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Research and development for turbo machinery-based electric generation in a sustainable energy system

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2003-10-06

SUMMARY

The overall goal of the Swedish Energy Agency is the adjustment of the current Swedish energy system to a future sustainable energy system with requirements for CO2 free processes, low emissions, high efficiencies, low cost and high availability. The future processes also would be fuel-flexible and have the quality to produce secondary products such as chill/heat/steam.

Gas turbines, compressors and expanders will be the key components when introducing the “Green electricity”. These components are all vital parts in future CO2-free fuel-based processes as well as in Combined Cycles, IGCC, CHP and Gas compressor stations (mechanical drive). They are also key components in new processes such as the Humid Air Turbine, the Trigeneration turbine, the Air Bottoming Cycle and cycles combining bio-mass fuels and natural gas

The economy of scale for the different techniques is discussed. The gas turbine itself could be a small-scale technology if suitable fuel is available, while some of the fuel production techniques are large-scale techniques for cost reasons. Some other techniques produce fuels which cannot be distributed over a long distance and also has to be of a big scale for cost reasons and therefore also the gas turbine in some cases has to be of a big scale. It is therefore a big challenge to develop small-scale technology for electricity production based on biomass.

A brief U.S. outlook shows a renewed interest in IGCC research. It appears for example in the new U.S. project “FutureGen – A Coal-Fuelled Prototype for a Hydrogen Production/Carbon Sequestration Power Plant”. This is a $1 billion dollar project which is intended to build the world’s first integrated sequestration and production research zero-emission coal power plant. The plant will produce electricity and hydrogen from coal, while capturing and sequestrating the CO2 generated in the process. The project will employ coal gasification integrated with combined-cycle electricity generation and sequestration of CO2. The time frame for the project is 10 years and an industrial consortium representing the coal and power industries will lead it. The DoE’s research attention turned to the next-generation gas turbines that will be capable of burning coal-derived gases at the same high levels of efficiency as natural gas-fuelled turbines due to increasing natural gas prices in the U.S. coinciding with an abundance of low-cost coal.

Within the GTC program, three case studies have been performed for “CO2 Neutral Turbines” with expected characteristics for the next-generation gas turbines with the sight 5-10 years:

- Hydrogen fuel
- Bio-mass fuel
- CO_2 capture and sequestration
  - New cycles
  - Known cycles

These three CO2-Neutral Turbines have been compared with the expected characteristics for natural gas-fired gas turbines in the same time period.

The development of the natural gas-fuelled gas turbines is focused on the improvement of efficiency, energy density, lifing and durability. The main focus for the development of the natural-fuelled gas turbines is the increase of Turbine Inlet Temperature (TIT) and Pressure Ratio (Π). Large gas turbines for power generation today reach TIT=1500°C and the most advanced aero engines reach TIT=1600°C. The ongoing development of the gas turbine further decreases the emissions of NOx, CO and unburned hydrocarbons (HC) toward practically zero levels. The focus today is to reduce NOx with CO and HC emissions remaining extremely low. The "benchmark" value of NOx for modern power-generation gas turbines is 25 ppm @15% O2. In California and Japan, the requirements for large gas turbines are 9 ppm, which the gas turbine manufacturers will meet. Locally in California the requirement today is even more stringent, 3 ppm. Also looking at the smallest gas turbines, microturbines for distributed generation, the U.S. DoE goal is 7 ppm.

There are several processes which have been proposed for CO_2 capture and sequestration in power production processes. This study has been focused on the following three processes:

- Humid air
- Oxygen rich atmosphere. Mixed Conduction Membrane, MCM, reactor. Combustion in an O_2/ H_2O/CO_2 atmosphere
- CO_2 atmosphere. Air separation process producing O_2. Stoichiometric combustion in O_2/ CO_2 atmosphere

It has also been identified that there is no common bio-mass gas turbine. The performance and design features of bio-mass-fuelled gas turbines therefore have been evaluated for each fuel due to large variations in properties. These alternative bio-mass fuels have been evaluated:

- LCV gas: Gasified bio-mass.
- MCV gases: Pyrolysis gas, landfill gas and sewage gas.
- Wood sawdust
- Bio-oils: Pyrolysis oils and oils derived from synthetic gas
    - Pyrolysis oils
    - Oils derived from synthetic gas
- Alcohol: Methanol, ethanol
- Dimethylether, DME, (CH_3-O-CH_3)

The impact of these CO2 capture and sequestration processes, as well as the impact of the hydrogen and bio-ass derived fuels on the gas turbine cycle, fuel system, combustor, turbine, heat exchangers, materials are identified and discussed.

The research areas which are necessary to facilitate the "CO2 Neutral Turbines" have been identified and tabled. The research areas are related to the research going on for the natural gas-fuelled gas turbines. A number of research topics also have been identified. The relevance of these topics for the different Turbines has been identified.

NOMENCLATURE

AFR	Air Fuel Ratio
CHP	Combined Heat and Power
CLC	Chemical Looping Combustion
CO	Carbon Monoxide
DLE	Dry Low Emission
DME	Dimethylether
EVGT	Evaporative Gas Turbine
HAT	Humid Air Turbine
HC	Hydrocarbons
HEET	High Efficiency Engines and Turbines (U.S. Research Program)
HHV	Higher Heating Value
IGCC	Integrated Gasification Combined Cycle
LHV	Lower Heating Value
LPP	Lean Premixed Prevapourized
MCM	Mixed Conduction Membrane
MCV	Medium Calorific Value
NOx	Nitrogen oxides
RAM	Reliability, Availability and Maintainability
TBC	Thermal Barrier Coating
TBO	Time Between Overhaul
TIT	Turbine Inlet Temperature
Π	Pressure Ratio

CONTENTS

1. ELECTRIC GENERATION IN A SUSTAINABLE ENERGY SYSTEM

The overall goal of the Swedish Energy Agency is the adjustment of the current Swedish energy system to a future sustainable energy system with requirements for CO2 free processes, low emissions, high efficiencies, low cost and high availability. This profile with focus on sustainable energy use and environmental concern means that the following alternative raw energy can be considered:

- Fossil fuels coupled with CO2 capture and sequestration
- Biomass fuels
- Hydrogen fuel
- Water
- Wind
- Solar energy

The electricity generation prime mover alternatives are turbogenerators (steam and gas turbines, hydraulic turbines, wind power plants), piston engines and electrochemical processes (cells). The special design of the turbogenerators for hydraulic and wind power as well as solar cells implies that these prime movers will be left outside the scope of this study. This is also applicable for the piston engines.

The fuel-based CO2-free electric generation processes have the necessary conditions to comply with the requirements of a future sustainable energy system. The future processes also would be fuel-flexible and have the quality to produce secondary products such as chill/heat/steam. The alternative prime movers for these systems are steam turbines, gas turbines, fuel cells and hybrids.

Gas turbines, compressors and expanders will be the key components when introducing the “Green electricity”. These components are all vital parts in future CO2-free fuel-based processes such as:

- Fossil fuel-based systems with CO2 capture and sequestration; all will include gas turbines, compressors and expanders in any form.
- Fuel cells for electricity generation require gas turbines in hybrid systems to obtain high electric efficiency.
- Utilization of bio-mass-derived fuels necessitate compressors and gas turbines to obtain high electricity efficiency
- Utilization of hydrogen requires compressors and gas turbines to obtain high electricity efficiency.

The gas turbines, compressors and expanders also are vital components in Combined Cycles, IGCC, CHP and Gas compressor stations (mechanical drive). They are also key components in new processes such as the Humid Air Turbine, the Trigeneration turbine, the Air Bottoming Cycle and cycles combining bio-mass fuels and natural gas, (hybrid cycles as in Helsingborg, Avedör), etc. Such processes facilitate fuel flexibility, high efficiency and reduced CO2 emissions.

It is of interest to discuss the economy of scale for the different techniques mention above. The gas turbine itself could be a small scale technology if suitable fuel is available. Unfortunately some of the techniques produce fuel which cannot be distributed over a long distance and therefore the gas turbine has to be of a big scale if the fuel preparation plant is of a big scale for cost reasons. Below the techniques a sorted into two groups.

Big scale Techniques (more than 50 Mwe):

- CO2 sequestration techniques
- Hybrid cycles
- Thermal Gasification Techniques
- H2 based techniques

Small scale Techniques (less than 50 Mwe):

- Natural Gas-based Techniques
- Liquid Fuel-based Techniques
- MCV gas-based Techniques

Some interesting research activities are ongoing to change this situation. One example in Italy has Pyrolyse gas from biomass produced in a rotary kill, which is indirectly heated by the hot gas from the char combustion so that the pyrolys gas can be used in a small scale gas turbine (4 MWe). Some reasearch projects are also trying to use direct firing of biomass in small scale gas turbines. Others are trying to make small-scale hybrid plants based on microturbines.

There is a big challenge to develop small-scale technology for electricity production based on biomass.

The gas turbine today dominates the propulsion of aircraft and probably will get an increased importance both for marine- and land-based vehicles. The Swedish strategy to focus on bio-mass means that the gas turbine will be a competitive prime mover in distributed power production, as the gas turbine is commercial in a wide power range from approximately 100kW and up to some hundred MW.

2. BRIEF U.S. OUTLOOK

A renewed interest in IGCC research appears in the new U.S. project “FutureGen – A Coal-Fuelled Prototype for a Hydrogen Production/Carbon Sequestration Power Plant”, Ref. 1. This is a $1 billion dollar project, which is intended to build the world’s first integrated sequestration and hydrogen production research zero-emission coal power plant. The plant will produce electricity and hydrogen from coal, while capturing and sequestration of the CO2 generated in the process. The project will employ coal gasification integrated with combined-cycle electricity generation and sequestration of CO2. The time frame for the project is 10 years andit will be led by an industrial consortium representing the coal and power industries.

Looking at the U.S. DoE Vision 21, Ref. 2, the new approach to producing energy addresses pollution control as an integrated part of high-efficiency energy production. A 21st Century Energy Plant would be fuel-flexible and produce a number of products such as electric power, clean fuels, chemicals or hydrogen. Secondary products such as heat/steam for industrial use also could be produced. The plant has two features:

- The first feature is the focus on environmental issues. Emissions of air pollutants such as sulphur dioxide, nitrogen oxides and mercury would be reduced to essentially zero levels. Emissions of CO2 would be dramatically reduced because of higher efficiency. The plant would also include an option for capturing and sequestering CO2.
- The second feature is the efficiency maximation. The Vision 21 power plant efficiency goal is to achieve systems with 75% (LHV) efficiencies on natural gas fuels and 60% (HHV) efficiencies on coal fuel"

The Vision 21 time schedule includes the development of enabling and supporting technologies by 2012 and the complete virtual demonstration (commercial plant design) of the 21st Century Energy Plant by 2015. Examples of supporting programs:

- Materials:high temperature heat exchanger materials, advanced refractories and hydrogen membrane materials
- Advanced computational modelling and development of virtual demonstration capability
- Advanced controls and sensors
- Environmental control technology: Advanced low-NOx combustion technology, advanced PM control technology, coal combustion by-products management technology, revolutionary approaches to CO2 capture and separation, and integration of energy systems with terrestrial sinks

The DoE is concluding in Ref. 3 that "gas turbines will dominate the choice of technologies for new power plants in the United States. Clean, increasingly fuel-efficient and relatively low-cost gas turbine technology could be installed in nearly 90 percent of the electric power plants to be built in the United States between 2000 and 2020". In this context, the follow-on program to the ATS program, Ref. 4, called the High Efficiency Engines and Turbines (HEET) Program, Ref. 3, is in process. The products of the DoE's HEET Program are a new generation of turbines which are rugged, reliable, and durable enough to handle coal-based or other hydrocarbon fuels. These turbines will be critical components of the Vision 21 concept. The program performance goals are:

- To develop advanced power systems capable of achieving 50% thermal efficiency at a capital cost of $ 1000 per kW or less for a coal-based plant by 2008.
- Reduced life-cycle cost of the plants by 15%.

To achieve the economic performance goals, the turbines' reliability, availability and maintainability (RAM) must be enhanced. As turbines are pushed to operate in increasingly more severe environments, new sensors and controls will be needed to adjust for optimum performance and signal the onset of potentially damaging operating conditions.

The DoE's research attention turned to the next- generation gas turbines that will be capable of burning coal-derived gases at the same high levels of efficiency as natural gas-fuelled turbines due to increasing natural gas prices in the U.S. coinciding with an abundance of low-cost coal.

3. CO2 NEUTRAL TURBINES

Based on the technology's past history, it can be assumed that the timing for the development of a new gas turbine will take 5-10 years, while the development of a new gas turbine concept will take 10-15 years.

Within the GTC program, three case studies will be performed for "CO2 Neutral Turbines" with expected characteristics for the next-generation gas turbines with the sight 5-10 years:

- Hydrogen fuel
- Bio-mass fuel
- CO_2 capture and sequestration
  - New cycles
  - Known cycles

These three CO2-Neutral Turbines will be compared with the expected characteristics for natural gas-fired gas turbines in the same time period.

The expected gas turbine characteristics and the related research areas will be summarised in a table as a mean for the evaluation of GTC project proposals.

4. GAS TURBINES FOR NATURAL GAS FUEL

The development of the gas turbines is focused on the improvement of efficiency, energy density, lifing and durability for natural gas, diesel and aviation (Jet-A) fuels. Looking at the gas turbines for power generation, natural gas is the dominating fuel. The main focus for the development of the gas turbines is the increase of Turbine Inlet Temperature (TIT) and Pressure Ratio (Π). During the last 40 years, the TIT has increased with about 13 K/year, Ref 5.

The gas turbine pressure ratio and turbine inlet temperature parameters are dependent on the gas turbine size and application. Large gas turbines for power generation today reach TIT=1500°C and the most advanced aero engines TIT=1600°C.

In the simple-cycle application, an increased pressure ratio at a given TIT results in an efficiency increase. Increasing pressure ratio also gives more benefit of increased TIT, resulting in increased power and efficiency. However, when increasing the TIT at a given pressure ratio, the power output increases, while there is a sacrifice of efficiency due to the increased cooling air losses necessary to keep the life of hot parts unchanged.

In the combined cycle, the pressure ratio has a less pronounced effect on efficiency, while increased TIT results in increased efficiency. This means that the optimum cycle parameters are not the same for the combined cycle as for the simple cycle. The simple cycle maximum efficiency is achieved with high-pressure ratios, while the combined cycle maximum efficiency is obtained at lower pressure ratios and higher TIT.

When increasing the cycle parameters, the cooling of the first stage turbine nozzle has an essential impact on the cycle performance. Air cooling has been extensively developed and used in all aero engines and also in the power generation engines. However, increased TIT has pushed the steam-cooled nozzle development. This cooling technology has a twofold positive effect on efficiency and power output: reduced nozzle material temperature at a given TIT, and a reduced gas temperature reduction between nozzle and rotor

A general summary of the today gas turbine parameters is tabled below.

	Pressure ratio	TIT
	Bar	°C
	Today	Today
Power generation		
• Combined and simple cycle	10-40	->1500
• Recuperated cycle	<10	->1100
Aero engines	20-40	->1600
Microturbines (Recuperated cycle)	4-6	1000

The ongoing development of the gas turbine further decreases the emissions of NOx, CO and unburned hydrocarbons (HC) toward practically zero levels. The focus today is to reduce NOx with CO and HC emissions remaining extremely low. The "benchmark" value of NOx for modern power-generation gas turbines is 25 ppm @15% O2. In California and Japan, the requirements for large gas turbines are 9 ppm, which the gas turbine manufacturers will meet. Locally in California the requirement today is even more stringent, 3 ppm. Also looking at the smallest gas turbines, microturbines for distributed generation, the U.S. DoE goal is 7 ppm.

The efficiency of the gas turbines is depending on the turbine size. The today status of the compressor, turbine efficiency, as well as the today status and 10-years sight of the turbine inlet temperature and thermal efficiencies, are tabled below.

The gas turbine availability has been increasingly important when the gas turbine now is used for base-load power generation. The today figures are included in the table below.

Power	Turbine inlet temp		Pressure ratio, Π	Compr. eff.	Turbine eff.	Thermal efficiency	
	Today	10 years sight	Today			Today	10 years sight
MW	°C			%	%	%	
Simple cycle, non recuperated							
5-15	1100	1315 $^{\text{Rem.1}}$	10->20			31->35 $^{\text{Rem7}}$	40 $^{\text{rem.1}}$
40	1400	1650 $^{\text{Rem 8}}$	20->30 $^{\text{Rem2}}$	92	91	37->40 $^{\text{Rem2}}$	45-47 $^{\text{Rem3}}$
100	1400	1650 $^{\text{Rem 8}}$	15-20			37-40	45-47 $^{\text{Rem3}}$
Simple cycle, recuperated							
0.1	1000	1350 $^{\text{Rem6}}$	4-6			32	40 $^{\text{Rem5}}$
5-15	1100	1350 $^{\text{Rem6}}$	9-10			40 $^{\text{Rem4}}$	

Remarks:

1. ATS program < 20 MW engines: Allison 701-K, 13.5 MW (size interval 5-15MW), Ref. 4, 6,
2. GE LM6000, Ref. 7
3. DoE goal: Flexible Midsize Gas Turbine, FMGT, Ref. 4, 6
4. Solar Mercury 50, Ref. 4, 6
5. DoE goal: Microturbines, Ref. 8
6. Ceramic turbines. US, European and Japan programs for small ceramic gas turbines
7. Solar Titan, 14.3 MW, Ref. 7
8. DoE goal: Fuel-flexible Turbines, Ref. 2

5. HYDROGEN GAS TURBINE

5.1 Hydrogen specific properties

Hydrogen is in some respects an ideal fuel for combustion, clean burning and no CO2 production. However, there are a number of specific parameters which have to be taken into account when hydrogen is used for gas turbine applications. In the table below, important differences compared to natural gas are tabled.

	Hydrogen	Natural gas
LHV, MJ/kg	119.8	48
LHV, MJ/scm	10.2	37
Wobbe index, MJ/scm	38	48
Dissociated stoichiometric temperature, °C	2097	1950
Flammability limits, vol%	4-75	4.8-14.7
Laminar flame speed at 20°C, m/s	2.7	0.37
Auto-ignition temperature, °C	550	570

5.2 Performance and design features of hydrogen-fuelled gas turbine

5.2.1 Advantages of hydrogen as a gas turbine fuel.

- No CO2 production
- No CO, unburned hydrocarbons or soot emissions

5.2.2 Specific problems and design features of hydrogen-fuelled gas turbines.

Fuel system

- Aging embrittlement of fuel system materials. Changed material grades.

Combustor

A major development effort has to be focused on the combustor design. Even if hydrogen is a clean and from the scientific point of view, a well-known fuel, the combustor concepts for this gas are not common.

- Fuel injection. Due to the high flame speed, the flame can stabilise on the fuel injector. Measures therefore have to be taken to avoid flow separations and to keep high-flow velocity in the injector region. Flame holding adjacent to the fuel injector otherwise will cause material over-temperatures and structural problems.

- Fuel/air mixing. In low NOx combustors, fuel and air is premixed to produce a homogeneous mixture prior to combustion. In the case of hydrogen, the high flame speed means an obvious risk of flashback and also a risk of detonation. Therefore premixing is not an alternative for hydrogen fuel.

  However, to obtain low NOx emissions, a homogeneous fuel/air mixing is a necessity. Also looking at the dissociated stoichiometric temperature, 2097°C compared with natural gas 1950°C, this is even more important than for the natural gas-fuelled gas turbines. Because of the low density of hydrogen, jets are strongly deflected by the air stream and the mixing process is more difficult. Therefore hydrogen fuel most probably has to be distributed and mixed locally into the combustion zone.

- Combustor volume and gas turbine turn down ratio. Due to the higher value of hydrogen flame speed, 7x natural gas, it is reasonable to assume that hydrogen can be burned to a lower Φ-value. This means a smaller combustor volume and also that a wider operation window can be obtained for hydrogen-fuelled gas turbines

- NOx emissions. As noted above, the higher stoichimetric temperature of hydrogen requires a homogeneous fuel/air mixing to reduce NOx emissions. However, due to the wider flammability limits and the higher flame speed, it will be possible to operate the hydrogen combustor at a lower temperature, which means the potential to achieve ultra-low NOx emissions if the perfect hydrogen/air homogeneity can be obtained.

Turbine

- The properties of the working gas to the turbine will change from natural gas to hydrogen fuel according to the table below (at reference condition 15% O2)
- The increased H_20 concentration in the combustion gas leads to new turbine issues to be studied:
  - The TIT level has to be studied from the cycle point of view.
  - Improvement to the turbine cooling, internal convective cooling, external film cooling, steam cooling, new concepts.
  - The lifing has to be further studied and developed due to the humid, high temperature atmosphere.

	Hydrogen	Natural gas
AFR	103.6	16.6
Equivalence ratio (dry)	0.333	0.305
R, J/kg, K	305.1	291.8
M	27.25	28.5
Cp, J/kg, K	1046	998
Exhaust composition, vol%:		
H2O	13.9	6.9
CO2	0	3.2

5.3 Optimised gas turbine parameters

The evolution of the pressure ratio and TIT will follow the natural gas-fuelled gas turbine.

5.4 Specific research areas

- Fuel system materials
- Fuel injection systems
- Fuel/air mixing
- Turbine cooling

6. BIO-MASS GAS TURBINE

6.1 Bio-mass fuels for gas turbines

Alternative bio-mass fuels for the gas turbines are:

- LCV gas: Gasified bio-mass.
  - Main combustible species: H2, CO, CH4
  - Inert gases: N2 + CO2
  - LHV: 4.5-6 MJ/Nm3

- MCV gases: Pyrolysis gas, landfill gas and sewage gas.
  - Main combustible species: CH4
  - Inert gases: CO2 and N2
  - LHV: 18-21 respectively 21-26 MJ/Nm3

- Wood sawdust
  - Wood particle size < 2 mm
  - Moisture content into the combustor 20-25%. Dried from 35-50%
  - LHV, 18-20 MJ/kgdry
    14-15 MJ/kg at 20-25% moisture
  - High alkali content
  - Relatively low ash melting temperature

- Bio-oils: Pyrolysis oils and oils derived from synthetic gas
  - Pyrolysis oils
    LHV: 16-18 MJ/kg
    High content of water and oxygen
    High viscosity
    High alkali content

  - Oils derived from synthetic gas
    LHV: 43-47 MJ/kg
    Clean oil, which can be adapted to any fuel oil quality such as diesel fuel and Jet-A

- Alcohol: Methanol, ethanol
  - LHV: 19.8 respectively 27 MJ/kg
    Clean combustible fuels

- Dimethylether, DME, (CH_3-O-CH_3)
  - LHV: 31.8 MJ/kg
    Boiling point: 1 bar -24.8°C

20	75
30	96

- Clean combustible fuel which can be injected in gaseous or liquid state.

6.2 Performance and design features of bio-mass-fuelled gas turbine

The advantages and specific problems and design features of bio-mass fuels have to be evaluated for each fuel. The general advantage is the neutral CO_2 production of bio-mass fuels, but besides this, the different gaseous and liquid fuels have to be evaluated separately due to large variations in properties.

6.2.1 LCV gas: Gasified bio-mass.

Gas turbine cycle

- Due to the very low LHV, the gas turbine has to be re-matched. This means that the High Pressure and Power Turbine effective areas have to be increased. An alternative can also be to reduce the compressor effective area.
- A duel fuel system can be necessary to have the possibility of using a separate pilot fuel when burning extreme LCV gas, or if there is a request for a back-up fuel. When natural gas fuel will be used, the performance figures and the runnability have to be evaluated. Measures such as control system modifications, bleed or variable geometry have to be introduced.
- The gasification process can be run at atmospheric or pressurised conditions. In both cases air or bio-gas has to be pressurised to a pressure level 3-4 bar over the gas turbine cycle pressure. This over-pressure will deteriorate the cycle efficiency. The EU project ULECAT was studied as an example of this problem. For the base 2.9 MW gas turbine ($\Pi = 18$) with an atmospheric gasifier, the gas compressor power was calculated to 1.0 MW. This resulted in an efficiency decrease from 32% to 27%.

Combustor

- The LowNOx DLE combustors, which today are standard for industrial gas turbines, will create running problems for LHV values lower than 10 - 15 MJ/Nm3 due to the decreasing stoichiometric temperature. This results in increased HC and CO emissions and combustion stability problems. Therefore a rich/lean concept is more promising.
- The bio-mass-derived LCV gas in general has a high fuel-bound nitrogen content, 500 – 3000 ppm, which means a NOx emission of 40 – 200 ppm @ 15% O2 (conversion rate 80 to 65%) in an conventional or lean combustion process. Therefore the rich/lean concept also is an alternative looking at NOx reduction. Another alternative is the catalytic combustion process with a sectioned catalyst, where a first section will convert a part of the NH3 to N2.

Turbine

- The gasified bio-mass LCV gas in general has a high particle and alkali content. Cleaning processes increase the fuel cost. When optimising the bio-mass IGCC-plant, a reduced gas turbine performance (reduced Π and TIT) can be the best economic alternative.
- Material and TBC development to reduce turbine corrosion and erosion. Improve life and increase TBO.
- Re-matching of the turbines as described above.

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6.2.1.1 Optimised gas turbine parameters

- The high volume of LCV gas to be compressed means that the gas turbine optimum pressure ratio, Π, is decreased compared to a natural gas-fired gas turbine.
- The LCV gases in general are saturated with water at the turbine fuel system entry. This increases the heat transfer coefficients of the combustion gases, which then increase the turbine section metal temperature. TIT therefore has to be reduced to keep the turbine life unchanged. Alternatively, the cooling scheme has to be improved.

6.2.1.2 Specific research areas

- Gas Turbine Cycle rematching/optimisation
- Combustor concepts. Example: Rich/lean, catalytic, etc.
- Turbine cooling
- Turbine materials and coatings to minimise corrosion and erosion (increased lifing and TBO)

6.2.2 MCV gases: landfill gas and sewage gas.

Gas turbine cycle

- The reduced LHV value compared to natural gas can be handled without gas turbine re-matching as for the LCV gas. However, attention has to be made to the control system as the pyrolysis, landfill and sewage MCV gas operating window is smaller than for natural gas (see below). This is an issue especially during the start-up ramp to idle condition. The use of pyrolysis gas from biomass requires special attention to tar-content and particles.

Combustor

- The LowNOx DLE combustors, which today are standard for industrial gas turbines, can create running problems due to the high CO2 content and the absence of H2 and CO when running on landfill gas (LHV=18-21). CO2 reduce the flame speed. CO2 also reduces the adiabatic temperature due to increased specific heat capacity, and also increases the flame radiation resulting in reduced flame temperature. When converting from natural gas to MCV gas, therefore the combustor has to be operated richer. The problems to be solved are ignition, stability and HC / CO emission problems. However, there are no specific NOx emission problems due to the absence of fuel-bound nitrogen.

Turbine

- The MCV gas in general has a high particle, alkali and hydrogen sulphide (H2S) content. The cleaning processes increase the fuel cost and there is an interest in optimising the gas turbine components to cope with the corrosion problems.
- Material and TBC development to reduce turbine corrosion and erosion. Improve life and increase TBO.
- The market for landfill and sewage gas turbines is to be found in the low power range (<5MW). These turbines generally are not optimised for high Π and TIT.

6.2.2.1 Optimised gas turbine parameters

- The high volume of LCV gas to be compressed means that the gas turbine optimum pressure ratio, Π, is decreased compared to a natural gas-fired gas turbine.
- The LCV gases in general are saturated with water at the turbine fuel system entry. This increases the heat transfer coefficients of the combustion gases, which increases the turbine section metal temperature. TIT therefore has to be reduced to keep the turbine life unchanged. Alternatively the cooling scheme has to be improved.

6.2.2.2 Specific research areas

- Gas turbine cycle optimisation
- Combustor concepts: rich/lean, catalytic, etc.
- Turbine cooling
- Turbine materials and coatings to minimise corrosion and erosion (increased lifing and TBO)

6.2.3 Wood sawdust

A program to develop bio-mass as an alternative fuel was performed by Aerospace Research Corporation, USA, 1980 - 1989, supported by the U.S. Department of Energy. This program focused on the evaluation of wood sawdust as an alternative fuel for gas turbines and culminated in the construction and installation of a power plant using a 3 MW Allison T-56 gas turbine at Red Boiling Springs, Tennessee. The turbine was equipped with a two-stage cyclone combustor, Ref 9.

The main conclusions from this project:

- The wood feed system was built up with three rotary valves in series. The third valve served as a fire stop and heat shield for the valves above. Seal materials and pressure-drop equalization were reported as the main problems. Therefore it was reported that long-term operation of the feed system should be a major goal for any future program.

- The two-stage cyclone combustor followed by a hot gas cyclone filter was reported to function well at the reduced gas turbine reduced TIT = 1450 F (see below).
- It was necessary to limit the turbine inlet temperature, TIT, to 1450F = 790 °C to control the rate of ash deposition on the turbine blades and stator.
- Periodic cleaning of the turbine components was necessary. After 26 hours running at 1450 F, the engine was cleaned with walnut hulls. An alternative method is cleaning with high pressure water
- Due to the reduced TIT, the gas turbine efficiency was reduced. From the standpoint of the Allison T-56 engine performance, the loss in power output was an even more significant factor. At TIT = 1494 F, the power output was 700 kW compared with the nominal 3000 kW at the gas turbine design conditions. Therefore either steam or water injection into the combustor or a combination with a humid air system will be required to obtain the gas turbine design power. However, the gas turbine compressor/turbine areas have to be rematched. The compressor surge limit specifically has to be examined.

In Sweden, the development of sawdust combustion in a cyclone combustor has been performed at the Department of Heat and Power, KTH, and at Department of Mechanical Engineering, Luleå University.

6.2.3.1 Optimised gas turbine parameters

- Due to the low ash melting temperature of wood sawdust, the TIT has to be limited. In the Red Boiling Springs plant, TIT was reduced to 1450 F = 790 °C compared with the TIT of approximately 1100°C in modern gas turbines. This means that the specific power output of a gas turbine would be substantially reduced compared with the today natural gas fired turbines. This is also the case for the gas turbine efficiency.

6.2.3.2 Specific research areas

- Gas turbine cycle optimisation
- Cyclon combustor at high combustion temperatures (Red Boiling Spring experienced up to 1450 F = 790°C)
- The use of additives and optimised gas cleaning systems to reduce or eliminate the ash deposits on turbine blades in order to increase the turbine inlet temperature
- Material/coating to minimise corrosion and erosion (increased lifing and TBO)

6.2.4 Bio-oils: Pyrolysis oils and oils derived from synthetic gas

The bio-oils have a general advantage from the transportation point of view. When looking at the gas turbine, however, the oils have to be treated quite differently.

6.2.4.1 Bio-oil derived from synthetic gas

The bio-oil derived from synthetic gas can be adapted to any fuel oil quality such as diesel fuel and Jet-A. There is a possible optimisation of the fuel composition in order to reduce the aromatic content, which makes it possible to increase loading of gas turbines for these fuels compared to gas turbines for the conventional diesel and Jet-A fuels.

Specific research areas

- Turbine cooling

6.2.4.2 Pyrolysis oils

The general pyrolysis oils properties are dependent on the storage time and temperature history due to the fact that these oils will polymerise. Therefore the gas turbine fuel system and components must be capable of adjusting to fuel property variations. These fuels also are toxic due to the content of alkyds, furans and unsaturated oxides.

Fuel system

- Low pH value of the fuel. Choice of material for fuel system components and gaskets.

Combustor

- Pyrolysis oils have a high viscosity. Due to the polymerisation process as described above, the viscosity also will increase with storage time. The fuel injection and fuel/air mixing process therefore have to be evaluated and advanced techniques have to be adopted.
- The ignition and stability performance is deteriorated due to the low LHV and high water content. Special actions have to be taken such as separate ignition fuel or separate ignition injector.

Turbine

- The pyrolysis oils have a high particle and alkali content. When optimising the gas turbine plant, a reduced gas turbine performance (reduced Π and TIT) can be necessary.
- Material and TBC development to reduce turbine corrosion and erosion,improve life and increase TBO.

Specific research areas

- Liquid fuel injection systems
- Liquid fuel/air mixing
- Turbine materials and coatings to minimise corrosion and erosion (increased lifing and TBO)

6.2.5 Alcohol: Methanol and ethanol

Methanol and ethanol are clean fuels from the gas turbine point of view. Experiences show that low HC and CO, as well as NOx emissions, will be obtained. When optimising the gas turbine cycle, there are no specific restrictions. Increased Π and TIT as for the natural gas fuels therefore can be adapted for the gas turbine cycle efficiency optimisation.

6.2.5.1 Specific research areas

- Turbine cooling

6.2.6 DME

DME (Dimethyl Ether, CH3-O-CH3) is a clear and colourless, non-toxic fuel with the following characteristics, Ref 10, 11:

Property	DME (pure)	Comparison: propane
Boiling point, °C at 1 atm	-24.9	-42.1
Vapour pressure at 20°C, bar	5.1	8.4
Liquid density at 20°C, kg/m3	668	501
LHV, MJ/kg liquid	28.4	46.0
Auto-ignition temperature, °C	235	Approx. 500
Lower/upper flammability limit in air, vol%	3.4-17	2.1-9-4

The fuel-grade DME would contain some methanol (approx. 8 wt%), which is toxic.

The DME fuel is supplied to the power plant boundary in liquid state. The fuel is then pumped to the fuel injection pressure and vaporised by utilisation of hot water/steam or exhaust gas. This DME vaporisation increases the cycle efficiency. In the gas turbine, the DME therefore is treated as a gaseous fuel and takes advantage of the DLE NOx combustor technology. However, the auto-ignition temperature of DME is lower than for natural gas, 235°C compared to 540-590°C. This means that special attention has to be paid to the fuel/air premixing in the DLE premix zone.

Test results at General Electric have shown emissions properties and other key combustor parameters, including dynamic pressures and metal temperatures, that are comparable to natural gas, Ref. 12.

DME can be fired in existing gas turbines which use natural gas. The evolution of gas turbine parameters such as pressure ratio, TIT and critical component life will follow the natural gas-fuelled gas turbine.

6.2.6.1 Specific research areas

The DME specific research areas will follow the natural gas-fuelled turbine. However, special attention has to b taken to the fuel/air premixing in the DLN premix zone.

7. GAS TURBINES FOR CO2 CAPTURE AND SEQUESTRATION

There are several processes which have been proposed for CO_2 capture and sequestration in power production processes as described inRef. 13.These methods can be brought together in three groups:

Pre-combustion processes: Fuel reforming or utilisation of bio-mass derived fuels:

- Hydrogen rich fuels: reformed fossile fuels with water shift reaction where CO is converted to CO_2, which results in an energy-rich mixture of hydrogen and CO_2 from which CO_2 can be removed. Combustion in an atmosphere of $H_2/N_2/O_2/$ rest-CO_2. The research areas of gas turbines for this process are similar to the hydrogen gas turbine, chapter 5.
- Weak gas from SOFC
- LCV gas. The development of gas turbines for LCV gas is described in chapter 6.2.1.

Combustion in “new” atmospheres:

- Humid air
- Ethanol in humid air
- Oxygen rich atmosphere. Example: Mixed Conduction Membrane, MCM, reactor producing O_2. Combustion in an $O_2/$ H_2O/CO_2 atmosphere with H_2O/CO_2 recirculation. (O_2 produced in the process)
- CO_2 atmosphere. Example: Air separation process producing O_2. Stoichiometric combustion in $O_2/$ CO_2 atmosphere with CO_2 recirculation (O_2 produced outside the process).
- CO2 rich atmosphere. Chemical Looping Combustion, CLC.

Post-combustion processes:

- CO_2 removal from exhaust gas.

In CO2 capture and sequestration power production processes, CO_2 has to be compressed to the level 70 bar. This means that high-pressure compressor research also will be included in the future programs.

This study will focus on the following three processes and the CO_2 compressor:

- Humid air
- Oxygen rich atmosphere. Mixed Conduction Membrane, MCM, reactor. Combustion in an $O_2/$ H_2O/CO_2 atmosphere

- CO_2 atmosphere. Air separation process producing O_2. Stoichiometric combustion in O_2/ CO_2 atmosphere

7.1 Humid air

In the Humid Air Turbine (HAT) or the Evaporative Gas Turbine (EVGT), the energy in the exhaust gas is recovered directly into the gas turbine cycle, which results in a substantially increased thermal efficiency. In the cycle, heated water is vaporised in the compressed air from the compressor, resulting in increased mass flow to combustor and turbine, hence higher specific power output and efficiency due to the added water vapor. The key components in this cycle are:

- Gas turbine
- Recuperator
- Aftercooler
- Humidification tower
- Economiser
- Exhaust gas condenser

From the CO_2 capture and sequestration point of view, this process is of interest due to the increased thermal efficiency and to the increased CO_2 concentration in the exhaust gas after the water vapor is condensed.

The main characteristics of a gas turbine for the HAT or EVGT cycle can be summarised as follows:

- Compressor/turbine rematched compared to a simple cycle resulting in an increased turbine area or a decreased compressor/increased turbine area
- Combustion in a humid air atmosphere
- New turbine working gas composition
- New material requirements due the high water vapor content of the working gas
- Recuperator

Gas turbine cycle

The following gas turbine cycle issues have to be studied:

- The cycle has to be optimised with the new working medium regarding compressor/turbine rematching, cycle pressure ratio and TIT.
- Operation range and control philosophy

Combustor

The combustion in humid atmosphere has to be further studied, experimentally and theoretically. The main issues are:

- Choice of combustor concept. Conventional modified diffusion, LPP or catalytic combustor

- Degree of humidification
- Flame stability
- CO, HC and NO_x emissions
- Fuel dependence (natural gas, LCV gas with variation of the H2/CO/CH4/inerts concentration)
- Reaction kinetics modelling

Turbine

The high H_20 concentration in the combustion gas leads to new turbine issues to be studied.

- The TIT level has to be studied from the cycle point of view.
- Improved turbine cooling, internal convective cooling, external film cooling, steam cooling, new concepts.
- The lifing has to be further studied and developed due to the humid, high-temperature atmosphere

Heat exchanger

The heat exchanger, recuperator, and operating temperature is in the order of 500-600°C when burning liquid or gaseous fuels. Alternatively, when utilizing a solid fuel closed cycle, the temperature is equivalent to the turbine inlet temperature which has to be maximised.

Material

Due to the high temperature humid atmosphere, extensive material studies have to be performed. These studies will include long term durability tests on component and system level.

- Metallic high temperature and ceramic materials

7.2 Oxygen rich atmosphere

By integration of a high-temperature gas-separation membrane as an integrated reactor, in which O_2 is separated from air in the gas turbine cycle, the combustion process can occur in an N_2-free atmosphere. Essentially the MCM-reactor, which combines the oxygen-separation, combustion and heat transfer processes, replaces the conventional combustor in a standard gas turbine power plant.

The hydrocarbon fuel will be burnt in an $O_2/H_2O/CO_2$ atmosphere where CO_2/H_2O will be re-circulated within the gas turbine cycle from the exhaust gas. This results in an exhaust gas mainly consisting of CO_2 and H_2O.

In the MCM reactor, oxygen is separated at pressurised, high temperature conditions up to 1200°C. This MCM reactor is an integrated assembly of three components:

- MCM membrane

- High temperature heat exchanger
- Combustor

Gas turbine cycle

The following specific gas turbine cycle issues have to be studied:

- Cycle performance optimisation when including the MCM reactor (membrane, heat exchanger, combustor)
- Life Cycle Cost optimisation due to new operating parameters

Combustor

The $O_2/H_2O/CO_2$ atmosphere and the combustor new operating temperatures (inlet, outlet temperatures required from the gt cycle) mean that new combustor concepts have to be developed.

- Combustion stability within the MCM reactor: stable combustion must be maintained in spite of the necessary high level of exhaust gas dilution (CO_2 and H_2O) and moderate combustion temperatures (<1200°C).
- Alternative combustor concepts: conventional homogeneous combustion and catalytic combustion.

Turbine

The high CO2 concentration in the combustion gas leads to new turbine issues to be studied.

- The TIT level has to be studied from the cycle point of view.
- The increased radiation of the CO_2 atmosphere means that there is a necessity to improve the turbine cooling, internal convective cooling, external film cooling, steam cooling, and new concepts.
- The lifing has to be further studied and developed due to the high temperature CO_2 atmosphere.

Heat exchanger

The high temperature heat exchanger is one of the three integrated with the MCM reactor. Due to the operating temperature 450 to 1250°C the design and material choice are of vital importance. SiC is the most likely candidate material due to its heat exchange capability and thermo-mechanical stability.

7.3 CO_2 atmosphere

The CO2/oxygen cycle ("oxy-fuel") as described in Ref. 13 is characterised by near stoichiometric combustion with oxygen in a Gas Turbine Combined Cycle using a semi-closed gas cycle with CO2 re-circulation.

The oxygen is produced in an air separation process outside the gas turbine cycle. A hydrocarbon fuel (ex: natural gas) is burnt at near stoichiometric condition which produce CO2 and H2O as the combustion products. In order to keep the combustion temperature at permissible limits in the gas turbine hot section, most of the CO_2 is re-circulated after the exhaust gas is cooled and water is condensated and separated.
The gas turbine working medium is mainly CO_2 and the water produced from the hydrocarbon combustion.

There are a number of challenging research and development areas for achieving the optimal process. Specifically, the power cycle has to be studied as well as the combustion process in a "new atmosphere" and the turbine design with the CO_2/H_2O working medium.

Gas turbine cycle

The following gas turbine cycle issues have to be studied:

- The semi-closed CO_2 Gas Turbine Combined Cycle has to be optimised with the new working medium regarding cycle pressure ratio, TIT.
- Performance impact due to increased turbine-cooling requirement.
- Operation range and control philosophy for the integrated air separation and GT Combined Cycle processes.

Combustor

In Ref. 13, the combustor research and development issues have been discussed. Simulation of combustion with oxygen at near-stoichimetric conditions in a CO_2-rich atmosphere showed extremely high peak temperatures, which led to high NO_x formation even with small amounts of N_2 and to high levels of radiative heat transfer to the nozzle and combustor walls. They also showed incomplete combustion (that is, high levels of CO, H_2 and OH) due to the near-stoichiometric conditions. Therefore, the challenges of this concept are:

- Obtaining sufficient mixing of fuel and O_2
- Avoiding excessive levels of CO
- Handling radiation due to high peak temperature

The combustion in CO_2 atmosphere has to be further studied, both experimentally and theoretically. Model development and validation is essential for the further development of the CO_2 atmosphere combustion.

Turbine

The high CO2 concentration in the combustion gas leads to new turbine issues to be studied.

- The TIT level has to be studied from the CO dissociation point of view.

- The increased radiation of the CO_2 atmosphere means that there is a necessity to improve the turbine cooling, internal convective cooling, external film cooling, steam cooling, new concepts.
- The lifing has to be further studied and developed due to the high temperature CO_2 atmosphere

8. SUMMARY OF RESEARCH AREAS OF THE CO2 NEUTRAL TURBINES

Three case studies have been performed for " CO2 Neutral Turbines" where the characteristics and the technology barriers have been identified for the next generation gas turbines with the sight of 5-10 years:

- Hydrogen fuel
- Bio-mass fuel
- CO_2 capture and sequestration

The natural gas-fuelled gas turbine characteristics today with the sight of 5-10 years have been identified as a basis of this study.

The research areas, which are necessary to facilitate the three "CO2 Neutral Turbines", have been identified in Table 1.

In Table 2, a number of research topics have been identified. The relevance of these topics for the different Turbines has been identified. It should be noted, however, that the scope of work is not the same for all turbines (example: cycle optimisation, fuel injection, etc. is specific for each gas turbine alternative).

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10. TABLES

1. Research areas which are necessary to facilitate the three “CO2 Neutral Turbines”. The natural gas-fuelled gas turbine has been identified as a basis.
2. Identified research topics for the different “CO2 Neutral Turbines”.

Gas turbine	Gt cycle	Compressor	Combustor	Turbine	Heat exchanger	Material
0. Reference case. Gas turbine for natural gas.	• Recuperated cycles	• Increased Pressure ratio, Π	• Mixing quality • Low emission combustion • Cooling • New concepts • Increased COT	• Increased TIT • Cooling	• Recuperator	• High temperature metallic materials • Ceramics
Specific issues beyond the scope of the natural gas-fuelled gas turbine						
1. Hydrogen gas turbine			• Fuel injection • Fuel/air mixing	• Cooling		• Fuel system materials (ageing embrittlement)
2. Bio-mass gas turbines						
2.1. LCV gas: Gasified bio-mass	• Rematching / optimisation		• Combustor concepts (Rich/Lean, catalytic, etc.)	• Rematching/redesign • Material/coating to minimise corrosion and erosion (increased lifing and TBO) • Cooling due to increased heat transfer from humid combustion gases		• Material/coating to minimise corrosion and erosion (increased lifing and TBO)
2.2. MCV gases: Landfill gas and sewage gas	• Optimisation		• Combustor concepts (Rich/Lean, catalytic, etc.)	• Material/coating to minimise corrosion and erosion (increased lifing and TBO) • Cooling due to increased heat transfer from humid combustion gases		• Material/coating to minimise corrosion and erosion (increased lifing and TBO)
2.3. Sawdust	• Optimisation		• High temp sawdust combustion • Gas cleaning	• Material/coating to minimise corrosion and erosion (increased lifing and TBO)		• Material/coating to minimise corrosion and erosion (increased lifing and TBO)
2.3. Bio-oil derived from synthetic gas				• Cooling		
2.4. Pyrolysis oil			• Cooling	• Cooling		• Material/coating to

			• Liquid fuel injection • Liquid fuel/air mixing	• Material/coating to minimise corrosion and erosion (increased lifing and TBO)		minimise corrosion and erosion (increased lifing and TBO)
2.5. Alccohol				• Cooling		
2.6. DME						
3. Gas turbines for CO2 capture and sequestration						
3.1 Humid air	• Optimisation (Π, TIT etc.) • Control philosophy		• Combustor concepts (Conventional modified diffusion, LPP, catalytic, etc.) • Degree of humidification • Fuel dependence • Combustion kinetics	• Cooling • Lifing	• Recuperator	• Metallic high temperature materials • Ceramics
3.2. Oxygen rich atmosphere	• Optimisation when includiing MCM reactor (membrane, heat exchanger, combustor) • Life Cycle Cost optimisation		• Combustor concepts (Conventional modified diffusion, LPP, catalytic, etc.) • Combustion parameters due to new atmosphere (stability, emissions, etc.)	• Cooling • Lifing	• Recuperator	• Metallic high temperature materials • Ceramics
3.3. CO2 atmosphere	• Optimisation (Π, TIT etc.) • Control philosophy		• Combustor concepts (Conventional modified diffusion, LPP, catalytic, etc.) • Combustion parameters due to new atmosphere (stability, emissions, etc.)	• Cooling • Lifing		• Metallic high temperature materials • Ceramics

Table 1. Research areas which are necessary to facilitate the three “CO2 Neutral Turbines”. The natural gas-fuelled gas turbine has been identified as a basis.

Research topic	Natural gas	Hydrogen	Bio-mass							CO2 capture and sequestration		
			LCV gas	MCV gas	Sawdust	Bio-oil from synthetic gas	Pyrolysis oil	Alcohol	DME	Humid air	Oxygen rich atmosphere	CO2 atmosphere
Cycle optimisation			x	x	x					x	x	x
Increased Π	x	x				x			x	x	x	x
Increased TIT	x	x				x			x	x	x	x
Aero-elastics	x	x				x			x	x	x	x
Combustor cooling	x	x			x	x	x	x	x	x	x	x
Fuel injection		x	x	x	x	x	x	x	x	x	x	x
Fuel/air mixing	x	x	x	x	x	x	x	x	x	x	x	x
Combustor concepts	x	x	x	x	x	x	x	x	x	x	x	x
Turbine cooling	x	x			x	x	x	x	x	x	x	x
Heat exchangers	x	x							x	x	x	
Metallic high temp. materials	x	x	x	x	x	x	x	x	x	x	x	x
Ceramic materials	x	x	x	x	x	x	x	x	x	x	x	x
Lifing	x	x	x	x	x	x	x	x	x	x	x	x

Table 2. Identified research topics for the different “CO2 Neutral Turbines”