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Short Summary

Author/Corresponding author(s)	DLR: Melanie Herbst, Martina Hohloch UNIGE: Mario L. Ferrari RINA: Lorenzo Dall'Oro MTT: Luc Hamilton Hiflux: David Barnes
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List of Acronyms

Bio-HyPP	Biogas-fired Combined Hybrid Heat & Power Plant (project name)
CHP	Combined Heat & Power
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center)
FC	fuel cell
FLOX®	flameless oxidation
HyPP	Hybrid power plant
kW	kilo Watt
MGT	micro gas turbine
MGT test rig	Hybrid power plant test rig consisting of real MGT and emulated SOFC
MTT	Micro Turbine Technology B.V.
PI	proportional integral
PID	proportional integral derivative
PLC	programmable logic controller
LCA	life cycle assessment
LCC	life cycle cost
LEAP	low emission advanced power systems
SLCA	social life cycle analysis
SOFC	solid oxide fuel cell
SOFC test rig	Hybrid power plant test rig consisting of real SOFC and emulated MGT
UNIGE	University of Genoa
TU/e	Technical University of Eindhoven
WP	work package

1 Introduction / Summary

The Bio-HyPP project has aimed to generate and publish knowledge about hybrid power plants fed by different biogas compositions, consistently improving the efficiency of CHP systems while simultaneously widening the biomass feedstock base as well as increasing operational flexibility [36]. A hybrid power plant combines two subsystems - a solid oxide fuel cell (SOFC, subsystem 1) and a micro gas turbine (MGT, subsystem 2) [27]. It is suitable for usage as a combined heat and power plant. The focus of the project has been the experimental demonstration of the technology to prove the functional capability of the plant concept, followed by detailed characterization and optimization of the integration of both subsystems. At the same time the characteristics of the single components were analysed and optimized.

The hybrid power plant has been investigated in two different layouts reflecting these subsystems to prove the concept and characterize components: the aim of the top-performance layout has been to utilise the SOFC for maximum efficiency while the aim of the top-economic layout has been to utilise standard components within a hybrid power plant for low cost. For the top-performance layout, two separate test rigs have been set up and investigated: an MGT test rig with emulated SOFC and an SOFC test rig with emulated MGT. Building a demonstrator of a real coupled hybrid power plant has not been reached within the project, as insights on the two separate test rigs showed the necessity of concept adaptations. Therefore, in this layout, the focus has been towards characterization of the MGT and SOFC subsystems, their component characteristics and their interactions and influences on each other. The top-economic layout demonstrator, consisting of a turbocharger and a fuel cell emulator, has been set-up and characterized [18].

For the **top-performance layout** the MGT and SOFC subsystems and subcomponents have been characterized, adjusted and optimized by a multidisciplinary design approach using numerical and experimental measures to ensure a proper balance of plant. Therefore, emulation plants have been used for characterization of the subcomponents and to develop a suitable control system - taking into account both the necessary SOFC and the MGT system specifications. Two separate test rigs for the top-performance layout have been set-up and experimentally analysed:

- the MGT hybrid power plant test rig (real MGT with emulated SOFC) and
- the SOFC hybrid power plant test rig (real SOFC with emulated MGT)

In addition, an integrated control system has been developed and implemented to achieve a reliable operation of the coupled subsystems.

Several key components of the hybrid power plant have been analysed, optimized and demonstrated within the project: the MGT components turbine, compressor, generator, recuperator and a combined combustion chamber suitable for SOFC off-gas and natural gas /

biogas. Knowledge of control concepts has been developed and demonstrated for safe transient operation such as start-up, load changes, shut down and emergency conditions.

The **top-economic layout** has been studied at the University of Genoa from both theoretical and experimental point of views. The designed system is based on the coupling of the SOFC subsystem with a turbocharger instead of a micro gas turbine. This subsystem also includes a recuperator manufactured with standard materials (stabilised stainless steel) for cost containment reasons. Pressurising the SOFC using a turbocharger instead of a micro gas turbine is a solution which combines high efficiency (the pressurized SOFC) with reduced-cost plant layout (the turbocharger). The utilization of turbochargers can produce a significant cost decrease, due to the mass manufacturing of these automotive components and the removal of electrical generator and power electronics.

The experimental activities on this type of plant have been carried out with a new emulator test rig based on the turbocharger, recuperator, pressure vessel components, including inert ceramic materials and two burners necessary for obtaining the temperature values of a real SOFC system. Thanks to a real-time connection with a dynamic model, the system emulation has been carried out in cyber-physical mode (the model has been used to calculate the performance of components not physically present in the rig). The results have been able to demonstrate the feasibility and the operability of this innovative layout during dynamic conditions.

The experimental work has been accompanied by numerical investigations using different tools, not only to determine the optimization issues relating to these components and the plant layout, but also to verify control strategies. The tools were validated using the experimental data.

Furthermore, a detailed analysis of different **European markets**, economic and technical constraints in terms of biogas production potentials has shown the suitable regional sizes and attractive performance conditions of the power plant system. To identify **cost reduction potentials** an economic analysis has been performed.

2 Project technical description and implementation

The project has been divided into 6 work packages (WP) with 4 of them being technical:

- WP1: Hybrid power plant system analysis
- WP2: Component development and optimisation
- WP3: Subsystem testing and subsystem emulation
- WP4: System Integration and demonstration
- WP5: Dissemination, exploitation and stakeholders engagement
- WP6: Project management and coordination

In order to investigate the biogas-fired hybrid power plant system, the following scientific tasks have been executed.

- Market analysis, identification of possible business models and study of a techno-economic model for the biogas-fired Hybrid Power Plant system. Performance of a sensitivity analysis with respect to the impacts generated by the system though its life cycle, including environmental, economic and social aspects, health and safety and certification analysis of the system and identification of recommendations for further improvement of the system safety (WP1).
- Identification of technical component requirements (WP1) and technical development of new components (WP2).
- Development of integration strategies of both subsystems MGT and SOFC using thermodynamic models, with the aim of demonstrating cost effectiveness (top-economic layout) on one hand and efficiency (top-performance layout) on the other with respect to an optimal matching of the coupled subsystems (WP1).
- Mitigation of coupling risks by characterization of both SOFC and MGT subsystems while emulating the thermodynamic and fluid dynamic properties of the other subsystem (WP3 & WP4).
- Development and implementation of a combined control strategy for the entire system by implementing and testing the control on two separate emulation test rigs. Revision of a coupled Hybrid Power Plant technology demonstrator concept on the basis of top-performance layout (WP4) after characterization and testing on the emulation rigs (WP4). Commissioning of a Hybrid Power Plant technology demonstrator for the top-economic layout based on a turbocharger coupled to an SOFC emulator. Characterization of the entire system (WP4).

In addition to the scientific research activities a detailed analysis of different European markets, economic and technical constraints including legislative framework and supporting schemes in terms of biogas production and exploitation potentials have been performed. Business models including most promising regional sizes and performance specifications in relation to entire cost structure (life cycle analysis), biogas feedstock quality and availability have been identified in strict collaboration with a network of stakeholders, experts in the fields of biogas and power generation and distribution. Market conditions in selected European countries derived from the market analysis have also been evaluated (WP1 & WP5).

3 Results achieved

Within the project the following results have been achieved:

3.1 Models and market analysis

An **analysis of the current market** opportunities for the exploitation of biogas in small size hybrid heat and power systems (up to 500 kWe) has been carried out for the countries represented within the Consortium [1]. The biogas potential production and quality from different second generation biomass has been evaluated at country level. The existing gas fed heat and power system technologies and the most suitable scenarios for the future penetration of the Bio-HyPP system in the market have been defined.

An evaluation of the previous existing **business models** has been performed, three promising business models have been chosen and the most promising scenarios for Bio-HyPP installation have been identified (Figure 1, [4]). The business models have been analysed, re-shaped for small size CHPs and adapted according to suggestions received by stakeholders to the Bio-HyPP system. Techno-economic feasibility analysis of the system has been carried out.

Figure 1: Most promising scenarios for Bio-HyPP installation

A screening of **life cycle** cost analysis (LCCA) has been done on the manufacturing and use phases of a system composed by Bio-HyPP system components. The objectives and scope for life cycle assessment (LCA), LCCA, and social life cycle analysis (SLCA) studies have been defined and data on the components for the lab installation of the test rigs has been collected to perform the analyses on the Bio-HyPP systems. The analyses take into account the production and use phases [6].

Also, **safety requirements** for the laboratory in Savona (Genoa) for the top-economic layout have been analysed and defined and published in [7].

Steady-state thermodynamic simulation models of the top-performance and top-economic layouts including the characteristics of the micro gas turbine, the solid oxide fuel cell and coupling elements as well as heat and pressure losses have been set-up [2]. The models have been used to define the specifications for the main subsystems and components of the power plant concept. Possible operating limits have been identified and strategies to broaden the operating range have been defined ([33], [42]). Moreover a mixed data-driven physics-based dynamic modelling approach for fuel cell gas turbine hybrid systems has been developed and validated. With the experimental data gained from the emulation facilities, the thermodynamic models have been validated and used for further detailed analysis of the operating range, operation strategies and for defining components' input conditions for further optimization [5]. The models have been refined with detailed knowledge about heat losses and have been used for refined boundary conditions.

3.2 Component development and optimization

A **combustion system**, which meets the needs for both SOFC off-gas combustion and biogas/natural-gas-fired combustion has been developed [31], manufactured [8], tested under atmospheric conditions and analysed concerning the operating range [32]. To widen the operating range, adding supplementary fuel has been investigated. The combustor for the MGT hybrid test rig including a new liner concept has been designed and manufactured. The combustion system and its interfaces have been adapted constructively (Figure 2) and have been integrated into the hybrid emulation test rig and it has been tested on the test rig. In the test rig the combustion chamber has been successfully tested under pressurized conditions.

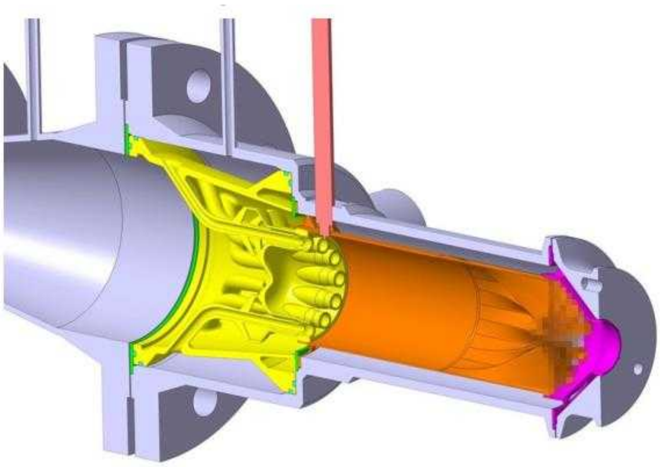

Figure 2: Combined combustion system for hybrid system integration [33]

Performance of the micro gas turbine (MGT) has been improved by efficiency improvements of the turbomachinery components. Improvements on the turbine generator have been studied [11] and an adapted generator has been implemented.

A significant performance improvement has been obtained, mainly as a result of the combination of small optimizations on the **turbomachinery components** (introduction of compressor pre-whirl vanes, compressor diffuser vanes, compressor scroll cooling, compressor leading edge modification and modification of turbine heat shield), leading to an 840 W electrical power output increase for the 3 kW MGT.

Electrical and mechanical operating limits of the electromechanical subsystem have led to redefinition of an optimal generator design (stator, rotor and housing) concerning torque constant, efficiency, cooling and manufacturing issues. Power electronics have been redesigned and qualified to be able to manage the higher power output of the MGT. **Power conversion optimization** has focused on the development of a new and innovative toroidal stator design, its manufacturing possibilities and efficiency. Unfortunately, high-frequency effects showed too high thermal losses during the prototyping experiments with different stator configurations, with the result that this toroidal solution could not be applied for the MGT. Alternatively, a modified design of the existing generator concept has been found with reduced number of coils that fulfils operational requirements and which is considered a promising solution for automation of volume production and as a result improves future low-cost manufacturability of the generator.

Rotordynamic-thermal models have been developed and validated and used for design definition of an MGT prototype with **air bearings**. Air bearings together with the whole power module (turbine, compressor, generator and bearings) have been designed and parts have been manufactured and tested. A simulation model for the air bearings has been set up and validated with the test data serving for concept refinement. Components for experimental investigations have been manufactured and tested in cold conditions.

Designs for the two **recuperators** for the top-performance (Figure 3) and the top-economic (Figure 4) power plant have been defined. A 'wide cell' aerodynamic test rig has been built to experimentally verify the fulfilment of the required low pressure loss. Following this, the recuperators have been built incorporating adaptions in the design and manufacture of sub-components (nozzles, manifolds and cells) to achieve the new requirements. This has led to a recuperator capable of operating at high temperatures with improved performance at significantly lower costs.

Figure 3: Recuperator for the top-performance layout

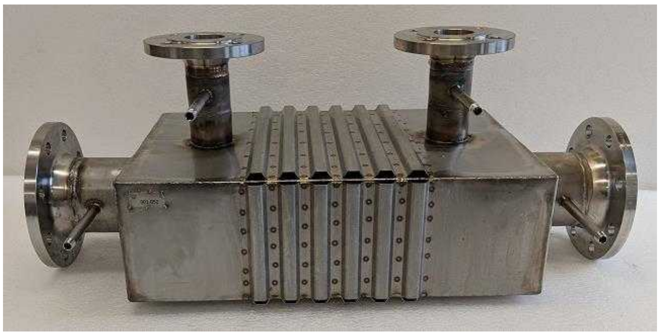

Figure 4: Recuperator for the top-economic layout

Experiments with **SOFC stacks** have been carried out to determine the influence of CO_2 content in the fuel on SOFC performance on cell level [9].

The **recirculation blower** characteristics for the hybrid power plant have been analysed. The experimental tests and additional analysis of the recirculation blower have shown that the recirculation blower is suitable for controlled operation for methane and biogas operation [10]. Yet, this auxiliary unit has failed twice and needed to be repaired by the manufacturer.

3.3 Control strategy

The control strategy of the top-economic layout system has been developed from a PI controller towards a cascade PID controller to reach better performance. A dynamic model has been created and calibrated with experimental results to simulate the transient behaviour of the emulator. A real-time model has been developed for Hardware-in-the-Loop (HiL) operations [3] to be carried out with the emulator test rig. It evaluates the performance of components not physically included in the experimental facility, such as the SOFC and the reformer.

A **model predictive control** based on multiple tools has been developed for control optimization **of the top-economic layout** [14]. It has been possible to reduce temperature oscillations to decrease thermal stress in the SOFC. Compressor surge under large variable volumes has been analysed [15] to identify surge precursors ([38], [39]). The impact of transient operations (e.g. operations on the cold bypass valve) on the compressor stability have been identified and tested. SOFC degradation has been investigated and analysed ([33], [35]).

The control strategy for the separate emulator test rigs has been derived from the **control concept for the top-performance layout**. The system is composed of a PLC (programmable logic controller) for the control of the facility including a state machine and a separate safety PLC to assure personnel safety. The control systems have been set-up and commissioned successfully at both test rigs. The control strategy for the MGT test rig is published in detail in [29]. During experimental operation the controllers have been parametrized and improved. Procedures for start-up, load change and shutdown have been developed and successfully adapted to the characteristics of the components in a hybrid power plant.

3.4 Test rigs and facilities

The existing **emulation facilities based on real MGTs (100 kW and 120 kW machines) coupled to SOFC emulators** have been upgraded within this project [12] and used for the investigation of surge at different volume sizes, with focus on surge precursors for instability avoidance [13] and experiments to define necessary valve control to avoid these critical conditions ([14], [15], [39], [40]). Also, experiments have been used for model verification to assist in the choice of operating strategy and to define start-up procedures. On the test rigs, experiments have been performed to analyse operating conditions of the demonstration plant at experimental level without the risk of damaging the fuel cell stack. Models including model predictive controller have been connected to the experimental plant. Different control strategies considering degradation have been evaluated ([34], [35]).

Two separate test rigs for each **top-performance layout** subsystem have been set-up with emulation of the other subsystem. Set-up and choice of components has been supported by thermodynamic models. The test rigs have been assembled in the lab, including all the components, piping, control system, instrumentation and safety concept: the SOFC test rig (Figure 5) and the MGT test rig (Figure 6, Figure 7) each emulate their counterpart. Two control systems derived from a joint control concept (for the real coupling) have been developed (see chapter 3.3), commissioned and iteratively adapted. Various components have been tested before integration into the test rigs (see chapter 3.2). To investigate the influences of one system on the other, a 'hardware in the loop' model has been set-up and integrated into the MGT test rig [30].

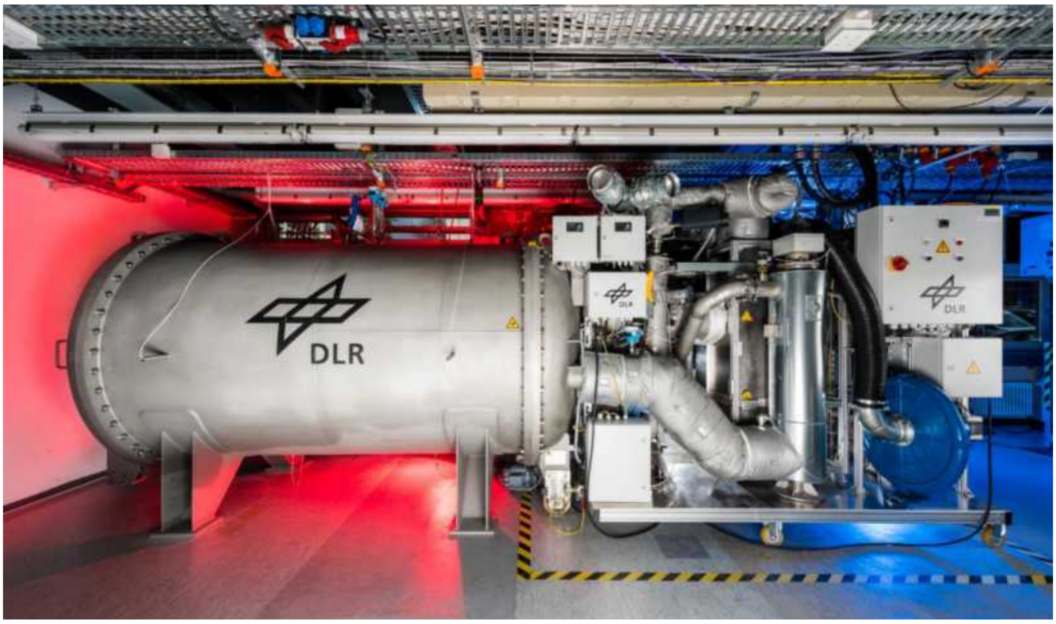

Figure 5: SOFC test rig of the top-performance layout

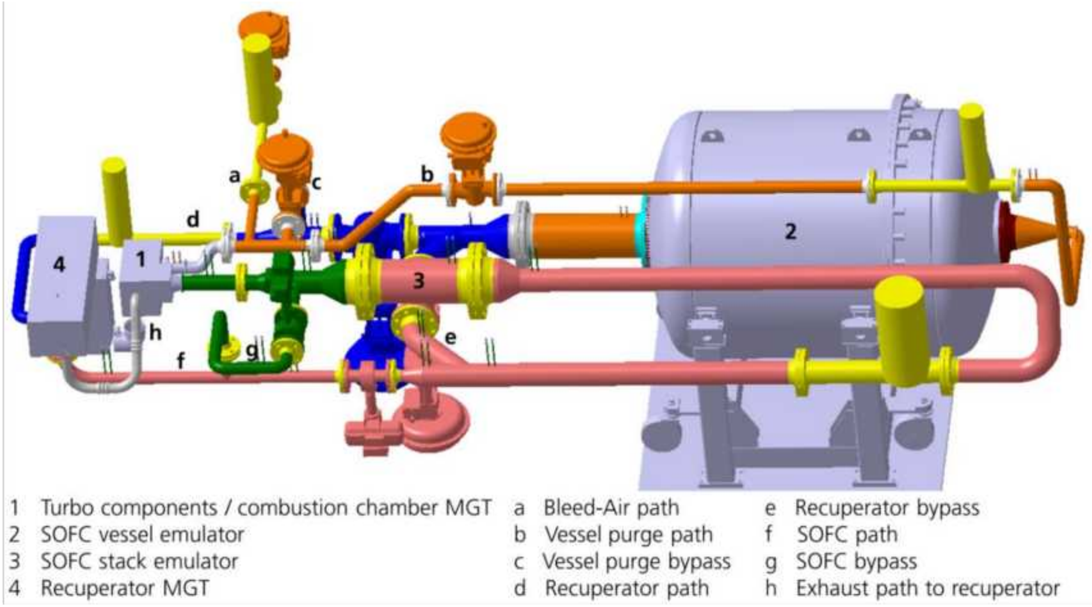

Figure 6: Engineered design of the MGT test rig of the top-performance layout ([16], [25])

Figure 7: MGT test rig of the top-performance layout

The test rigs have been used for the investigation of the operation range, the characterization of the subcomponents and their behaviour under hybrid conditions. For the MGT based test rig [28] transient manoeuvers have been developed for start-up, load change and shutdown. Limitations for gradients of transients have been identified and included in the control concept. Critical events have been analysed [41], emergency routines have been defined [17] and necessary adaptations for the coupling concept have been derived [20].

Figure 8: Test rig of the top-economic layout [18]

For the **top-economic layout** (Figure 8, [18], [37]) a steady-state model has been developed and the components have been specified by this model. A test rig to measure performance of turbochargers in cold and hot conditions has been built and turbochargers have been tested experimentally. The turbocharger for the top-economic layout has been chosen through validated design calculations and experimental tests. Control approaches for the different valves and for part-load operations have been analysed with the simulation tools. Components like recuperator and burner have been designed. Risk mitigation solutions and a plan to involve fire managers have been defined.

3.5 Dissemination

A **communication and dissemination** strategy of the project has been outlined, focusing on the key target groups. A **website** ([21], [26]), leaflets [22] **and newsletters** have been set-up and updated constantly with the latest information on the project to keep interested persons informed. The Bio-HyPP Consortium has participated at several **international conferences** and workshops at which facts and insights about the project have been presented. **Papers** have been published and presented at different sessions. Also, a **LEAP workshop** (low emission advanced power systems) has been organized within a conference (SUPEHR 2019).

A **Stakeholders Group** has been created for collection and analysis of their perspectives. Within this group, distributed generation of energy is foreseen as a promising opportunity within the future energy market. Also the European micro-CHP market is expected to grow in the next 15 years with optimistic estimates. The installation of CHP systems within micro-biogas grids have been evaluated as a feasible and promising solution. Stakeholders identify the high system efficiency as the most important feature in terms of market value: this aspect will represent the real advantage of the system in respect to other existing solutions and will be the key feature to catch customers' interest.

Stakeholders have been updated about the project via the newsletters and have engaged through online questionnaires covering topics such as the business models ([23], [24]). Activities have been devoted both to the planning and to the development of future exploitation strategies.

All activities have been supported by a robust **project management** structure using effective processes and tools. The project implementation and organizational approach has been reflected in lessons learned [19].

4 Impact

The Bio-HyPP intends to strengthen Europe's technology leadership by creating market impact, socio-economic impact, energy impact and environmental impact. Table 1 shows the overview of the expected impacts and the project results.

Table 1: Overview of the expected impacts and the project results

	What	Results supporting the Impact
Market Impact	• Make biogas-fired Hybrid Power Plant a viable technology • Keep a solid leadership in advanced energy technologies with complete EU manufacturing skills • Increase the competitiveness and the market penetration of the optimized subsystems MGT and SOFC and components like turbo machinery, recuperator, heat exchangers or generators • Nurture the development of industrial capacity to produce components and systems and open new opportunities with respect to market penetration	• Efficiency improvements >2% of the turbomachinery components (compressor pre-whirl, compressor diffuser vanes and turbine heat shield) experimentally confirmed • Generator efficiency improvements (facilitate further increase of MGT efficiency and power output) • High-speed generator prototype expected to significantly reduce stator assembly costs and ease the assembly of the MGT • Low loss, high temperature recuperator has been developed and test rig has been built • Combustion system suitable for natural gas, biogas and SOFC off-gas has been developed
Socio-Economic Impact	• Requirement of skilled job positions in high-tech • Guidance to policy makers and opinion leaders • Revitalization of agricultural sector	• An analysis of existing business models has been done and the most profitable potential target customer profiles have been identified • The results named under 'market impact' all support the expansion of small size CHP systems

Energy Impact	• Game changer in the electrical grid market • Long term substitution of most gas-fuelled dispatchable power technologies • Enabler of further renewable sources penetration	• Dynamic system models have been developed to identify proper control strategies (valve control) • SOFC cells have been testes with different fuel compositions. Composition has only a minor effect on stack performance • An MGT prototype with air bearings has been developed using rotordynamic-thermal models • Thermodynamic performance models support finding ideal matching for power plant components • Stack degradation has been integrated into model and can therefore be taken into account from beginning
Environ-mental Impact	• CO_2 friendly technology • Negligible pollutant emission, also without exhausts treatment	• Combustion system suitable for natural gas, biogas and SOFC off-gas has been developed and manufactured; tests under atmospheric pressure conditions confirm low emissions • Efficiency improvements >2% of the turbomachinery components (compressor pre-whirl, compressor diffuser vanes and turbine heat shield) experimentally confirmed • Concept of hybrid power plant with high electrical energy has been validated and adapted

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