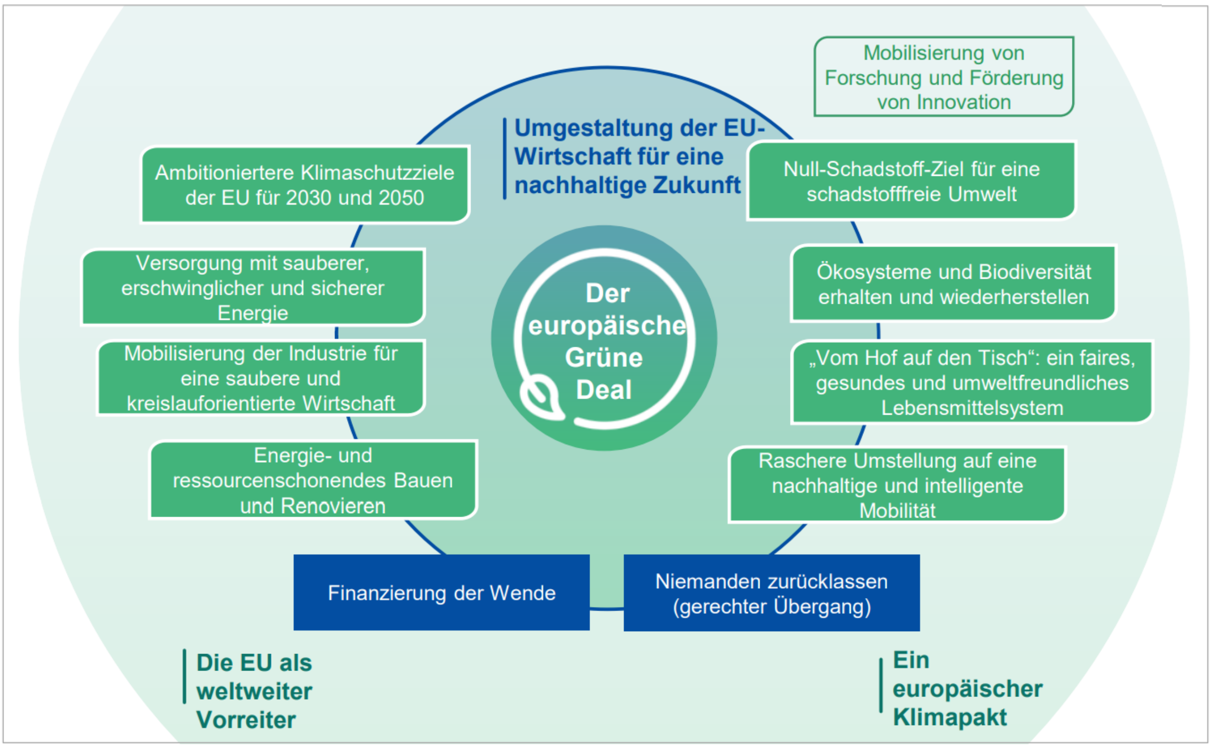


Figure 1- : Schematic representation of the principles of the European Green Deal [6]

In this context, the European Union is pursuing the ambitious goal of making Europe the first climate-neutral continent by 2050, while maintaining its economic prosperity, global technological edge and continued commitment to a just and open society. On these principles, see Figure 1-12, the so-called "European Green Deal" is based on these principles. [6]which was adopted in December 2019 and for the first time translated the non-binding agreements of the Paris Agreement into legally binding requirements, thereby positioning itself as a global guideline for climate protection.

The measures of the European Green Deal can be summarised in eight main points:

1. The goals already set by the initiative "A Clean Planet for All" [7] have already been achieved. [7] are to be tightened so that CO_2 emissions are reduced by at least 50% and ideally by 55% compared to 1990.
2. The availability of clean, affordable and reliable energy should be ensured for all.
3. The sustainability of industrial processes is to be increased through the massive introduction and promotion of a circular economy and new technologies, such as artificial intelligence.
4. The efficiency of energy use in buildings (which alone are responsible for 40% of energy consumption) is to be increased through renovation programmes.
5. Transport and transport-related emissions to be reduced by 90% by 2050.
6. The food supply chain is to be redesigned according to the principles of sustainability and climate protection (farm-to-fork policy).
7. Biodiversity and ecosystems, especially forests and oceans, are to be protected.
8. The contamination of the environment, food and drinking water or groundwater with harmful substances is to be holistically prevented from 2021 onwards through a "zero pollution policy".

In addition to the above-mentioned points, the Green Deal programme takes accompanying measures to steer capital markets and research towards renewal and ultimately sustainability. For this purpose, targeted budgets have been increased and investments amounting to about 30% of the EU Invest Fund have been foreseen, but also increased flexibility in the use of VAT revenues by the member states for the purpose of implementing the eight main directives. The eight main guidelines of the European Green Deal programme follow the overarching vision of future environmental integrity (*do no harm policy*), according to which all measures should contribute to structural change for the realisation of a sustainable and fairer, yet prosperous and technologically advanced society.

The European Green Deal programme was successively adjusted in 2020, 2021 and again in 2022, in particular to counteract the economic and social global crises caused by the COVID 19 pandemic. [8], [9] and [10]. As part of the associated Fitfor55 programme. [8] further overarching measures were adopted to consolidate and strengthen the European Green Deal programme, which are primarily intended to ensure a fair and affordable energy transition and, in particular, to combat the poverty of the socially weaker strata of society associated with the energy transition (e.g.: Social Climate Fund, Modernisation and Innovation Fund), cf. Figure 1-13. The measures of the Alternative Fuels Infrastructure Regulation aim at promoting climate-neutral means of transport by expanding and upgrading the fuel and energy supply infrastructure for road and air transport (electric mobility, Sustainable Aviation Fuel (SAF), green hydrogen). The FitFor55 package now sets a 40% integration of energy from renewable sources in the European energy mix as a new target for our future energy supply (a further 8% above the previous target of 32%).

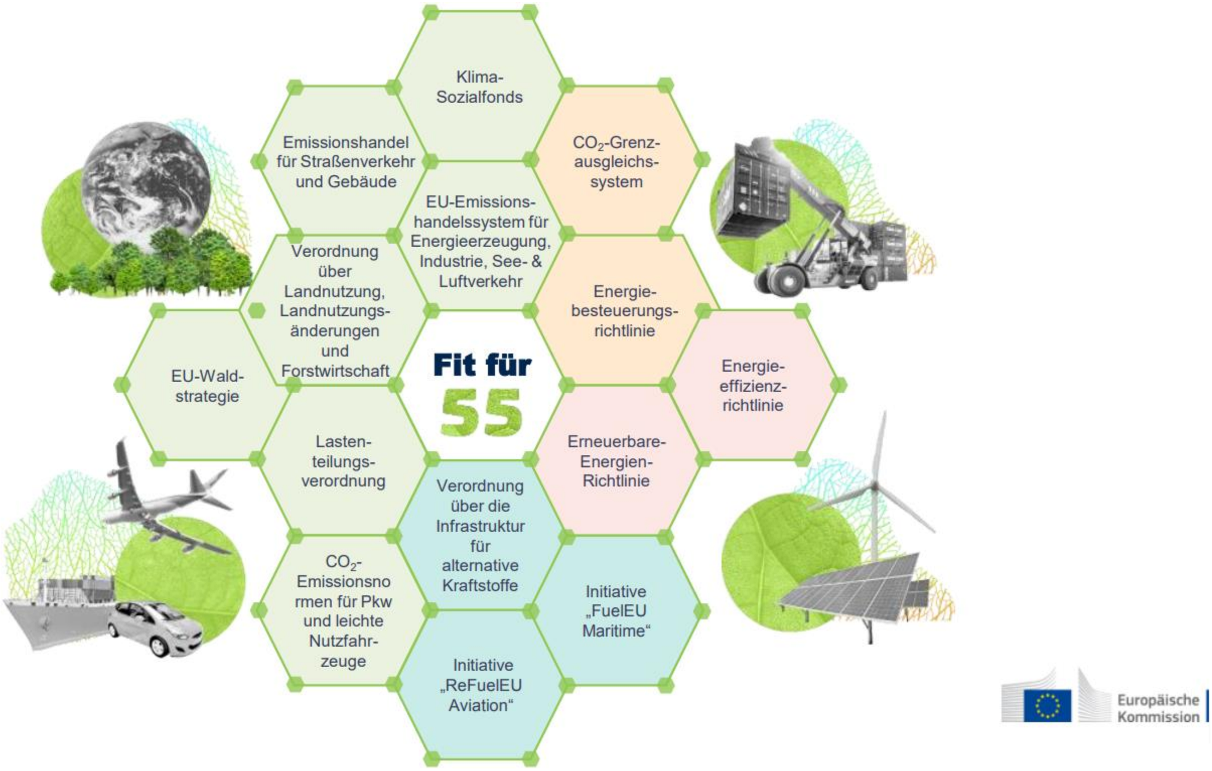


Figure 1- : Schematic representation of the FitFor55 measures. [8]

German research objectives. As a pioneer of the energy transition and in line with international and European energy policy programmes, Germany has already set out its research objectives with the adoption of the 7th Energy Research Programme. [11] in September 2018, Germany has already set the framework for a fundamental transformation of the energy industry, with the fundamental principles of security of supply, reliable affordability and climate compatibility forming the so-called energy policy target triangle of the programme.

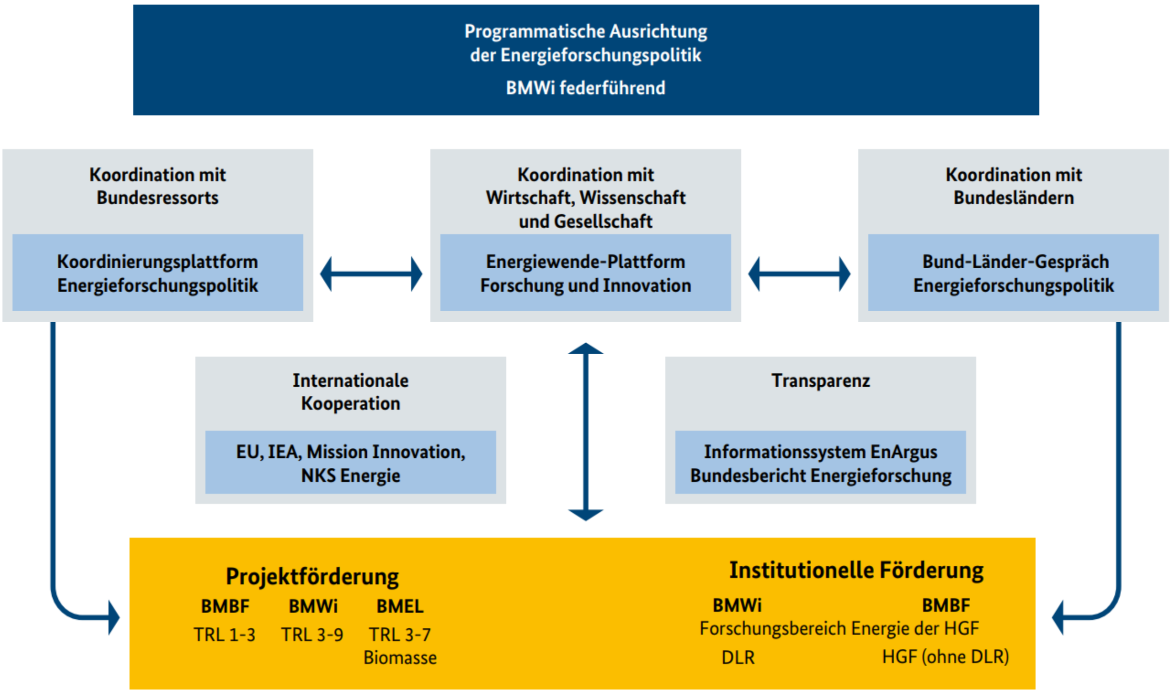


Figure 1- : Structures of energy research in the 7th Energy Research Programme [11]

Through the combination of institutional and project-related funding, which is supported by the three federal ministries BMWi/K, BMBF and BMEL on an interdepartmental basis, the funding programme takes into account the full spectrum of technology maturity levels (TRL) and the technological diversity that is necessary for the success of the energy transition (see Figure 1-14).

The funding policy objectives of the 7th Energy Research Programme are expressed in six essential points:

1. Acceleration of the market-oriented expansion of renewable energies, especially through integrated consideration of all sectors and their intelligent networking.
2. Increase energy efficiency at all system levels, halving primary energy consumption by 2050 compared to 2008.
3. Intelligent use of the energy infrastructure through innovative networking of the existing infrastructure with the facilities to be built for the new technologies.
4. Ensuring the security of energy supply by expanding storage technologies and increasing the technical robustness and resilience of the supply system.
5. Strengthening environmental and climate protection by taking into account the consumption of materials and resources associated with innovative energy technologies.
6. Consideration of societal impacts through targeted, regional economic and political support for structural change, see Structural Strengthening Act. [12]

The research and development priorities envisaged in the 7th Energy Research Programme are directed at those central technological and scientific challenges that society must face in order to ensure a secure, reliable, affordable and sustainable energy supply for Germany as an industrial location.

With this position paper, the AG Turbo would also like to contribute to the currently pending design of the new 8th Energy Research Programme, which is currently being planned.

2 The role of turbomachinery in the successful implementation of the Guidelines

2.1 Electrification of all sectors: Increased demand for electricity

The objective of increasing electrification of the sectors of our national economy and the solution approach of coupling our energy sectors are closely linked. Sector coupling is replacing the traditionally largely independent structures of electricity, heating and cooling supply. This process is driven by the urgent need for decarbonisation, which is to be achieved by switching the energy supply as completely as possible to electricity, in Germany especially from renewable energies.

The path to an "all-electric society" can only be achieved through a comprehensive transition process that will eventually enable completely CO_2 -neutral electricity generation. First of all, this requires the development of renewable energy sources such as photovoltaics and wind energy, whose reliable utilisation is only possible operationally through additional energy storage infrastructures due to their high volatility. The essential problem of sector coupling is to extend the contribution successes achieved so far by renewable energies to decarbonisation to the energy- and emission-intensive sectors of transport, heat supply, agriculture and heavy industry, with the aim of making net zero CO_2 emissions in Germany achievable in the near future and in this way completely replacing oil, coal and gas.

The pursuit of climate neutrality through the implementation of sector coupling results in a considerable additional demand for electricity. On the one hand, electricity is becoming an energy source in an increasing number of economic sectors, and on the other hand, electrical energy must be used to generate CO_2 -neutral fuels for systems that cannot be supplied from the electricity grid. This applies to the mobility sector, especially air and sea transport, but also to industrial processes. In the area of electricity-based industrial processes, the supply of electricity from renewable energy sources is progressing successfully, while the transport and heat generation sectors continue to use a high proportion of oil and natural gas. In 2012, 23% of Germany's electricity consumption was covered by renewable energies, and 43% by 2020. Power-to-X technologies for CO_2 -neutral generation of hydrogen or heat are either still at the experimental stage or not yet applicable on a large scale.

Compared to liquid or gaseous fuels, electricity has the disadvantage that it must be stored electrochemically in batteries or in converted form, for example as hydrogen gas in power-to-X processes, in pumped storage or in torque storage. The associated conversion steps are always accompanied by unavoidable energy losses. In particular, batteries are costly and ecologically controversial in terms of construction and raw material supply. Power-to-X solutions are exposed to competition on the market with the cheaply available fossil energy sources. Flexible electricity storage solutions are a prerequisite and at the same time a result of sector coupling and electrification.

Electrification can be extended to new sectors based on existing technologies. Polymer production in the plastics and chemicals industry, for example, can be carried out using fossil-free hydrogen (from electricity and water) and carbon dioxide, and in this way bind more CO_2 during the process than is released. In the agricultural sector, the electrification of artificial fertiliser production opens up noteworthy potential.

Studies show ([16] and [17]) that with increasing electrification of the heat and mobility sectors, electricity consumption could increase by up to 400-800 TWh by 2050. This forecast is based on so-called scenarios, for example scenario "C" in [18]which consistently point to a significant gap between projected installed capacity and demand or consumption. The reliable coverage of electricity supply for "deep decarbonisation" [19] requires, on the one hand, adequate storage capacity and, on the other hand, a flexibilisation of the electrical load in the case of direct and indirect electrification. For this purpose, thermal storage systems can be used in particular, in which flexible turbomachinery plays a central role (see chapter 2.4 and Figure 2-26).

2.2 Green energy sources

Chemical energy carriers enable the storage and transport of energy up to the large-scale and allow the temporal and spatial decoupling of the energy supply from the current energy demand at times when the electricity generated by renewable energy sources cannot be used directly. In 2010, the term "power-to-X" was introduced for this purpose [19]which summarises the corresponding conversion of surplus electricity into CO_2 -neutral feedstocks such as hydrogen from electrolysis and the possible subsequent further processing into synthetic energy carriers such as ammonia, methanol or Sustainable Aviation Fuels (SAF). Accordingly, hydrogen as a versatile energy carrier is a central element for the successful decarbonisation of future society. For this reason, the National Hydrogen Strategy was launched in Germany in 2020. [20] was presented. This forms the starting point and outlines the path of transition from fossil-based energy conversion and mobility and the associated infrastructure to CO_2 -neutral energy use based on a hydrogen economy in almost all sectors.

The basis is the CO_2 -free production of hydrogen. Without restrictions, this only applies to so-called green hydrogen, which is produced from CO_2 -free electricity generation - especially from photovoltaic, wind and hydropower plants - by electrolysis of water. This hydrogen can either be used directly or forms the basis for other synthetic energy carriers (power-to-X) and is already the basic material for many subsequent processes in the chemical industry, such as ammonia.

Figure 2-21 gives an overview of the over- and underproduction of electricity in Germany within an entire year and puts this in relation to various energy storage options. It is shown, for example, that if around 44 million electric cars with a capacity of 20 kWh were connected to the grid in Germany, only 0.44 TWh of storage capacity could be covered and, with a load of 60 GW, could only stabilise the grid for a few hours. In contrast, chemical storage such as gas reserves with comparable discharge capacity could cover this demand for about 3 months. Green hydrogen and its power-to-X downstream products are thus the link between volatile electricity production from renewable sources such as photovoltaics and wind power and consumers in all sectors, e.g. for electricity and heat generation or mobility. Both the generation and use of power-to-X energy yields will use turbomachinery, e.g. for compression, transport or expansion, and are thus indispensable for a decarbonised energy system of the future.

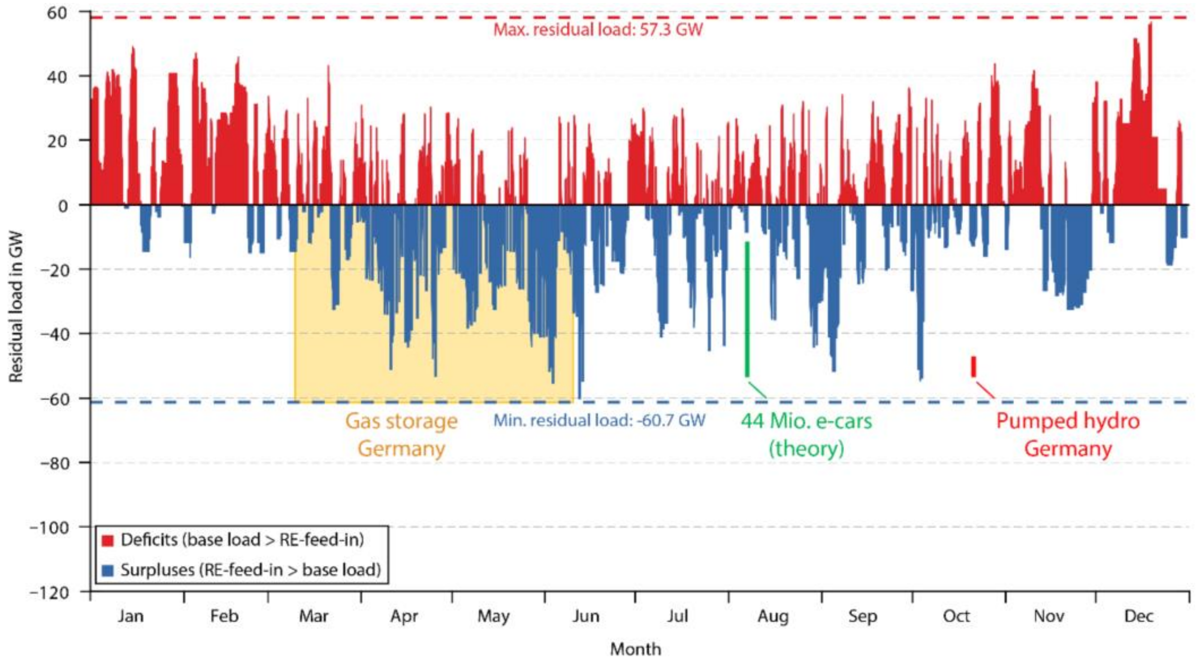


Figure 2- :Deficits and surpluses for 100% climate-neutral electricity generation in Germany (from [19] and sources cited there).

2.3 Regenerating electricity: from natural gas to green hydrogen

Green hydrogen will play a central role in power-to-X applications for storing energy. A first step is the displacement of natural gas by sustainable hydrogen to enable climate-neutral power plant operation, as no CO_2 is produced during hydrogen combustion. The gas turbine offers ideal conditions due to its high fuel flexibility, which also comes into play in a broad power range from less than one to several hundred megawatts. As the availability of green hydrogen increases, natural gas power plants can be converted to run on increasing amounts of hydrogen or even pure hydrogen. As shown in Figure 2-22 the relationship between CO_2 reduction and hydrogen volume content is nonlinear. For 50 V olumen percent hydrogen in natural gas, the CO_2 reduction is only approx. 23%. For 50% CO reduction$_2$, about 80% hydrogen by volume must be added. Accordingly, very high hydrogen contents are required for a sustainable CO_2 reduction.

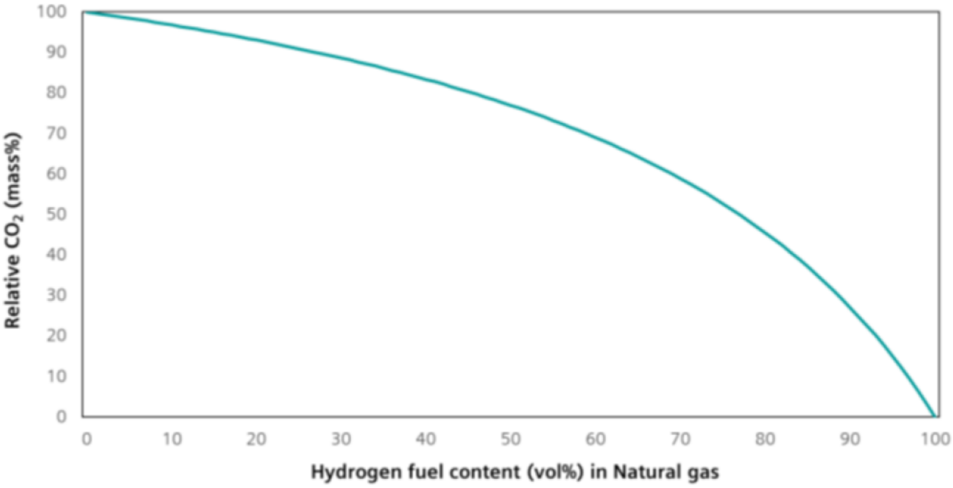


Figure 2- : Relative CO_2 reduction with increasing H_2 content in natural gas [21]

However, the safe control of hydrogen combustion is subject to several challenges. Since this fuel differs significantly from the natural gas used so far due to its high reactivity and a greater flame speed, problematic phenomena such as flashback, thermo-acoustic combustion instabilities and increased nitrogen oxide emissions can occur. Hydrogen has combustion characteristics that pose additional challenges for gas turbine combustion systems, which to date have been designed primarily for natural gas. The flame temperatures for hydrogen under adiabatic and stoichiometric conditions are almost 300ºC higher than for methane. The laminar flame speed of hydrogen is more than three times that of methane and the autoignition delay time of hydrogen is more than three times lower than that of methane, as shown in Figure 2-23 for flame temperatures of 1600°C and gas turbine conditions. With these properties, hydrogen is a highly reactive fuel and controlling the combustion to maintain the integrity of the combustion system and achieve the desired emission level is a formidable challenge. Here, due to the close cooperation between research institutions and industry, the AG Turbo offers outstanding framework conditions to efficiently and purposefully develop the necessary methods and technologies for safe and low-emission hydrogen combustion.

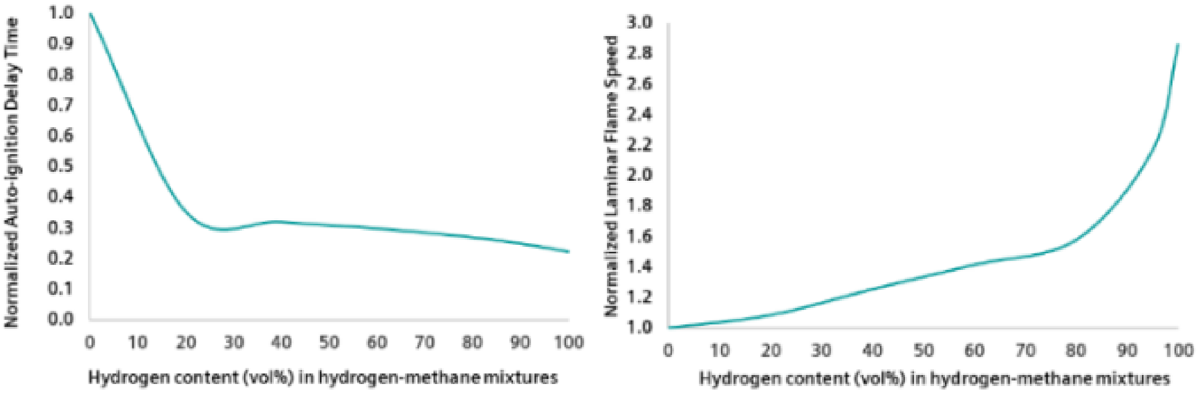


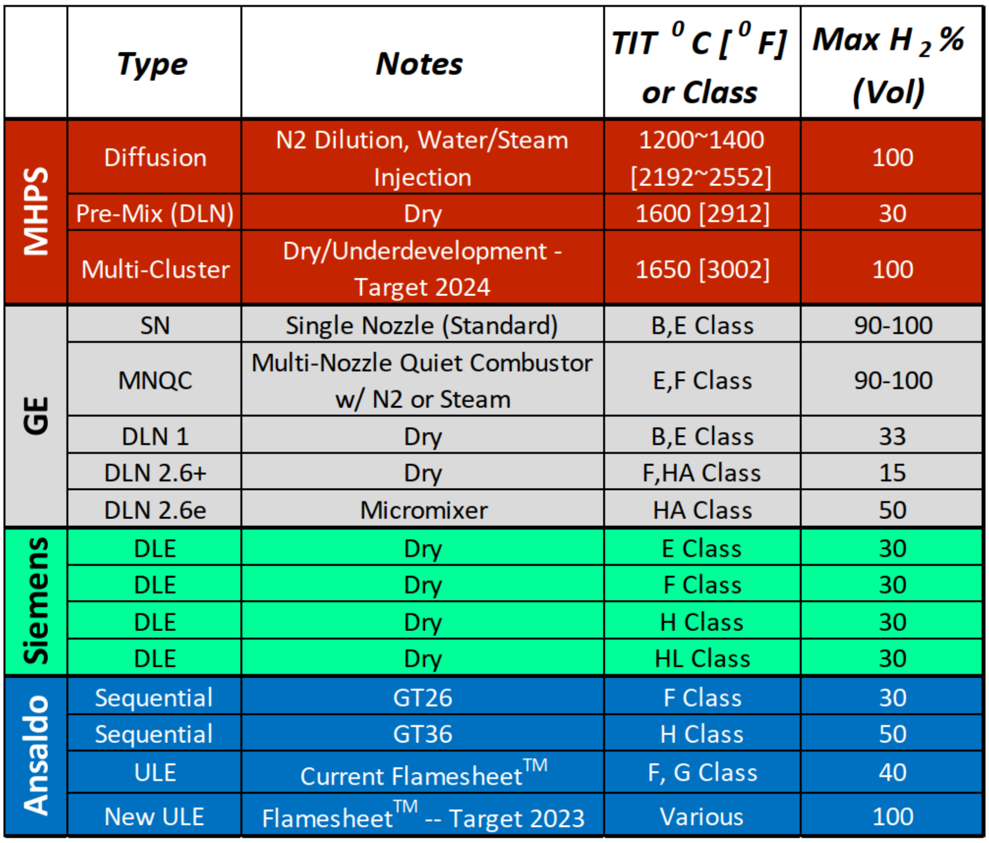
Figure 2- : Influence of hydrogen content on ignition delay time and laminar flame velocities for methane/hydrogen mixtures. [21]

For the power sector in particular, the use of hydrogen in gas turbines has further advantages. For operators, the use of hydrogen fuels reduces CO_2 emissions from existing generation facilities. It allows these facilities to participate in low-carbon energy markets and avoids lost assets due to emission reduction regulations. For the electricity grid, gas turbines running on hydrogen fuel or hydrogen fuel mixtures are dispatchable and provide flexible generation capacity. Compared to electrochemical reconversion processes (e.g. fuel cells), they also make a fundamental contribution to frequency stability due to their rotating mass. The retrofitting and continued use of the installed gas turbine fleet avoids major capital costs and CO_2 emissions associated with the construction of new plants to support the intermittent renewable energy market. Gas turbines in cogeneration plants in various applications can provide steam and heat that would otherwise have to be replaced by electric heating or biomass plants.

There are currently four established suppliers on the global market for large and highly efficient H-class gas turbines: GE Energy (USA), Siemens Energy (Germany / USA), Mitsubishi Power (Japan) and Ansaldo Energia (Italy / Switzerland). In the medium term, Doosan Heavy Industries (South Korea) and Shanghai Electric (China) could join them. In addition, there is a broad portfolio of heavy-duty gas turbines above 100 MW (E and F class) as well as a large number of other suppliers of smaller gas turbines below 100 MW. These include Solar Turbines (USA) and MAN Energy Solutions (Germany). The primary energy sources used are mainly natural gas, but also various synthesis gases with - as a rule - lower calorific values. Oil plays a rather subordinate role, especially as a secondary fuel. In the case of gas combustion, the combustion systems used are based almost exclusively on dry premix combustion, which - even at very high turbine inlet temperatures (up to approx. 1600°C) - enables very low nitrogen oxide emissions.

As shown in Figure 2-24 shown, today's combustion systems of modern gas turbines are approved by the manufacturers for hydrogen volume fractions between 30 and 50%. However, all leading gas turbine manufacturers are working intensively to develop combustion systems in the next few years that will enable operation up to 100% hydrogen in premix mode. Flamesheet technology with trapped-vortex flame stabilisation (PSM/Ansaldo), micromixer technology (GE and Kawasaki) and multi-cluster technology (MHPS) appear particularly promising.

Today's swirl-stabilised combustion systems with lean premixed combustion are - depending on the design - only suitable for up to about 30 to a maximum of 75% H_2 admixture. For higher hydrogen volume fractions and 100% hydrogen combustion, novel burner systems for safe operation at low nitrogen oxide emissions (NO_X) are necessary, which still require considerable research and development.



	Type	**Notes**	**TIT $^0C\ [^0F]$ or Class**	**Max H_2% (Vol)**
MHPS	Diffusion	N2 Dilution, Water/Steam Injection	1200~1400 [2192~2552]	100
	Pre-Mix (DLN)	Dry	1600 [2912]	30
	Multi-Cluster	Dry/Underdevelopment - Target 2024	1650 [3002]	100
GE	SN	Single Nozzle (Standard)	B,E Class	90-100
	MNQC	Multi-Nozzle Quiet Combustor w/ N2 or Steam	E,F Class	90-100
	DLN 1	Dry	B,E Class	33
	DLN 2.6+	Dry	F,HA Class	15
	DLN 2.6e	Micromixer	HA Class	50
Siemens	DLE	Dry	E Class	30
	DLE	Dry	F Class	30
	DLE	Dry	H Class	30
	DLE	Dry	HL Class	30
Ansaldo	Sequential	GT26	F Class	30
	Sequential	GT36	H Class	50
	ULE	Current Flamesheet^{TM}	F, G Class	40
	New ULE	Flamesheet^{TM} -- Target 2023	Various	100

Figure 2- : Permissible hydrogen contents of various burner concepts [22]

With regard to the comparability of nitrogen oxides (NOx) for fuels with different hydrogen contents, it must be taken into account that the usually used conversion to dry flue gas with a residual oxygen content of 15% is at the expense of fuels with a higher hydrogen content and the simultaneous decrease or elimination of carbon dioxide in the flue gas significantly shifts the relative ratio of NOx. An example of this influence is shown by means of a kinetic calculation in Figure 2-25 for typical boundary conditions in stationary gas turbines. [23].

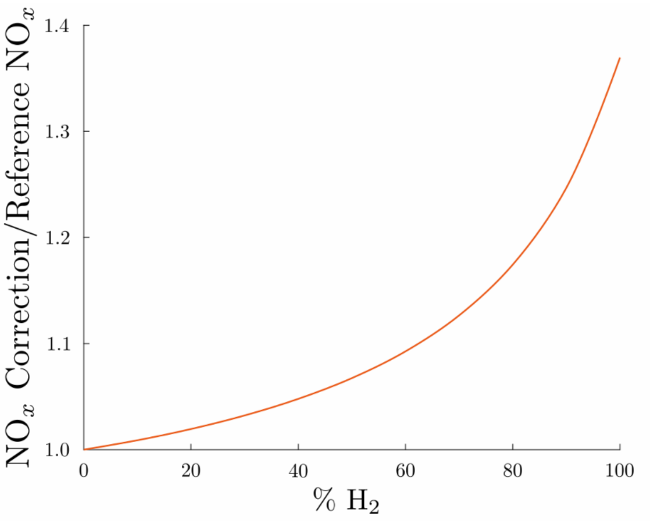


Figure 2- : Calculated (dry) NO_X emissions at constant temperature for different H /CH_{24} ratios related to pure methane [23].

In addition to the influence on combustion behaviour, the special material properties of hydrogen generate potential challenges in connection with storage and auxiliary systems for gas turbines. As the smallest molecule, hydrogen diffuses much more easily through the walls of pipelines and storage tanks. However, unless long uncontrolled lifetimes occur, this effect is negligible in systems that are usually metallic. With certain metallic materials, however, accelerated material embrittlement can occur. This aspect is particularly relevant if storage and pipeline systems were originally developed for use with methane or comparable fuels. Here, if not taken into account, considerable impairment of the material integrity can occur and undetected leakages can occur. In conjunction with the highly sensitive ignition properties, these result in major safety risks.

All of the above challenges require extensive research and development activities to bring gas turbines to a technically mature and reliable level comparable to today's natural gas-fired plants. This also includes the support of specifically developed measurement techniques and simulation processes.

2.4 Turbo machines for storage applications and innovative cycles

The determination of the storage demand in Germany and worldwide shows that despite the excellent progress of research and development in recent decades, a sufficient ratio of storage duration and capacity (months/TWh) can only be achieved by thermomechanical or chemical storage methods, as expressed by the CAES, LAES and Power-to-X approaches ([13] and [14]).

Energy can be stored electrically, electrochemically, mechanically, thermally or chemically. The energy storage types differ not only in terms of their capacity, but also in the possible storage time of the energy to be stored. For the storage of very large amounts of energy over long periods of time, only chemical energy storage systems come into consideration. It is precisely these storage technologies for the long-term range and large storage quantities that require the use of compressors and turbines. Numerous innovative energy storage systems are based on turbomachinery. Figure 2-26 shows an overview of different energy storage technologies.

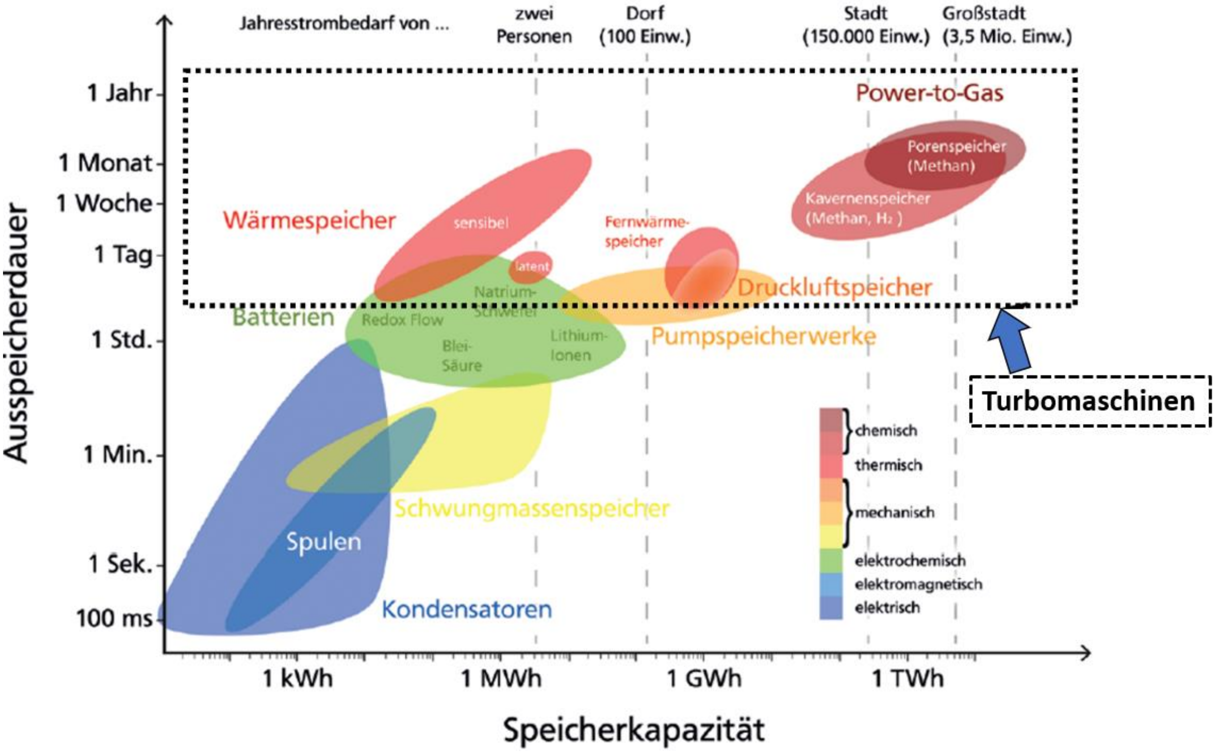


Figure 2- : Storage capacity and retrieval duration of different storage technologies according to [13]

In the field of thermal energy storage, compressors are used as heat pumps. The requirement profiles for these heat pump compressors differ from those for compressors that have so far been used in the power plant sector, the chemical and process industry, and in air traffic. This gives rise to research tasks, e.g. to make the heat pump compressors suitable for high discharge temperatures or to adapt them for innovative heat transfer fluids. In future energy storage systems, other circulating fluids will also be used than the usual ones such as water and air. These could be ammonia, CO_2 (trans- or supercritical) or ORC fluids (Organic Rankine Cycle). For storage unloading, on the other hand, turbines are required that are based on steam turbine and/or gas turbine technology. Here, too, technological adaptations are necessary, some of which must be supported by fundamental research.

Compared to the classical application profile of turbomachinery for energy supply (thermal power plants), the high volatility of renewable energy sources (wind and solar) requires a predominantly transient operation of future turbomachinery, the implementation of which can synergetically benefit from technological knowledge of aeronautics research. In addition, however, the use of currently rather unusual working media, which are present in new cycle processes, means entering new territory due to their thermodynamic and chemical properties, such as in supercritical CO_2 processes for storage technologies and in the distribution and reconversion of hydrogen. Consolidated design methodologies are losing their validity due to changing similarities and ratios [27]. A large number of new questions arise, which may concern, for example, the aerodynamic analysis and optimisation of compressors and expanders for thin or extremely dense gases at very high mass flows or the effect of corrosive fluids on the machine surfaces. This is creating a strong process of change in turbomachinery research, which is of central importance for the success of the energy transition due to the key role of the turbomachine.

Grid stability in the current power grid is largely ensured by the large steam turbine sets with their enormous flywheel masses. In addition, the turbomachine-based thermal power plants are usually capable of black-starting, so that they can independently resume power production operations and restore the power supply in the event of power grid failures. In the future, fossil power plants will no longer be available to fulfil these tasks. Energy storage systems that provide energy by means of turbomachines offer the possibility of providing the aforementioned functions of **grid stability** and **black start capability.**

The largest new energy storage facilities of the future will be in the field of hydrogen and synthetically produced methane storage. The operation of these storage facilities will probably be significantly different from the operation of conventional natural gas storage facilities known today. In the field of hydrogen compression, there is already a wealth of experience in the chemical industry. This can be used to adapt the existing technologies to future tasks. One aspect of this is, for example, scaling up to significantly larger plants, as considerably larger quantities of hydrogen will have to be transported in the future. In some cases, this will also lead to changes in technology, such as the use of low-maintenance, highly available turbo compressors instead of piston compressors.

When energy is provided by renewable energy sources such as solar thermal and geothermal energy, the conversion of stored thermal energy into electrical power is also carried out by turbomachines, in this case usually steam turbines. In combination with large thermal storage units, solar thermal energy, unlike photovoltaics and wind energy, offers the possibilities of a continuous energy supply - electricity and heat - as is the case with geothermal energy. Such turbines have to be adapted to volatile operating conditions, innovative heat transfer fluids and high process parameters (e.g. temperature and pressure) in such a way that maximum reliability can be realised with economically favourable efficiency. Future turbomachinery solutions, as outlined here, are to be promoted and further developed within the framework of a highly interdisciplinary research environment, supported by close cooperation between research institutions and industrial partners.

2.5 Synergies with aircraft engines

Steam and gas turbines for power and heat generation have many technological similarities with aero-gas turbines for powering aircraft. The highly loaded aerodynamics in the compressor and turbine ensure high pressures and high power densities with component efficiencies of over 90% in both applications. In the gas turbine, comparable maximum temperatures of over 1,800 K are achieved for both applications. This inevitably leads to very similar to identical problems in the design of these machines, since the technical complexity of the components in stationary and flying applications is also comparable (see Figure 2-27). Likewise, the requirements for safe and reliable operation are very high in both cases and demand a correspondingly well-founded technological basis for the design. Modern design tools for turbomachinery can therefore generally be used to design components for both stationary plants and aircraft engines.

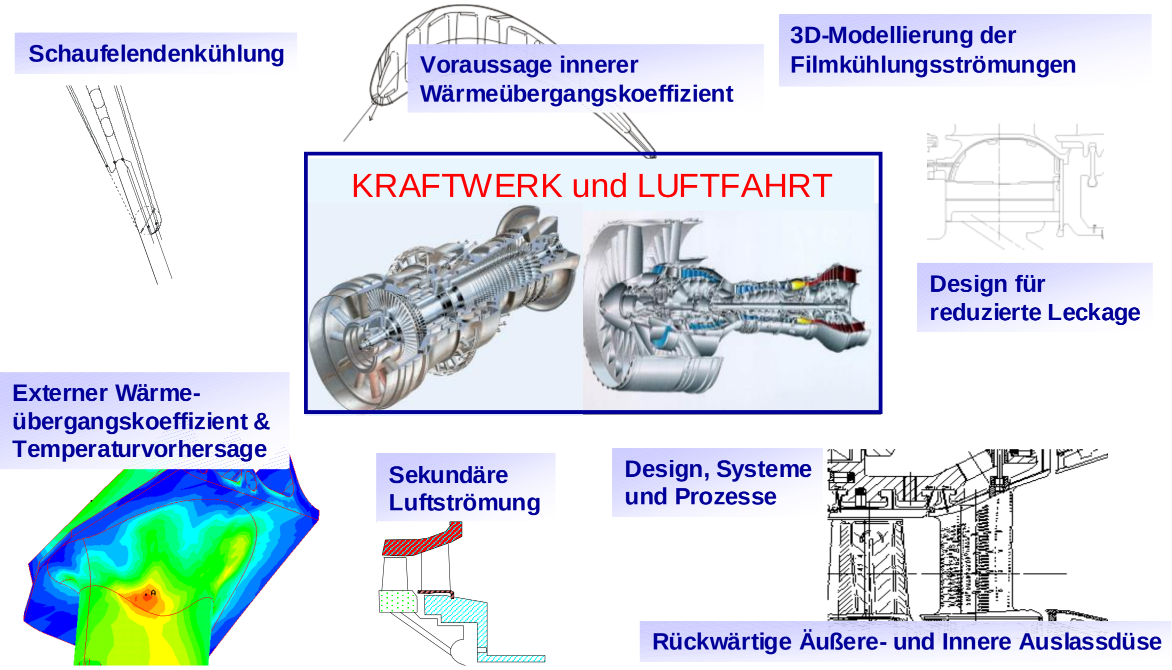


Figure 2- : Examples of comparable technological issues for stationary and flying gas turbines

In aviation, the weight of the aircraft is a crucial variable that must be minimised. Therefore, not only the power-to-weight ratio of the gas turbine is of great importance in these applications, but also the high efficiency of the energy conversion is an important goal. Lower fuel consumption allows for higher range and/or more passengers or cargo. Technical innovations of the gas turbine that support these goals are therefore often first realised in aircraft engines. In many cases, aviation is therefore also an important driver for the future technological development of the gas turbine and its components.

Hydrogen is expected to play an important role in the future decarbonisation of global air transport. Airbus, among others, is currently developing concepts for aircraft [24] that will use hydrogen instead of paraffin or Sustainable Aviation Fuel (SAF) for propulsion. These should enable CO_2 -free flying from 2035 onwards with use up to medium-haul applications - comparable to the A320 or Boeing 737. The use of hydrogen as an energy carrier will result in further synergies in the technological development of gas turbines for stationary and flying applications.

The planning and joint implementation of pre-competitive research projects within the framework of the AG Turbo bundles the expertise from science and industry in Germany in the field of turbomachinery research. This avoids duplication of work and optimises the use of existing research funds and resources. The long-term coordination of joint research activities allows, for example, the sustainable construction of complex test benches at research institutions that can be used by different partners across several research projects. The results obtained with significant financial participation by the German engine industry thus fully benefit the improvement of turbomachinery in modern power plants.

3 Supporting technologies

In addition to the classic component technologies, the more recent developments in digitalisation (Industry 4.0, Digital Twin) and modern manufacturing processes such as additive manufacturing and laser sintering in particular also have high synergy potential.

Industry 4.0 and digitalisation. Industry 4.0 refers to the digitalisation of production with continuous networking of systems and self-controlling elements in production facilities. The aim is to make production processes more flexible, robust and efficient. In the context of Industry 4.0, the digital twin also has a special significance for industry. In industry, digital twins exist for products, production facilities, processes and services, for example. Product models of the digital twin (target twin) can also exist before the real product (actual twin), for example as design models of future products. The different data models can be used to collect, analyse and evaluate data from the use of the real twins. Appropriate modelling approaches open up possibilities to simulate the behaviour, functionality and quality of the real twin under every relevant aspect and thus predict the behaviour of the turbomachinery. This enables improved turbomachinery design and better product characteristics as well as the saving of physical prototypes.

Particular technological challenges are posed by this:

- Consistent data structures for geometric mapping and linking with property characteristics over the entire life cycle of a turbomachinery component - from product creation, manufacturing and in operation,
- Data preparation and provision according to specific requirements in the process,
- Efficient data management and methods for data reduction, especially in the manufacturing environment and in turbomachine operation,
- Realistic simulation of component behaviour, both single-discipline with high detail resolution and multi- or interdisciplinary for the prediction of mutual influences during operation, as well as
- Data link between target and actual twin (individual components) and feedback into the turbomachinery design process.

With the increasing availability of computer power and largely digitised information and data, artificial intelligence (AI) is gaining importance in a wide variety of application areas. The main focus is on the automation of intelligent behaviour and machine learning, for example, in order to emulate certain human decision-making structures.

Current focal points in the field of technology and product design are:

- Knowledge-based systems that model a form of rational intelligence for so-called expert systems. On the basis of formalised expert knowledge and logical links, user-specific questions can be answered, such as for force-optimised component structures or deviations in technical systems.
- Pattern analysis and pattern recognition enable images or shapes to be recognised and analysed and structures to be derived or transferred from them. Applications include, for example, the evaluation of measurement data and simulation results or industrial quality control and production automation (the latter in combination with robotics findings).
- Pattern prediction as an extension of pattern recognition in combination with simulation tools and further prediction algorithms then make it possible, for example, not only to

recognise a specific object in a single image (pattern recognition), but also to be able to make probability-based predictions about an object based on a series of images.

Digital manufacturing & additive manufacturing processes. Continuous CAX process chains enable the effective use of CNC (Computerised Numerical Control) machine tools for component production. This allows components to be manufactured with high precision and reproduction rates, measurement steps to be integrated into the manufacturing process and extensive data to be recorded for quality assurance and documentation.

Additive processes such as laser powder bed fusion (LPBF) open up further potential for component design and production. In the LPBF process, components are produced by selective laser beam melting, in a layer-by-layer structure. The extremely thin layer thickness (10-200 µm) enables a high detail resolution of the components. The LPBF method thus contributes to an expansion of the possible component portfolio beyond the limits of conventional production and extends the possibilities of the feasible component geometry.

Challenges here include:

- Dimensioning and design of force flow-optimised structures to reduce component weight while improving mechanical integrity and service life, especially for thermally highly loaded components in the hot gas path and/or mechanically highly loaded rotating components,
- Simulation of the warpage behaviour in the build-up process and correction of the component target geometry data for the manufacturing process,
- Interactions of component design with the surface orientation to the direction in which the components are "printed" layer by layer (build-up direction),
- Verification of component integrity and homogeneity of the microstructure by in-situ process monitoring during the manufacture of safety-critical turbo components.

4 Summary and conclusion

To achieve the ambitious goal of climate neutrality by 2050, the expansion of renewable energy sources must continue. In addition, the demand for electricity will continue to rise due to the decarbonisation of other sectors such as transport (electromobility), housing (heat pumps) and industry. In order to ensure a reliable and affordable energy supply in the long term, the fluctuating renewable energies must be supplemented by highly flexible storage technologies and the corresponding infrastructure, which can compensate for both short-term and seasonal fluctuations in electricity production from water, wind or sun. At the centre of promising energy storage and conversion concepts (power-to-X-to-power) are modern turbomachines, whose areas of application and working conditions differ significantly from the classic operation in conventional thermal power plants and are characterised by instationarity and the use of non-ideal working media.

Under such conditions, consolidated design methodologies and maintenance strategies lose their validity and new, as yet unanswered questions arise concerning the aerothermodynamic as well as mechanical and constructive optimisation of the machines. Particularly important for the successful implementation of the energy research programmes and the achievement of their goals are:

- Design, optimisation and predictive-prescriptive maintenance methodologies of expanders and compressors to be used in unconventional cycles (e.g. ORC, supercritical cycles, hydrogen combustion as well as regeneration);
- Flexibility and scalability of the machines with a selected design in a wide performance range without reducing their efficiency;
- Manufacturing strategies to ensure structural strength while reducing production costs.

Answering such questions requires close cooperation and continuous exchange between technology development and basic research as well as a strongly interdisciplinary working environment. To this end, the exploitation of synergies with other sectors such as aviation and the accompanying and targeted development of supporting technologies (digitalisation, artificial intelligence and machine learning methods, additive manufacturing processes) is of utmost importance.

The AG Turbo represents a globally unique research network for cooperative energy and turbomachinery research and thus offers an ideal environment for university and industrial pre-competitive collaborative research to address the new requirements of turbomachinery design for the energy transition and to jointly develop and apply effective and innovative concepts and methods.

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