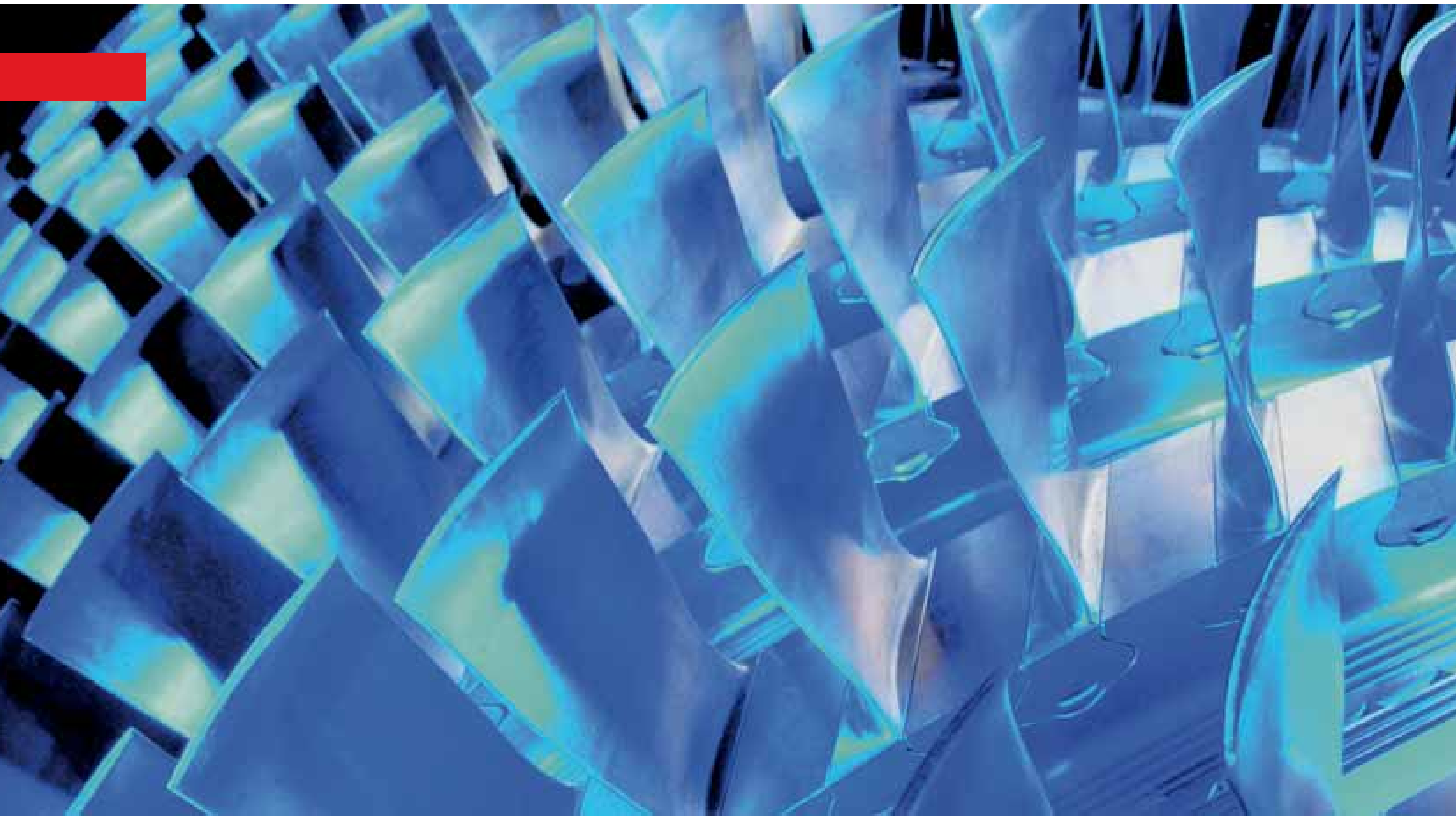
ENABLING NEW ENERGY TECHNOLOGIES

under Horizon 2020



A Roadmap on Turbomachinery Research

2014 – 2020

by EUTurbines

The gas and steam TURBINE 2020 has to be

HOT
for highest efficiency

FAST
for highly flexible power generation

ADAPTABLE
for new generation technologies and fuels

EUTurbines is the voice of the European gas and steam turbines manufacturers employing around 70.000 people across Europe with a turnover of around 25 billion Euros.

We are EUTurbines

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Content

Preface

Purpose of the Roadmap:

The roadmap should be seen as a facilitator for EU decision makers to take the right decision in funding energy related research. It is setting the framework for a research programme **"TURBINE 2020".** This programme will cover detailed project proposals necessary to enable our industry to develop the next generation of gas and steam turbines in the timeframe until 2020.

The European turbine industry outlines turbine related research steps that will be **necessary in order to accomplish successfully the European Industrial Initiatives laid out in the SET Plan.** In short: Without this research, no successful implementation of the new major energy technologies will be realistic. The roadmap indicates

- top priority technologies,
- necessary time for R&D, and
- an estimate of the R&D cost for it.

Qualitatively it is also shown, **where large scale demonstration is needed.** From today's perspective it would not be serious to quantify the necessary costs for all these topics due to the fact that this has to be done in the context of the entire systems and is not only turbomachinery related.

Original Equipment Manufacturers (OEMs) describe technological pathways for future energy conversion systems under the light of the European Industrial Initiatives outlined in the SET Plan. This roadmap shall be part of a solution given to society in order to meet challenges in energy production with active research in the next decade. We produced this paper as a multi – level guidance for EU policymakers involved in both Horizon 2020 policy making as well as in the development of concrete calls in the years to come.

What the Roadmap excludes

As component suppliers we can add some important aspects to the drawing of a picture of the coming energy infrastructure. However, **setting priorities for such infrastructure is up to the political institutions** to do and must be based on a process including all relevant stakeholders – with EUTurbines as the association of technology providers for energy conversion.

The Role of EUTurbines

Our roadmap proposes detailed research need and might be used as a basis for calls under Horizon 2020, with the next step, our proposal for a research programme **"TURBINE 2020"**, we will develop this further. Due to the successful, highly competitive situation in our market, it is not the generic role of EUTurbines to organise research consortia. Consequently, the roadmap should not be understood as an announcement that the companies involved are prepared to build exclusive consortia within EUTurbines in order to apply for calls which are in line with the roadmap or the following TURBINE 2020 programme. However, our member companies are interested in and see a need for research in the addressed areas and they are prepared to build up consortia with partners from the academia and other stakeholder groups such as utilities and other technology providers.

Roadmap on Turbine Research

The **European turbine industry has a very competitive position** and plays a leading role in the global market place. EUTurbines members are proud to **develop high technology solutions in Europe** and are committed to do so in the future to defend European entrepreneurship and innovation. In order to keep this prominent place and enhance the technology behind it, EUTurbines members are facing tremendous challenges in developing commercially viable technologies for more diversified and fuel efficient power generation in Europe and throughout the world. We know about this challenge and are ready to take it on.

New turbines are an enabler for new technologies

However, there are two important aspects to know. First – and this will be shown in the technology blocks described in this document – there are many different pathways drawn up for future energy supply in Europe and most of them would need new and specific turbomachinery. Due to the completely uncertain development of these potential markets, it is today extremely difficult and economically questionable to take the risk for expensive R&D activities. **It is up to policy to enable industry to make these investments by reducing these risks.** This risk reduction can be done by providing reliable conditions for the deployment of the technologies described in the Strategic Energy Technology Plan (SET) and in sharing the risk by public support for research. Second, and this relates to the aspects before, the conditions for developing the new technologies here in Europe, **the EU has to be a competitive location for R&D investments.** Horizon 2020 provides the opportunity for Europe to become competitive with other areas, especially with the US, Japan and some emerging countries, which are today economically preferable location for energy related research activities.

The Role of Turbomachinery

Today more than 80% of the electricity generated worldwide is produced by gas and steam turbines. These machines are core components in coal, nuclear, gas, biomass and solar-thermal power plants. Together with the related technology of hydro turbines the share in electrical power generation is today close to 98%.

Turbines do have a simple but **crucial role in power generation;** they are converting a chemical (fuel) or physical (from steam) energy into a kinetic one, the rotation needed to drive a generator to convert it into electrical power.

80% of the world's electrical power is produced by thermal Turbines

While in smaller systems – depending on the application – there is the alternative to burn fuel in reciprocating engines or fuel cells, there is no other way to do fuel or steam based power conversion in large scale systems.

Turbines are highly specialised cutting edge technologies. Even though some core technologies remain the same, the specific applications, sizes and fuels demand specific machines. A small steam turbine used for heat recovery in industrial processes and a gas turbine burning hydrogen rich gas in a power plant are as close together as a heavy duty bulldozer and a formula one race car.

Steam Turbines

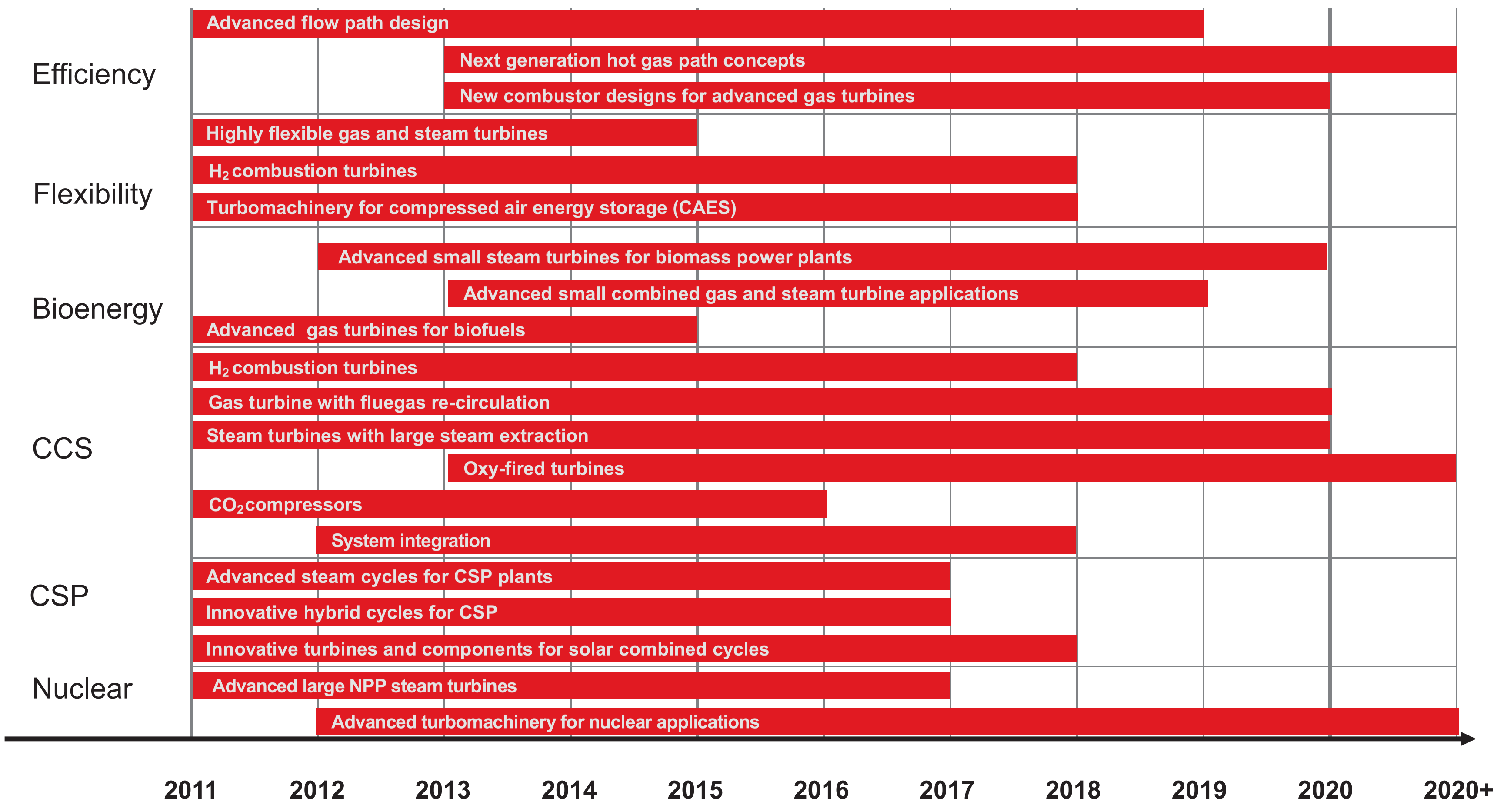
In a steam turbine, the steam's energy is extracted through the turbine and the steam leaves the turbine at a lower energy state. High pressure and temperature fluid at the inlet of the turbine exits as lower pressure and temperature fluid. The difference is energy converted by the turbine to mechanical rotational energy. Since the fluid is at a lower pressure at the exit of the turbine than at the inlet, it is common to say that the fluid has been "expanded" across the turbine. Because of the expanding flow, higher volumetric flow occurs at the turbine exit (at least for compressible fluids) leading to the need for larger turbine exit areas than at the inlet.

Turbines – and this applies to compressors as well – can be designed to work well in a variety of fluids, including gases and liquids, where they are used not only to drive generators for production of electricity, but also to drive compressors or pumps directly.

Gas Turbines

A gas turbine engine is more than just a turbine and typically includes a compressor, combustor and turbine combined to be a self-contained unit used to provide shaft or thrust power. The turbine component inside the gas turbine still provides power, but a compressor and combustor are required to make a self-contained system that needs only the fuel to be burnt in the combustor.

Turbomachinery Roadmap



Introduction

The horizontal specialists:
New energy infrastructure, the SET Plan and turbomachinery research

New Energy Infrastructure

Europe's energy infrastructure is the central nervous system of our economy. EU energy policy goals, as well as the Europe 2020 economic aims, will not be achievable without a major shift in the way European infrastructure is developed. Rebuilding our energy system for a low-carbon future is an important task for the energy industry and its manufacturers. Technological improvements, greater efficiencies and new flexibility will be necessary. The Energy Policy for Europe, agreed by the European Council in March 2007, establishes the Union's core energy policy objectives of competitiveness, sustainability and security of supply.

The internal energy market has to be completed in the coming years and by 2020 renewable sources have to contribute 20% to our final energy consumption, greenhouse gas emissions have to fall by 20% and energy efficiency gains have to deliver 20% savings in energy consumption. The EU has to assure security of supply to its 500 million citizens at competitive prices against a background of increasing international competition for the world's resources.

In the longer term, these issues are compounded by the EU decarbonisation goal to reduce our greenhouse gas emissions by 80-95% by 2050, and raise the need for further developments, such as an infrastructure for large-scale electricity, CO_2 and hydrogen transport and storage.

The SET Plan will not work without turbomachinery

The SET Plan carries the idea to establish energy technology policy for Europe. It supports and accelerates:

- Increase in knowledge and technology transfer
- Focus on the development of low-carbon energy technologies
- Transformation of energy technologies to meet 2020 Energy and Climate Change targets
- Contribution to the worldwide transition to a low carbon economy by 2050.

Implementation of the SET-Plan started with the establishment of the European Industrial Initiatives (EIIs). The EIIs bring together industry, the research community, the Member States and the Commission in risk-sharing, public-private partnerships aimed at the rapid development of key energy technologies at European level. In parallel, the European Energy Research Alliance (EERA) has been working since 2008 to align the R&D activities of individual research organisations to the needs of the SET-Plan priorities, and to establish a joint programming framework at the EU level.

For 2020, the SET-Plan provides a framework to accelerate the development and deployment of cost-effective low carbon technologies. With such comprehensive strategies, the EU is on track to reach its 20-20-20 goals by 2020.

For 2050, the SET-Plan is targeted at limiting climate change to a global temperature rise of no more than 2°C, in particular by matching the vision to reduce EU greenhouse gas emissions by 80-95%.

The SET Plan has so far identified nine European Industrial Initiatives. They focus on technologies for which the barriers scale of investment and risk can best be tackled collectively to carry out R&D. Some of these EIIs mentioned here would not become a success without extensive involvement of turbine applications and research on them.

1. European Industrial Bioenergy Initiative

Bioenergy is generated in two different ways. Biomass can be burned in boilers producing high pressure steam driving a steam turbine. In biogas applications, reciprocating engines or – in larger applications gas turbines are run on gaseous fuels produced by the fermentation of biomass or biomass gasification. Gas turbines and gas turbine power plants fired with biogas or gasified biomass have comparable operating and emissions characteristics to natural gas fired plants, therefore biomass power applications guarantee flexible power generation and are well suited to compensate fluctuating infeed from wind or solar power plants. Low NOx emissions and a high degree of flexibility are key to the success of this technology.

2. European CO_2 Capture, Transport and Storage Initiative

With regard to technically and economically feasible implementation of CCS, high-tech turbine technology is of highest importance in two areas: In the first place, turbine technology is the main lever to counteract the energetic cost of carbon capture, transportation and storage. Secondly, turbomachinery is needed in the entire chain to capture the carbon from burnt fossil fuels, compress it and transport it underground in a pipeline

3. Solar Europe Initiative

Concentrated Solar Thermal Power Plants (CSP) transform sunlight via large mirrors into heated, pressurised fluids that are converted indirectly (via heat exchanger) or directly into steam or gas turbine power which is converted by means of an electrical generator into electricity. The turbine technology is therefore the key to establish this promising way of harvesting the power of the sun.

4. Nuclear

Nuclear remains, albeit the disaster in Fukushima, an important source to generate electricity with a great potential of research. Turbines working directly or in secondary thermal conversion cycles form a crucial part of NPPs and directly influence their availability, efficiency and security. Nuclear power plants need more flexible turbines and advanced turbomachinery for current and future reactors. These are key fields to carry out R&D.

5. Supply Side Efficiency

Efficiency is a very important issue, where not only the demand but also the supply side should be taken into account.

Energy production should have no detrimental effect on environment and human health. Efficiency is the tool to sustainable CO_2 reductions. With installed BAT, we can meet the 7% of energy efficiency increase that is necessary to achieve climate goals. Power plants need to become more flexible in start-up, shutdown and load changes. Aerodynamic features and reduction of losses need to be improved.

Overview on requested funding

In this table, EUTurbines outlines a summary of the requested funding costs. Costs reflect the estimated amount to carry out research projects, but do not reflect the complete cost of developing the technology. Additional effort to validate and demonstrate the technologies will be needed; these efforts will be higher than the basis research.

Efficiency and flexibility are key in the development of the TURBINE 2020, therefore these horizontal aspects have a high priority for our industry.

European Industrial Initiative	Costs (50% co-funded)	Total Costs
Efficiency	97,5 M€	195 M€
Flexibility	115 M€	230 M€
Bioenergy	30 M€	60 M€
CCS	67 M€	134 M€
CSP	28 M€	56 M€
Nuclear	16 M€	32 M€
Total sum of requested funding	**353,5 M€**	**707 M€**

1. Efficiency in future thermal power plants

Investing in efficiency is a no regret option due to its applicability in all thermal power plants

a) Introduction

All over the world scientists, utility owners and manufacturers of power plants are convinced that the future sustainable energy system and the road to it will be a mix of many energy conversion systems for the production of electrical power, like fuel based power (non-fossil and fossil), hydro, wind, solar, and nuclear power. In this future energy system and in the transition period to it, it is foreseen that gas turbines or components in gas turbines (compressors, expanders, heat exchangers, combustors) and steam turbines will be key components in fuel based energy conversion systems.

The criteria for a sustainable energy system are that the energy system shall not have a negative impact on human beings or environment, and that the supply, availability and economy should be accepted by the society. The road to decrease CO_2 emissions in thermal power production is to use the fuel more efficiently, to use hydrogen rich fuels, to use biomass based fuels, and to capture the CO_2. To fully use the potential for CO_2 reduction with the introduction of solar and wind power plants in the electricity system, other power plants have to complement the flowing energy sources in an efficient way. Today's power plants have limited operational flexibility and improvable part load efficiency which means that the theoretical CO_2 gain at introduction of solar and wind power will be significantly reduced. It is thus necessary to develop efficient complementing power plant technologies to solar and wind power plants.

The average Chinese coal fired power plant is more efficient than its counterpart in Europe

The Energy Efficiency Action Plan (EEAP) focuses on measures to increase energy efficiency on both demand side and measures that will make generation of electricity (supply side) more efficient. The IEA estimates that of all efforts required to deliver a 50% reduction in global emissions by 2050 24% will need to come from end use fuel efficiency, 12% has to come from end use electricity efficiency and a further 7% will need to come from power generation efficiency. There is substantial potential for improving thermal efficiency of Europe's power plants. Our coal plants operate at an average 38% (BAT on new coal plants delivers 46%). Our gas plants operate at an average of 52% efficiency (BAT on new gas plants delivers more than 60%). Due to the age of the installed base, the average efficiency of Chinese coal plants is now higher than in Europe.

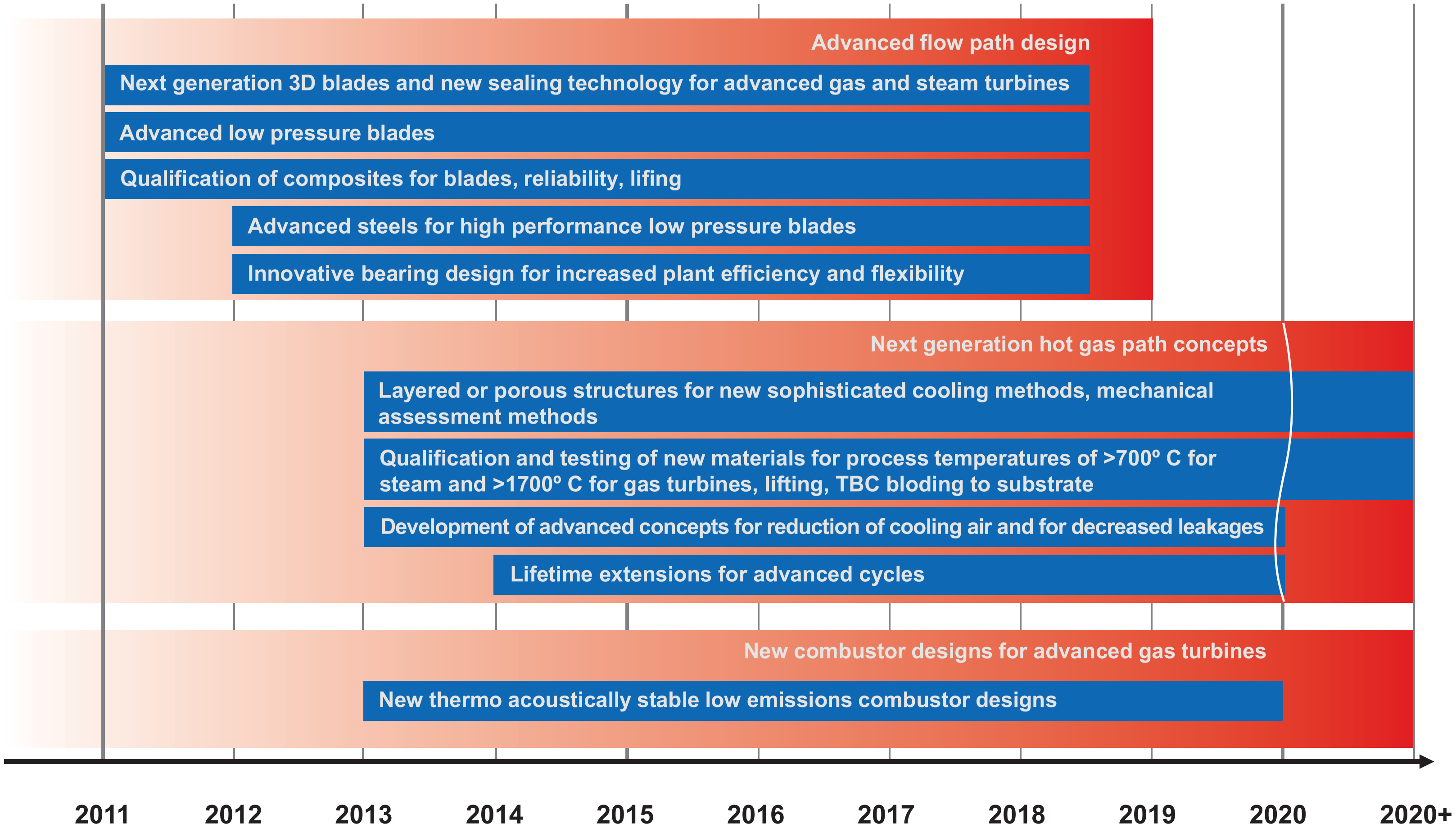
General measures to improve turbine efficiency are increasing Turbine Inlet Temperature (TIT) and compressor pressure ratio in parallel with cooling air reduction, more advanced aerodynamic concepts and loss reduction.

b) Technology blocks (red arrows)

Advanced flow path design

The potential for improvement of gas and steam turbine efficiency by aerodynamic optimisation adds to the contributions of cooling and sealing air reductions. In the high pressure end of the turbine with short blades and vanes the secondary losses constitute a large portion of the total losses. These losses can be reduced by introduction of advanced endwall shaping, 3D features in the aerodynamic design of airfoils and clearance control. Also the detailed design of the endwalls, steps between platforms and interaction with purge flows from rotor stator cavities can be improved.

Efficiency


Advanced flow path design
Next generation 3D blades and new sealing technology for advanced gas and steam turbines
Advanced low pressure blades
Qualification of composites for blades, reliability, lifing
Advanced steels for high performance low pressure blades
Innovative bearing design for increased plant efficiency and flexibility
Next generation hot gas path concepts
Layered or porous structures for new sophisticated cooling methods, mechanical assessment methods
Qualification and testing of new materials for process temperatures of >700° C for steam and >1700° C for gas turbines, lifting, TBC bloding to substrate
Development of advanced concepts for reduction of cooling air and for decreased leakages
Lifetime extensions for advanced cycles
New combustor designs for advanced gas turbines
New thermo acoustically stable low emissions combustor designs
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2020+

By decreasing the losses of kinetic energy at the outlet from the last stage of the turbine further increase of efficiency can be achieved. This can be done using longer last stage blades, where the aeromechanical stability problems and the ultra-high loaded airfoils are the main aerodynamic challenges, as well as improving the diffuser recovery and stability. Here, the separation prediction is the challenge.
During operation, the turbine efficiency is decreased along the lifetime of the flow path components. The mechanisms are mainly wear in sealings, increase of tip clearances by wear and oxidation, increased roughness and shape deviation due to erosion. Considerable amount of fuel can be saved with development of a low degradation technology, e.g. composites.

Next generation hot gas path concepts

As mentioned above, increased gas turbine performance is very much related to an increase of the Turbine Inlet Temperature (TIT). But the coolant mass flows will need to be minimised to achieve as high performance benefits as possible. Advanced cooling systems concepts should be developed for engine first stage components and tested experimentally in test rigs (existing and new rigs, like liquid crystal rig, thermal imaging rig, film cooling rig as required, and in new, cold flow, low cost, component internal cooling test rigs). New cooling surfaces as well as new cooling schemes should be studied by CFD modelling to use the coolant in the best possible way before it will leave the component.

To improve turbine efficiency today's levels of cooling air, leakage air and sealing air (air to keep the hot gas in the flow path) must be heavily reduced.

We need to develop materials for turbine blades to bear temperatures where metals start to fuse.

A phenomenon that must be further addressed in this context is hot gas ingestion that can cause unacceptably high rotor temperatures. We need to develop more advanced technologies that will handle hot gas ingestion to make sure that the hot gases will be confined in the cavity without reaching the rotor itself.
To use new sophisticated cooling methods based on porous structures a new thinking is necessary. Analysis methods and design concepts and criteria must be developed and tested for such structures in order to optimize the design for components with porous structures.

High temperature materials in gas turbines have properties that change significantly during the expected life of the component due to thermal exposure, mechanical load and the combination of the two. Issues that affect lifing and reliability and can cause serious problems are e.g. crack propagation commonly due to creep or fatigue. In many components early TBC (Thermal Barrier Coating) spallation will increase the material temperature of the component and reduce the safe life for which the component can be used. This makes it difficult to utilize existing materials in a safe and efficient manner, which implies that we now suffer from too low efficiency (CO_2 penalty) and too high costs. One measure to improve crack propagation estimates in high temperature components and that will be even more pronounced for new materials like composites is to develop 'long test time' rigs with a low cost per test hour, run qualification tests, perform basic Modelling and engine testing and compare with engine tests. This will also make it possible to improve and assure the quality of 'safety factors' in the real design of turbine components.

New combustor designs for advanced gas turbines

In combustors of premixed flame type pressure oscillation phenomena often referred to as 'combustion dynamics' are common. Combustion dynamics often start in the linear regime but if coupled to the heat release of the premixed flame it might cross over into the non-linear regime and very rapidly reach damaging levels. Typical amplitudes of such pressure oscillations may easily reach 5% of the mean pressure level and are highly destructive. These difficulties are typical for low emission combustion systems where they often may be avoided by adjusting the ratio of fuel to the pilot passage as compared to the main passage. Increased ratio leads to increased NO_x emissions and reduced ratio may lead to increased CO emissions and unburnt hydrocarbons. Therefore combustion stability is utterly important for low emission systems.

The overall objective for research work in this field should be to improve knowledge and Modelling capabilities (both flow and acoustics) in the field of combustion related pressure dynamics and emissions, and also on measures to damp the combustion dynamics by for instance using liner walls, i.e. porous walls of various types, which gives potential of emission reduction. Modelling efforts should include investigations of the merits of using an approach based on the Navier-Stokes' equations (NSE), either through linearised NSE or unsteady approaches and to evaluate and further develop existing eigenmode extraction tool(s) for realistic combustor cases.

c) The detailed research issues (blue arrows)

Table 1 Efficiency – Overview

Technology Blocks and Research Issues	Timeframe	Costs (50% co-funded)	Total Costs
Advanced flow path design	**2011-2019**	**30 M€**	**60 M€**
Next generation 3D blades and new sealing technology for advanced gas and steam turbines	2011-2019		
Advanced low pressure blades	2011-2019		
Qualification of composites for blades, reliability, lifing	2011-2019		
Advanced steels for high performance low pressure blades	2012-2017		
Innovative bearing design for increased plant efficiency and flexibility	2012-2017		
Next generation hot gas path concepts	**2013-2020+**	**37,5 M€**	**75 M€**
Layered or porous structures for new sophisticated cooling methods, mechanical assessment methods	2013-2020+		
Qualification and testing of new materials for process temperatures of >700 °C for steam and >1700 °C for gas turbines, lifing, TBC bonding to substrate	2013-2020+		
Development of advanced concepts for reduction of cooling air and for decreased leakages	2013-2020		
Lifetime extension for advanced cycles	2014-2020		
New combustor designs for advanced gas turbines	**2013-2020**	**30 M€**	**60 M€**
New thermo acoustically stable low emissions combustor design	2013-2020		

NB: Table does not reflect complete costs of developing the technology, cost estimate covers collaborative projects only

2. Flexibility – enabling intermittent renewables

Highly flexible power generation will enable all energy sources to become partners

a) Introduction

In the last years, in most countries, a requirement for newly built power plants with increasing importance is "flexibility". The request for flexible power plants originates from two sides:

- Frequency & Voltage: assurance of electric grid stability
- Market conditions: very high energy price spread between peak hours and night hours (The price might be too low at a certain point in time to run a power plant economically).

Grid Stability

Electric power generation and load demand (including grid losses) constantly require balance. Any imbalance between power generation and load demand results in a system-wide deviation of the frequency from its nominal value (50 Hz). The necessary control and balancing power is provided mainly by power generating facilities by means of primary, secondary and tertiary control reserves. In order to adjust Generating Units to match the actual demand it is necessary that these Generating Units are able to increase/decrease their production quickly and that generation reserve margins are available in both directions.

80.000kW in 10 seconds?
It will work!

To maintain the voltage in acceptable ranges throughout the network and to prevent the transmission systems from voltage collapses, the Generation Units have to be able to provide reactive power to the network within a definite range. Shortage of reactive power can lead to unacceptably low voltage levels and finally to a voltage collapse of the system.

In the last years, mainly due to the growth of the electricity markets (energy prices and power levels for each generator are defined every 15 minutes) and to the increasing of renewable sources such as CSP, wind and PV, whose power output is subject to ambient conditions, the electrical grids increased their frequency/voltage oscillations. Grid connection requirements for power plants have therefore been defined by the Transmission System Operator for Electricity.

Market

The future energy scenario has to take into consideration:

- An increasing energy production coming from the renewable sources, mainly CSP, wind and PV, which are highly dependent on the ambient conditions
- Increased energy saving (20 – 20 – 20 EU target commitment)
- It is likely that nuclear and coal power plants will continue to supply the "base load electrical demand", as it is less viable for them than for other units to Start-up and shutdown every day, if the energy price during the night hours will be very low.

As a consequence of this scenario, especially combined cycle or conventional steam power plant fed with expensive fuels must shut down every night and restart in the morning (two shifts operation) or stay at very low power level to reduce fuel consumption while maintaining acceptable emission levels.

This leads to the following requirements for all power plants:

- Load dispatching between a minimum environmental load and the maximum load maintaining the capability required by the Transmission System Operator for electricity to assure the grid stability.

For the high cost fuelled power plants:

- Daily start-up/shutdown, a lifespan of the plant of at least 25 years is economically necessary
- Fast and repeatable start-ups
- Minimum load operation

For the above reasons it is necessary that future power plants will fulfil more and more stringent characteristics for flexible operations. Flexible power plant operations are possible only if the gas turbines, steam turbines and the electrical generators are adjustable. To achieve this, a phase of evaluation or re-design of the machines (from mechanical, fluid dynamical, thermal, and electrical point of view) and the use of new materials is necessary.

Burning wind? Yes, with a new hydrogen turbine

Furthermore, in order to reach flexible operation and grid stability, new solutions could arise. Among them the most attractive are:

- Utilize the energy produced by the renewable sources or during night hours (electrical energy price of the same level as the natural gas cost) to store energy, for example by accumulating compressed air or by producing H_2. During peak hours (peak prices) the compressed air and the H_2 could be used to produce electrical energy
- Apply combined cycles fed by synthetic gas coming from coal gasification potentially including pre-combustion capture processes (see Carbon Capture and Storage paragraphs)
- Evaluate the R&D results considering the generators and electric grid behaviour

To evaluate and optimize new solutions it is necessary to develop new concepts and design and demonstrate corresponding advanced turbines and compressors.

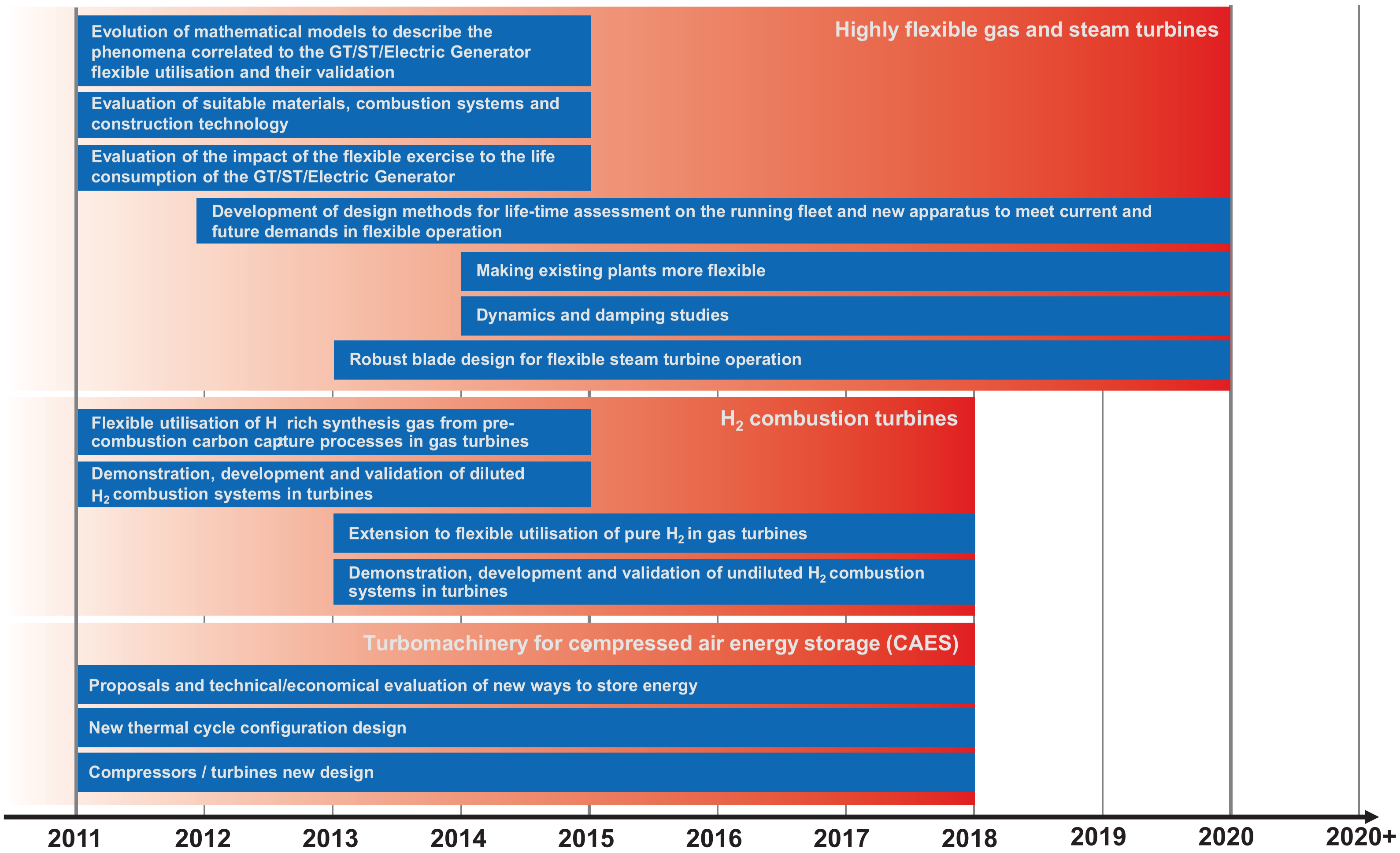
b) Technology blocks (red arrows)

Highly Flexible Gas and Steam Turbines

Combustion turbines and steam turbines in the new “flexible” scenario have to meet several different and often contrary requirements:

- Fast load ramps – reliable combustion stability (GT)
- Daily Start-up/shutdown operation – design for long life (maintaining or even increasing time intervals between major overhauls than base load GT/ST)
- Reducing the minimum environmental load – reducing overall emissions (as the Start-up/shutdown operations involve higher emission levels) (GT)
- Decreasing the start-up time while maintaining the permissible material stress inside acceptable values (GT & ST).

Flexibility – Enabling Intermittent Renewables



To achieve these goals it is necessary to improve the R&D activities on materials, and to focus on construction technologies and combustion systems. It is essential to validate the new solutions both by mathematical models and by testing and learning from demonstration. A challenge will be to evaluate the long term effects (lifing) of the “flexible” requirements by R&D.

Hydrogen (H_2) Combustion Turbine

Hydrogen (H_2) is a possible storage medium to use excess renewable power in turbine driven power generation.

In order to utilise H_2 e.g. from water electrolysis processes, modern gas turbines, especially their combustion systems and upstream portion of the turbine section, have to be significantly modified. Thus, the main challenges are to achieve clean and stable premixed H_2 combustion and heat balance optimisation at the first turbine stage without compromising efficiency, reliability or emission levels. This goal has not yet been reached by industry and a successful development, validation and demonstration of such a combustion concept would be an enabler for environmentally friendly power generation from excess renewable power.

Turbo Machinery for Compressed Air Energy Storage (CAES)

Long term R&D activities are essential in the design and testing of new thermal cycles involving completely new configurations. In these future developments we can include:

- Hybrid thermal cycle (CAES + conventional or combined cycles).
- Cycles utilizing compressed air energy storage (prerequisite the design of new advanced compressed air storage components)
- New combined cycles with separate compressor, combustion chamber and turbine sections.

Storing power in the air?
It will work with CAES

These concepts will lead to more flexible and economic solutions for producing electrical power, as well as to reduce the overall environmental impact of the future power plants.

In order to develop all these activities it is indispensable to face the problems relevant to the optimisation of advanced thermodynamic cycles. This means primarily a new design for the advanced compressors and turbines emission levels.

c) The detailed research issues (blue arrows)

Table 2 Flexibility – Overview

Technology Blocks and Research Issues	Timeframe	Cost (50% co-funded)	Total Costs
Highly Flexible Gas and Steam Turbines	**2011-2015**	**35M€**	**70 M€**
Evolution of mathematical models to describe the phenomena correlated to the GT/ST/Electric Generator flexible utilisation and their validation in field	2011-2015		
Evaluation of suitable materials, combustion systems and construction technology	2011-2015		
Evaluation of the impact of the flexible exercise to the life consumption of the GT/ST/Electric Generator	2011-2015		
Development of design methods for life-time assessment of the running fleet and new apparatus to meet current and future demands in flexible operation	2012-2019		
Making existing plants more flexible	2014-2020		
Dynamics and damping studies	2014-2020		
Robust blade design for flexible steam turbine operation	2012-2017		
H_2 combustion turbines (in combination with H_2 Gas turbine development in CCS section)	**2011-2018**	**30 M€**	**60 M€**
Flexible utilisation of H_2 rich synthesis gas from the use of energy coming from renewable sources	2011-2015		
Demonstration, development and validation of diluted H_2 combustion systems in turbines	2011-2015		
Extension to flexible utilisation of pure H_2 in gas turbines	2013-2018		
Demonstration, development and validation of undiluted H_2 combustion system in turbines	2013-2018		
Turbomachinery for Compressed Air Energy Storage (CAES)	**2011-2018**	**10 M€**	**20 M€**
Proposals and technical/economical evaluation of new ways to store energy	2011-2018		
New thermal cycle configuration design	2011-2018		
Compressors/turbines new design	2011-2018		
Demonstration/Validation	**2014-2020**	**40 M€**	**80 M€**

NB: table does not reflect complete costs of developing the technology, cost estimates covers collaborative projects only

3. Bioenergy

a) Introduction

The term biomass takes into account all kinds of organic feedstock which – converted into some sort of fuel – serve as a primary energy source in a very diverse range of power plant types. Additionally the term bioenergy includes organic material used as a basic material in petrochemical and other energy intensive products.

Areas of general research are systems analysis, agricultural topics like sustainability, bioenergy trade, standards, CO_2-balances, conversion technologies and last but not least mechanical engineering in the fields of power plant design.

In more and more decentralised power plant structures (overlapping with reciprocating engines but mostly with higher capacities) of future energy systems in the EU it is absolutely inevitable to focus research and development on gas and steam turbines of industrial size.
This power machinery is made for efficient electricity generation either from liquid, gaseous or solid biofuels. Research on gas turbines and steam turbines is needed to meet the special requirements of biomass combustive effects.

Decentralised power generation will require new turbine technologies

Without high efficiency turbines bioenergy will not reach the large shares of the future EU energy mix as requested by politics. For a future low carbon energy mix, biomass is going to play an important role.

b) Technology blocks (red arrows)

Advanced small steam turbines for biomass fired power plants

Especially small steam turbines will be of greater interest in a decentralised future energy system. To improve efficiency of those small (lower double-digit MW level) steam turbines, new concepts in cycle engineering as well as for the machine design are necessary. A reheat concept promises to be the most successful way of raising efficiency in small steam turbine plants. The goal is a lower double-digit MW steam power plant with an electrical net efficiency of about 40% excluding the auxiliary power demand.

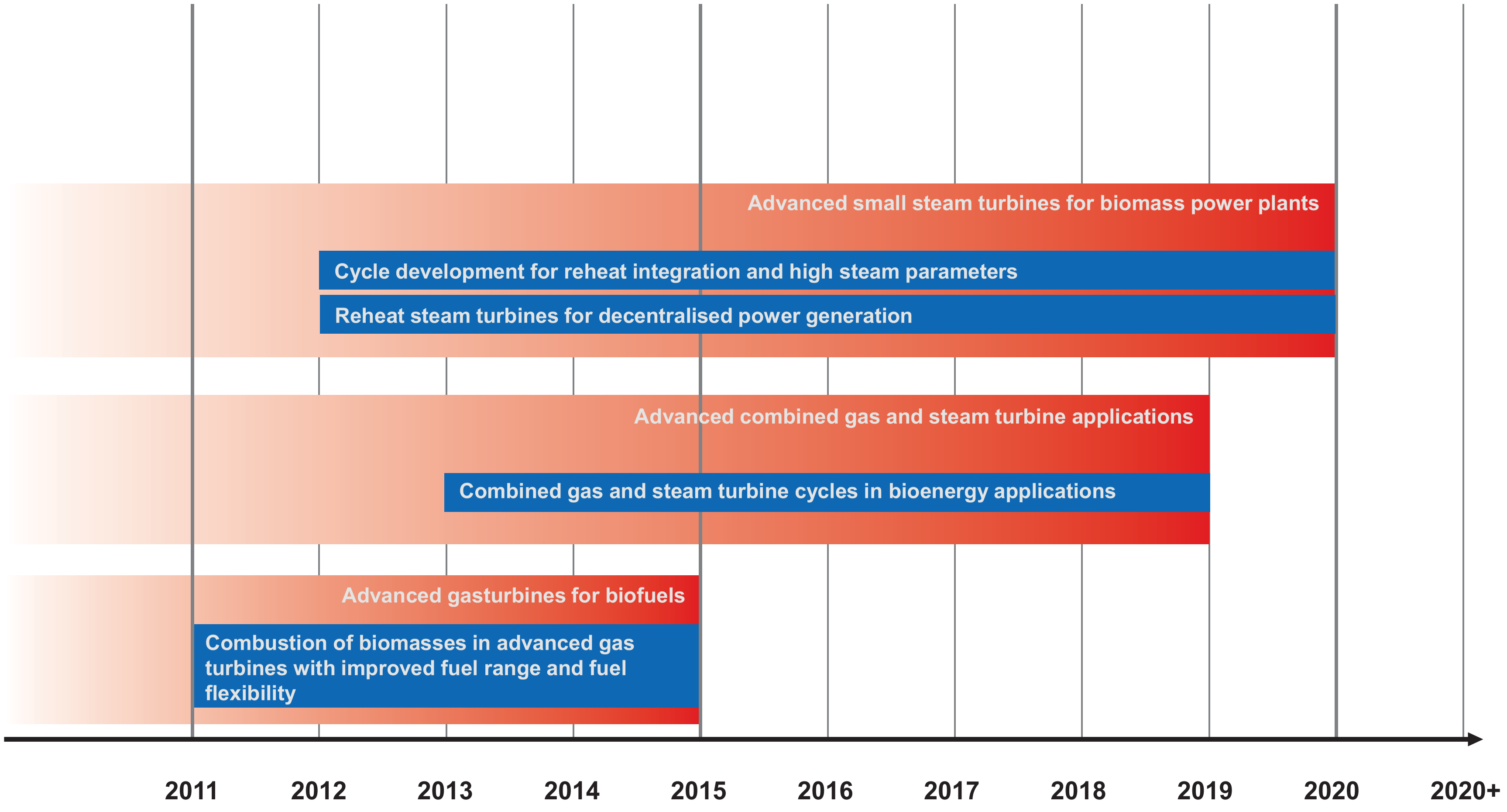
Advanced small combined gas and steam turbine applications

An efficient use of biomass will be possible in decentralised combined gas and steam turbine plants, exploiting both the high temperature energy level through a gas turbine as well as the lower temperature energy share through an attached steam turbine. Dedicated cycles will have to be developed regarding 10 to 40 MW machinery each.

Advanced small gas turbines for biofuels

Future gas turbines operating with biomass fuels as well as conventional backup fuels will have to tolerate a wide range of fuel qualities and parameters (e.g. heat value, radiant heat, corrosiveness, etc.). In this respect gas turbine technology will have to be adapted in order to provide greater fuel flexibility while keeping up the high standard in efficiency.

Bioenergy


Advanced small steam turbines for biomass power plants
Cycle development for reheat integration and high steam parameters
Reheat steam turbines for decentralised power generation
Advanced combined gas and steam turbine applications
Combined gas and steam turbine cycles in bioenergy applications
Advanced gasturbines for biofuels
Combustion of biomasses in advanced gas turbines with improved fuel range and fuel flexibility
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2020+

c) The detailed research issues (blue arrows)

Table 3 Bioenergy – Overview

Technology Blocks and Research Issues	Timeframe	Costs (50% co-funded)	Total Costs
Advanced small steam turbines for biomass power plants	**2012-2020**	**10M€**	**20 M€**
Cycle development for reheat integration and high steam parameters	2012-2020		
Reheat steam turbines for decentralised power generation	2012-2020		
Advanced combined gas and steam turbine applications	**2013-2019**	**10 M€**	**20 M€**
Combined gas and steam turbine cycles in bioenergy applications	2013-2019		
Advanced gas turbines for biofuels	**2011-2015**	**10 M€**	**20 M€**
Combustion of biomasses in advanced gas turbines with improved fuel range and fuel flexibility	2011-2015		

NB: Table does not reflect complete costs of developing the technology, cost estimate covers collaborative projects only

4. Carbon Capture and Storage

a) Introduction

In order to reach the emission levels compatible with climate change mitigation targets in the best technical and economical way will require deploying a portfolio of solutions in the area of power generation. There is and likely will be no “silver bullet” technology. In fact, energy efficiency in terms of supply and demand side, a suitable technology mix including renewable and nuclear energies as well as carbon capture and storage (CCS) or usage must be pursued and thoroughly aligned.

CCS is a technology under development, still several years from commercial deployment. As with many renewable energy or grid projects, the CCS processes now need to be demonstrated on a large scale in order to gain necessary experience and reduce the risk before commercialisation. At the same time innovative new concepts have to be progressed by corresponding R&D activities.

Reducing the cost of CCS? Invest in turbomachinery technology

Gas and steam turbine as well as compressor technologies play a crucial role in all of the three main carbon capture categories: in pre-combustion, post-combustion and oxyfuel processes. In fact, some of the implementation actions proposed by the CCS EII will not be possible at all if the related turbine technology and a corresponding product has not been thoroughly developed and validated, respectively.

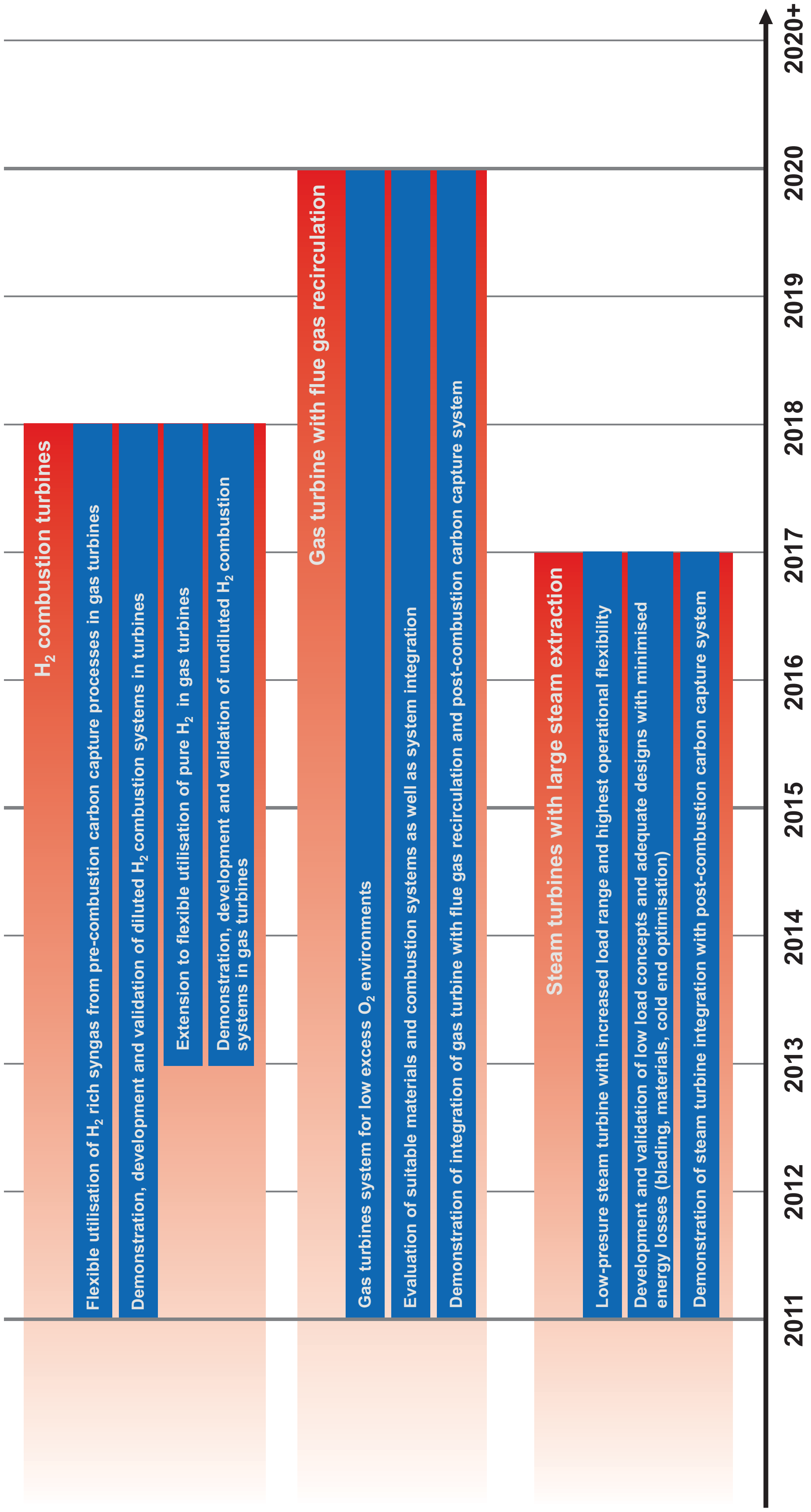
b) Technology blocks (red arrows)

H_2 combustion turbines for pre-combustion CO_2 capture

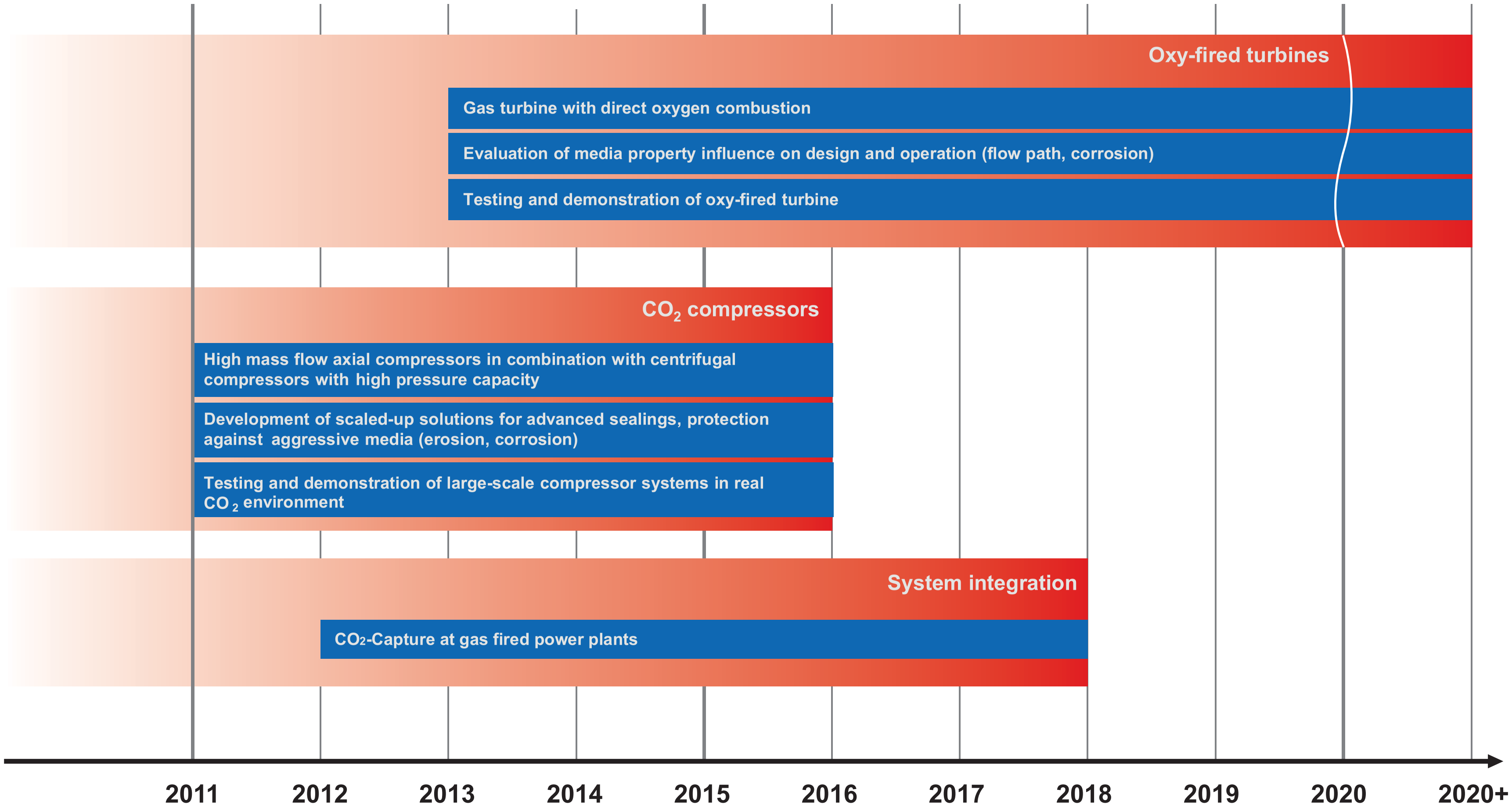
In integrated gasification turbine combined cycle (IGCC) plants with carbon capture, synthesis gas from the gasification process is converted in a shift reactor into CO_2 and H_2 rich fractions. As the CO_2 rich fraction is subsequently separated from the shifted synthesis gas, the H_2 rich stream remains and can be utilised in a H_2 turbine or further processed for other than power generation purposes.

In order to utilise synthesis gas with high concentrations of H_2 up to almost pure H_2, modern gas turbines, especially their combustion systems and upstream portion of the turbine section, have to be significantly modified. Thus, the main challenges are to achieve clean and stable premixed H_2 combustion and heat balance optimisation at the turbine stage without compromising efficiency, reliability or emission levels. Thus, the main challenge is to first achieve clean and stable premixed H_2 combustion without compromising flexibility, reliability or emission levels. This goal has not yet been reached by industry and a successful development, validation and demonstration of such a combustion concept would be an enabler for environmentally friendly power generation with pre-combustion CO_2 capture.

Carbon Capture and Storage



Carbon Capture and Storage



Gas turbine with flue gas re-circulation for post-combustion CO_2 capture

Post-combustion CO_2 capture processes are generally characterised by a CO_2 capture system being placed downstream of the power generation or industrial process unit in the CO_2 rich flue gas path. Typical post-combustion CO_2 capture processes use liquid or solid substances able to absorb CO_2 from the flue gas and release it controlled in high concentration for further processing steps.

Since flue gas compositions of gas fired combustion turbine based processes have relatively low concentrations of CO_2 (about 4% volume points), the effectiveness of post combustion capture processes can be increased by flue gas re-circulation. Therefore, flue gas still containing sufficiently high amounts of oxygen is re-circulated back to the compressor side and mixed with the inlet air flow. As a result, CO_2 concentration in the flue gas downstream of the gas turbine can be doubled. Also, NO_x emissions can be reduced with this method. Main R&D activities are required in the areas of stable, low-emission combustion, materials for low excess O_2 environments and optimised process integration followed by validation and demonstration of the whole concept.

Steam turbines with large steam extraction

The main reason for the reduction of efficiency of thermal power plants with post-combustion CO_2 capture is in most cases the large amount of low-pressure (LP) steam that is required for regenerating the CO_2 rich solvent. Instead of being utilised in the LP steam turbine, up to 50% of the LP steam flow is extracted and used as a heat source in the CO_2 capture process. The steam turbine, however, needs to be adapted to the full flow of steam in case of a capture system failure.

This has a significant impact on steam turbine design and operation. R&D activities need to address the new requirements maintaining high efficiencies and operational flexibility over the full load range followed by corresponding validation and demonstration steps.

Oxy-fired turbines

Systems for CO_2 capture based on the oxyfuel principle rely on burning fuel with relatively pure O_2, diluted with recycled CO_2 or CO_2/steam mixtures. Under these conditions, the primary products of combustion are H_2O (water) and CO_2, with the CO_2 separated by condensing the H_2O. In order to realise such an oxyfuel process, flue gas recirculation is necessary to limit the combustion temperature at a tolerable level, too.

In contrast to air-fired GTs with flue gas re-circulation, gas turbines that are operated with direct oxygen combustion and flue gas re-circulation require a completely new design due to the significantly changed composition of the working media (CO_2/H_2O instead of mainly N_2). In order to design such a machine, the whole range of aerodynamics, thermodynamics, combustion as well as materials R&D including testing is needed. In this respect, more scientific analysis and fundamental R&D work is required before product development could be initiated.

Transport
5.000.000t CO_2
with 100bar?
It's possible

CO_2 compressors

The pressure required for the CO_2 gas at the plant boundary limits depends on the conditions for transport and storage/utilisation. Typically, a pressure level of above 100 bar has to be achieved. The CO_2 compression system involves the use of axial and centrifugal compressors with multiple compression stages as well as the application of intercoolers.

CCS systems for large coal-fired power plant units will produce CO_2 in the range of 5 million tons per year. Although compressors for CO_2 transport are commercially available, new large-scale compressor designs combining high mass flow capability of axial compressors with high-pressure capability of centrifugal compressors are still to be developed and introduced to the market. This would support the build-up of an efficient CO_2 transport network. In this context, the selection of corrosion resistant materials and handling of impurities such as condensates are examples for a major challenge.

c) The detailed research issues (blue arrows)

Table 4 Carbon Capture and Storage – Overview

Technology Blocks and Research Issues	Timeframe	Costs (50% co-funded)	Total Costs
H_2 combustion turbines (in combination with H_2 Gas turbine development in flexibility section)	**2011-2018**	**20 M€**	**40 M€**
Flexible utilisation of H_2 rich synthesis gas from pre-combustion carbon capture processes in gas turbines	2011-2017		
Demonstration, development and validation of diluted H_2 combustion systems in turbines	2011-2017		
Extension to flexible utilisation of pure H_2 in gas turbines	2013-2018		
Demonstration, development and validation of undiluted H_2 combustion systems in turbines			
Gas turbine with flue gas re-circulation	**2011-2020**	**20 M€**	**40 M€**
Gas turbine system for low excess O_2 environments			
Evaluation of suitable materials and combustion systems as well as system integration	2011-2020		
Demonstration of integration of gas turbine with flue gas re-circulation and post-combustion carbon capture system	2011-2020		

Table 4 Carbon Capture and Storage – Overview

Technology Blocks and Research Issues	Timeframe	Costs (50% co-funded)	Total Costs
Steam turbines with large steam extraction	**2011-2017**	**8 M€**	**16 M€**
Low-pressure steam turbine with increased load range and highest operational flexibility	2011-2017		
Development and validation of low load concepts and adequate designs with minimised energy losses (blading, materials, cold end optimisation)	2011-2017		
Demonstration of steam turbine integration with post-combustion carbon capture system	2011-2017		
Oxy-fired turbines	**2013-2020+**	**8 M€**	**16 M€**
Gas turbine with direct oxygen combustion			
Evaluation of media property influence on design and operation (flow path, corrosion)	2013-2020+		
Testing and demonstration of oxy-fired turbine	2013-2020+		
CO_2 compressors	**2011-2016**	**8 M€**	**16 M€**
High mass flow axial compressors in combination with centrifugal compressors with high pressure capability	2011-2016		
Development of scaled-up solutions for advanced sealings, protection against aggressive media (erosion, corrosion)	2011-2016		
Testing and demonstration of large-scale compressor system in real CO_2 environment	2011-2016		
System Integration	**2012-2018**	**3M€**	**6 M€**
CO_2-capture at gas fired power plants	2012-2018		

NB: Table does not reflect complete costs of developing the technology, cost estimate covers collaborative projects only

5. Concentrated Solar Power

a) Introduction

Solar energy is one of the world's few freely available energy sources and by exploiting this energy source in a technologically advanced fashion provides the potential to produce electrical power in an environmentally friendly manner. Such technology operates with almost zero greenhouse gas emissions contributing to global reductions in CO_2 emissions. The earth is exposed to solar radiation of approximately 80,000 Terawatts.

CSP is a likely candidate for providing a major share of electricity from renewable sources because it is among the most cost effective solar technologies. Many different types of solar collectors have been developed that utilise different approaches to focus the captured thermal energy and different fluid media with which to transport the energy, including both liquid, pressurised gas and direct steam generation alternatives. The different collector designs and configurations affect thermal cycle conditions available to the turbine equipment. Currently the steam generated in the collector systems is generally low temperature and pressure leading to low thermal efficiencies and requiring special design considerations of the steam turbine. Moving to more advanced cycles with higher steam parameters will improve overall conversion rates. Increasing the unit size will also offer increased efficiency and reduced capital costs.

Sunlight is of course an intermittent energy source and this poses big challenges to turbine designs which will be required to follow closely the daily and seasonal variations, including very frequent shutdown/start-ups and significant operation off the design point. Introducing thermal storage facilities enable power generation to continue at times of low sun intensity.

b) Technology blocks (red arrows)

Advanced steam cycles for CSP Plants

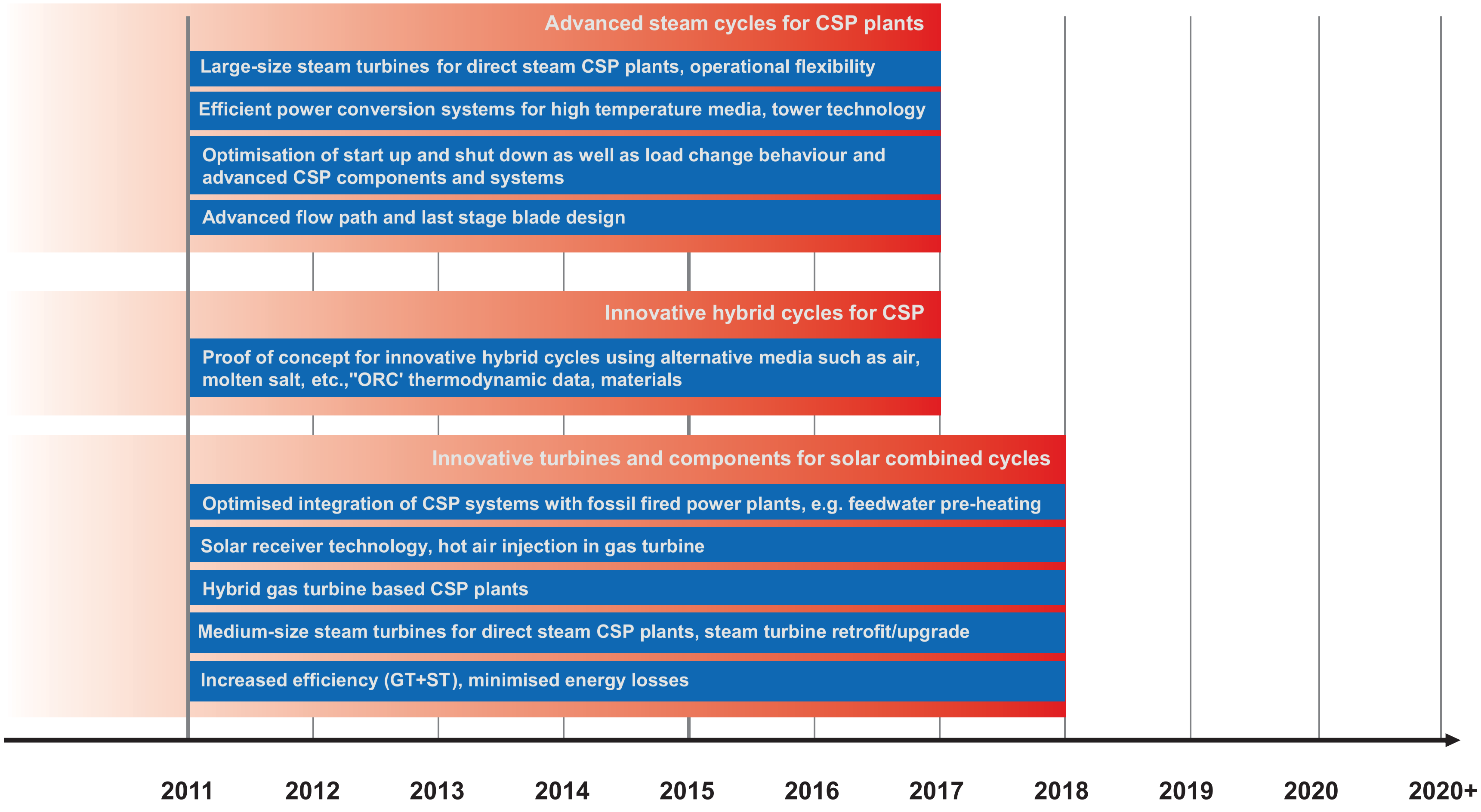
Steam cycles for CSP plants require a careful balance between energy capture conditions, thermal storage conditions and the turbine configuration. Increasing the fluid pressure and temperature to the turbine increases the available energy thus improving cycle efficiency. Higher fluid temperatures also lead to reductions in energy storage size and cost.

In general large steam turbines operate under high, stable steam parameters. In large direct steam CSP cycles the turbines become more complicated, having to accommodate low steam conditions and significant transient and operational changes. If the direct cycle does not have storage facilities, the cyclic demands on the turbine will increase further. R&D effort is required in ensuring suitable materials and design methods are employed to resist the effects of low steam conditions and high moisture content. Parabolic trough systems tend to operate at lower collector temperatures than CSP tower configurations. Higher cycle efficiencies can be achieved at higher temperatures but commercial/technical optimisation between the choice of tower and media is needed.

The transient and cyclic operation of steam turbines with CSP is a significant challenge. The daily changes (including short term clouding etc.) are further compounded by annual variations. The process for determining the optimal sizing (including multiple machines) and best efficiency operating point is complex requiring R&D effort.

CSP project specifications place great emphasis on reducing dependency on external non-renewable energy sources. In this respect, special attention to machine clearances, sealing steam requirements and maintenance of vacuum will be required to minimise usage of site resources. Many of the CSP plants will be constructed in arid areas and water consumption will be expected to be minimised.

Concentrated Solar Power



Innovative hybrid cycles for CSP

For low temperature collector systems an alternative solution is to adopt a cycle that uses different (to steam) working fluids such as the Organic Rankine cycle (ORC). With lower boiling points these fluids are superheated at lower temperature removing problems related to liquid droplets in early stages of the turbine. In addition systems operating at lower collector temperatures can result in improved collector efficiency due to reduced ambient losses and offer scope for reducing the overall size of the collector field thus reducing plant costs.

Most current CSP storage technologies involve the use of molten salt solutions which in solution offer high thermal conductivity and allow fluid temperatures to reach 600ºC. Other systems collect solar energy using lower temperature oils (390ºC) and then use heat exchangers to transfer this energy to molten salt storage vessels. Using such storage systems allows the extension of power generation into the night or during periods of reduced incident energy.

Changing the fluid from steam introduces a series of significant R&D challenges for turbine designers. Greater care will be required in containing the working fluid and ensuring contamination is avoided.

A pilot or demonstrator plant will be required to thoroughly prove out new CSP technology concepts.

Innovative turbines & components for solar combined cycles

With the majority (two thirds) of the worldwide electrical generation by 2035 still being provided by fossil fired power plants, the integration of Concentrated Solar Power into existing and new plants provides another opportunity to improve overall efficiency and reduce greenhouse emission. Steam generated by CSP can be injected directly into the main steam turbines, used as heating steam in the feedwater system or provide steam supplies for boiler feed pump turbines.

Combining sun and gas – a promising way to highly efficient power generation

Integrated Solar Combined Cycle Systems (ISCCS) provide high pressure solar generated steam to supplement the steam produced by the Heat Recovery Steam Generator (HRSG). These combinations allow very cost effective energy production under continuous and reliable operation.

R&D effort is needed to decide how best to integrate solar energy into existing power cycles. Direct intermittent or fluctuating injection of large steam flows into steam turbines needs further investigation along with feed heater design optimisation.

Based on a heavy-duty gas turbine and combined cycle approach, one can use solar energy to raise air temperature prior combustion combined with a booster burner to bring the gas temperature for maximum efficiency. Parabolic trough and Fresnel solar plants could benefit from the incorporation of aero-derivative gas turbines as their exhaust heat temperature is a suitable source of back-up heat for these solar technologies. This temperature match, combined with rapid startup and load following capabilities of aero-derivative gas turbines makes them an excellent match for integration. Utilizing existing turbine plants (brown field) repowered for CSP is an important contributor to reduction in Greenhouse gas emissions. R&D effort is needed to develop methods to assess current plant condition and suitability for CSP operation.

R&D effort is needed in developing high performance blading for CSP conditions (including high moisture) as well as for optimal last stage blades able to cope with significant variations in flow. In addition the volumetric flow of the turbines is high (low pressure) and methods of improving efficiency while keeping physical size as small as possible need improving. In addition further development of steam properties in low pressure high temperature regions will be required.

c) The detailed research issues (blue arrows)

Table 5 Concentrated Solar Power – Overview

Technology Blocks and Research Issues	Timeframe	Costs (50% co-funded)	Total Costs
Advanced steam cycles for CSP Plants	**2011-2017**	**10 M€**	**20 M€**
Large-size steam turbines for direct steam CSP plants, operational flexibility	2011-2017		
Efficient power conversion systems for high temperature media, tower technology	2011-2017		
Optimisation of start-up and shut down as well as load change behaviour and advanced CSP components and systems	2011-2017		
Advanced flow path and last stage blade design	2011-2017		
Innovative hybrid cycles for CSP	**2011-2017**	**8 M€**	**16 M€**
Proof of concept for innovative hybrid cycles using alternative media such as air, molten salt, etc.,''ORC' thermodynamic data, materials	2011-2017		
Innovative turbine components for solar combined cycles	**2011-2018**	**10 M€**	**20 M€**
Optimised integration of CSP systems with fossil fired power plants, e.g. feed water pre heating	2011-2018		
Solar receiver technology, hot air injection in gas turbine	2011-2018		
Hybrid gas turbine based CSP plants	2011-2018		
Medium-size steam turbines for direct steam CSP plants, steam turbine retrofit/upgrade	2011-2018		
Increased efficiency (GT+ST), minimised energy losses	2011-2018		

NB: Table does not reflect complete costs of developing the technology, cost estimate covers collaborative projects only

6. Nuclear

a) Introduction

For many years the nuclear power industry formed an important part of power generation offering reliable and relatively cheap energy production. After the Fukushima disaster in 2011 the position of Nuclear Power Plants (NPPs) in the world has been significantly shaken with some European countries fundamentally reconsidering the role of nuclear power in their energy mix.

Next generation nuclear power will require new turbomachinery

While the world outlook may be changing over the years to come, for some countries worldwide and also within the EU, nuclear power will still represent a viable option. In spite of current political uncertainty, nuclear power may in the future well complement the generation of electricity from renewable and other environmentally acceptable sources.

Therefore, the technological needs of the nuclear power generation industry have to be considered. Not only additional safety measures resulting from the Fukushima lessons-learned will be implemented, but also innovative yet inherently secure approaches to NPP modernisation, new planning and construction will be required. This applies to the primary nuclear island as well as to the rotating equipment in the energy conversion cycles, specifically for turbomachinery.

b) Technology blocks (red arrows)

Advanced large NPP Steam Turbines

Until recently, large power plants including NPPs have been expected to cover mainly the base load electricity generation. The recent developments have shown the necessity to change this approach – load changes with short reaction times are required even from medium and all large power plants gradually shifting such requirements also into the NPP segment. This is predominantly due to the increasing volume of the energy produced from the renewable sources. (cf. chapter on flexibility)

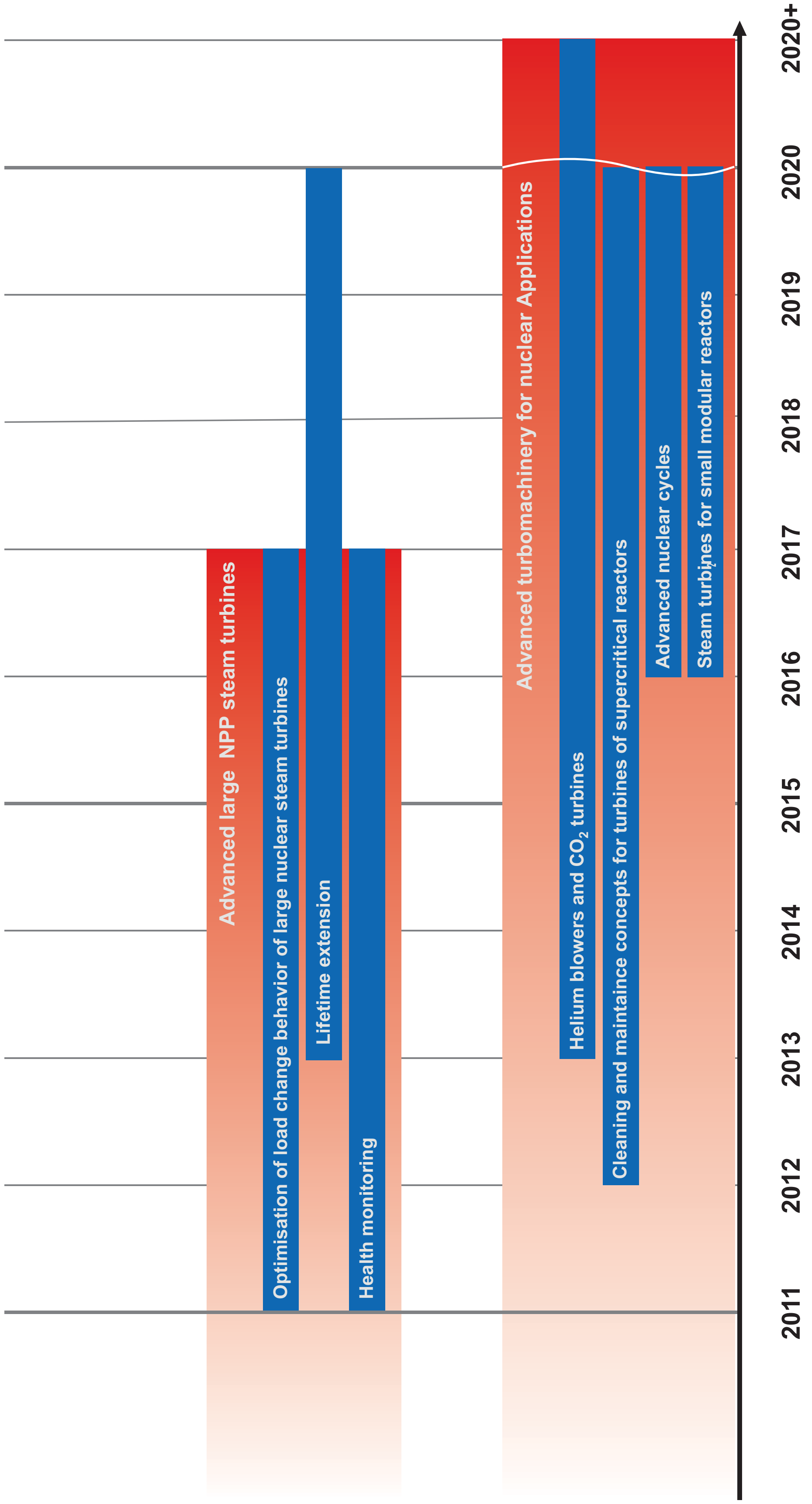
While innovative concepts of reactors for so called Generation IV are currently underway, fast load change capability and flexibility will be required both for existing and newly built nuclear power plants with reactors of the Generation III and III+. This means that the future development of turbines, their auxiliaries, control and diagnostic systems for future NPPs must reflect this changing environment. Reliable turbines with flexible characteristics and long operational life are needed for current and future NPPs.

In fact, the flexibility is expected from existing turbines while maintaining or even extending their original design lifetime.

Advanced turbomachinery for nuclear applications

The new situation around nuclear power generation requires new technological concepts. On the one hand nuclear power stations have also to become more efficient, flexible and safer (Generation IV), on the other hand completely new ideas such as very small reactors are in discussion. These new concepts require specific turbines and compressors.

Nuclear


Advanced large NPP steam turbines
Optimisation of load change behavior of large nuclear steam turbines
Lifetime extension
Health monitoring
Advanced turbomachinery for nuclear Applications
Helium blowers and CO_2 turbines
Cleaning and maintaince concepts for turbines of supercritical reactors
Advanced nuclear cycles
Steam turbines for small modular reactors
2011
2012
2013
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2020
2020+

c) The detailed research issues (blue arrows)

Table 6 Nuclear – Overview

Technology Blocks and Research Issues	Timeframe	Costs (50% co-funded)	Total Costs
Advanced Large NPP Steam Turbines	**2011-2017**	**10 M€**	**20 M€**
Optimisation of load change behaviour of large nuclear steam turbines	2011-2017		
Lifetime extensions	2013-2020		
Health monitoring	2011-2017		
Advanced Turbomachinery for nuclear applications	**2012-2020+**	**6 M€**	**12 M€**
Helium blowers and CO_2 turbines	2013-2020+		
Cleaning and maintenance concepts for turbines of supercritical reactors	2012-2020		
Advanced nuclear cycles	2016-2020		
Steam turbines for small modular reactors	2016-2020		

NB: Table does not reflect complete costs of developing the technology, cost estimate covers collaborative projects only

Glossary, Figures and Tables

BAT	Best Available Technology
BWR	Boiling water reactor
CAES	Compressed Air Energy Storage
CCPP	Combined Cycle Power Plant
CCS	Carbon Capture and Storage
CFD	Computational fluid dynamics
CO_2	Carbon dioxide
CSP	Concentrated Solar Power
EEAP	Energy Efficiency Action Plan
EERA	European Energy Research Alliance
EII	European Industrial Initiative
FPP	Floating Power Plant
GFR	Gas Cooled Fast Reactor
GT	Gas turbine
H_2	Hydrogen
H_2O	Water
HRSG	Heat Recovery Steam Generator
IGCC	Integrated gasification combined cycle
ISCCS	Integrated Solar Combined Cycle Systems
LFR	Lead Fast Reactor
LP	Low-pressure
LSBs	Last Stage Blades

LWR	Light Water Reactor
MW	Megawatt
N_2	Nitrogen
NDT	Non Destructive Testing
NOx	Generic term for the mono-nitrogen oxides NO and NO_2 (nitric oxide and nitrogen dioxide)
NPP	Nuclear Power Plants
NSE	Navier-Stokes' equations
ORC	Organic Rankine cycle
PV	Photovoltaics
R&D	Research and Development
SCWR	Supercritical water reactor
SET-Plan	Strategic Energy Technology Plan
SFR	Sodium Cooled Fast Reactor
ST	Steam Turbine
TBC	Thermal Barrier Coating
TIT	Turbine Inlet Temperature
VHTR	Very high-temperature reactor

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