Application to the Research Program TURBOPOWER

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SOLDEMO

Hybrid Solar Gas-Turbine Demonstration Unit

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Executive Summary

This research project is aimed at establishing a hybrid solar gas-turbine demonstration unit, showcasing this innovative technology, building confidence in its technical viability and allowing high-level research to be performed on solar gas-turbine systems. Hybrid solar gas-turbine units operate of a combination of concentrated solar energy and conventional fossil fuel, allowing significant increases in the fuel-electric conversion efficiency.

The proposed demonstration unit will be based around the extension of the solar receiver test facility at KTH, upgraded to allow the integration of a 3 kW_e recuperated micro turbine from the Swedish company COMPOWER AB. The coupling of the solar-lab with a micro turbine will allow the operation and testing of a solarised turbine unit in a controllable environment, and demonstrate not only the technical feasibility of the concept, but also the efficiency, flexibility and reliability of the unit. Furthermore, the research findings obtained from this small-scale unit will provide vital input for the scale-up of the technology to relevant industrial scales.

As with other on-going and completed projects in Phase I and II of TURBOPOWER, the present work will continue to add to the critical mass of competence and knowledge necessary to maintain the Swedish turbomachinery industries' competitive edge in the concentrated solar power market. This is realised in the context of the well-established collaboration between the Division of Heat and Power Technology and the Swedish gas turbine industry. Through this collaboration the research findings are directly utilised and implemented in the industrial value chain. The long-term goal of the project is to make hybrid solar gas-turbine technology a commercial reality.

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1. Background

Amongst the wide range of alternatives available for the sustainable generation of electrical energy, concentrated solar power (CSP) emerges as one of the most promising options. Through the use of thermal energy storage and/or hybridisation CSP can generate ***dispatchable power*** and is thus ideally suited to forming the cornerstone of a future energy grid based on renewable energy sources. Capable of being deployed in utility-size multi-megawatt plants, CSP benefits from economy of scale effects and, especially when installed in high-insolation areas, generate electricity at economically competitive rates.

The use of gas turbines in solar power plants (SPPs) would offer a number of advantages over conventional steam-cycle systems, chief among them a significant reduction in water consumption, reduction in start-up and load ramping times and ***increased flexibility through hybridisation***. Gas turbine-based SPPs also eliminate the need for an intermediate heat transfer medium, allowing the full potential of high temperature receivers and thermal energy storage to be harnessed. Hybridisation of SPPs with other energy sources (such as sustainably derived biogas) offers the possibility to combine the proven efficiency and cost-effectiveness of CSP technology with guaranteed power production, achieved by supplementing solar heat with combustion at times of insufficient solar supply. This makes SPPs a more attractive option for investment due to a reduction in the perceived economic risks. The use of gas turbines in hybrid SPPs also presents the advantage of eliminating the need for the construction of additional spinning reserve that accompanies the connection of conventional renewable energy resources to the grid. The output of a hybrid solar gas turbine power plant can be adapted to meet demand through ***control of the combustion chamber***, even during rapid solar transients.

At the current time, hybrid solar gas-turbine technology is at a relatively low technology readiness level. Only a handful of operating units have been successfully demonstrated, and there is enormous scope for new research facilities to investigate novel features of this technology. However, the testing of full-scale (i.e. multi-megawatt) hybrid gas-turbines is often prohibitively expensive, requiring large experimental facilities such as the Plataforma Solar de Almeria or Abengoa's test facilities in Seville.

The objective for the proposed SOLDEMO facility is to develop a small scale (i.e. multi-kilowatt) facility, based around an indoor artificial solar light-source, in which many key features and limiting criteria of hybrid solar gas-turbines can be explored. The SOLDEMO facility would be the ***only facility worldwide*** capable of operating a hybrid solar gas-turbine system using an artificial light-source, allowing operation and testing under 100% controllable conditions. The controllability of the demonstration facility will allow hybrid gas-turbine technology to be tested across the entire operating range, and phenomena such as receiver-combustor interaction studied under relevant conditions.

2. Objectives and Goals

The concept at the core of this project is the ***demonstration of a hybrid solar micro gas turbine***, operating on a combination of concentrated solar energy, and back-up fuel. The project aims to evaluate the efficiency and flexibility of the solarised gas turbine, as well as to investigate the interaction between solar receiver and gas turbine combustor.

In order to reach these goal, the solar-lab infrastructure at KTH will be modified to allow the integration of a gas-turbine unit into the ***existing solar receiver test-bed***. Pressurised air from the compressor will be redirected to the solar receiver where it is heated to high temperatures (in the region of 800°C). This hot air is then returned to the gas turbine combustor where fuel can be added to further heat the air if required. An existing micro gas turbine unit at KTH will form the basis of the solarised micro gas turbine unit: a 3 kW_e recuperated unit from COMPOWER AB.

In more precise terms, the proposed project will achieve the following goals:

1. Upgrade of the solar-lab facility and demonstration of the operation of a gas turbine unit using concentrated solar energy
2. Measurement of the efficiency of gas-turbine operation (fuel-electric as well as total conversion efficiency) with different intensities of solar heat input
3. Measurement of the flexibility of the solar gas-turbine (ramp-rate in %/min)
4. Evaluation of different control strategies for solar hybrid gas-turbine operation.

Furthermore, time constants will be obtained for the solar sub-system allowing the response-times of the hybrid gas-turbine to be determined. This information will also help with the development of ***better dynamic prediction models*** of the hybrid gas-turbine and allow validation of existing performance models. A further key focus for this demonstration facility is to act as a test plant for innovative Swedish receivers designs for gas-turbine applications and to investigate possible receiver/combustor arrangements.

The objectives need to be managed within the time frame of the TURBOPOWER program and thus a 2 year project is proposed. The upgrade of the solar-lab infrastructure will be performed first, followed by the solar gas-turbine integration and testing.

The final facility unit will consist of an integrated solar receiver and hybrid solar gas-turbine research test-bed, capable of demonstrating the operation of a micro gas-turbine unit on a combination of concentrated solar energy and fossil fuels. Furthermore, it will allow demonstration of the receiver concepts currently under development at KTH under real-world conditions.

The demonstration facility will be ***unique worldwide*** for its combination of a 100% controllable solar concentration system (through the use of an artificial light source) with a hybridized micro gas-turbine system. This combination results in a demonstration facility capable of operating under real-world conditions (as dictated by the gas-turbine system) whilst maintaining full controllability of the system through control of the light source and the gas-turbine combustor.

Concerning air-receiver testing (a critical component for hybrid gas-turbines), in other facilities, this is typically performed in an imitated environment, with simplified boundary conditions. In the TURBOPOWER facility gas-turbine receivers could be tested under real operating conditions, allowing the correct physics to be tested, and allowing the development and testing of commercially feasible designs.

3. Scientific Benefit

The focus of the study is the demonstration of the hybrid solar gas-turbine unit. Solar gas-turbine technology is an innovative technology and a large number of research questions remain as-yet unanswered, providing a rich field for research activities.

First and foremost, the establishment of a solar gas-turbine demonstration facility at KTH will give scientists and engineers in Sweden access to ***world-class research infrastructure***. At the current time no comparative facilities for solar gas-turbine research exist worldwide. While hybrid solar gas-turbine units have been tested at several facilities world-wide, these installations were all based on the use of solar collectors for testing, and are thus subject to the vagaries of the weather. The solar-lab at KTH is unique among existing gas-turbine research facilities in that it is equipped with an artificial light source, allowing operation and testing of the solar gas-turbine regardless of current weather conditions. The controllability of the solar input will allow accurate testing of the turbine unit across the entire operation range, and allow the interaction between the solar receiver and gas-turbine combustor to be examined in detail.

Furthermore, the integration of a gas-turbine unit into KTH's solar-lab facility will allow the currently on-going receiver design and testing (performed within the FP7 OMSOP project) to be performed in real-world conditions, with both mass-flows, operating temperatures and pressures determined by the gas-turbine. In this way, the ***physics of high-temperature receiver design*** can be studied with relevant boundary conditions.

The establishment of a solar gas-turbine demonstration facility will further reinforce the highly recognised position of KTH in the worldwide solar power research community, with over 25 published papers in the solar gas-turbine field and established collaborations with leading Swedish and European players. The presence of an on-site testing facility will allow KTH to increase its participation in European research programmes, and secure additional funding for research activities into a range of aspects of solar hybridisation and gas-turbine systems.

Two calls on hybrid solar power technology will be announced within the Horizon 2020 call. Construction of the SOLDEMO facility will allow EKV and KTH to play a key role in these projects, and the innovative receiver designs developed at EKV to be used in these and other projects. The facility will also allow EKV to participate in upcoming KIC InnoEnergy projects, including the proposed solar micro-turbine project. The dynamic modelling experience and validation data obtained from the facility will allow EKV to strengthen its already strong position in the performance modelling of solar thermal power plants.

The overarching goal is to demonstrate towards policy makers that there is Swedish capacity for innovative renewable gas-turbine power plants, to establish TURBOPOWER at the forefront of this R&D area, to build and maintain critical knowledge, as well as to position TURBOPOWER partners for up-coming research programs.

4. Industrial Relevance

The relevance of this project for the industry is multifaceted. Firstly, the demonstration and operation of a solarised gas-turbine unit will allow industrial partners to obtain crucial experience with this novel technology, and acquire confidence in its feasibility. The demonstration unit will prove the ***controllability*** of the hybrid solar gas-turbine unit, and its ability to maintain the desired operating point across a wide range of solar heat inputs.

The unique controllability of the artificial light source makes KTH's solar-lab facility the only facility worldwide that is capable of performing this type of research, as the solar heat input to the system can be directly controlled to ***examine the desired transient behaviour***. While a couple of other hybrid gas-turbine demonstrations do exist, they are all dependant on the Sun to provide heat input to the system, and as such can only test operation in a way that the weather allows. As such, they are more useful as a proof-of-concept facility rather than as a true demonstration and testing facility as they cannot control what they measure.

Where other research groups have accepts to artificial light sources, they are not designed for operation with a gas-turbine unit. As such, artificial light-source testing is typically performed only on a component-by-component basis, whereas the TURBOPOWER facility will allow the entire integrated hybrid gas-turbine to be tested under controllable conditions.

Secondly, the integration of a gas-turbine into KTH's solar receiver test facility will allow the creation of an ideal test-platform to study the operation of the turbine combustor with high and variable degrees of air pre-heat. This is a key technology challenge for hybrid gas-turbine systems, and successful demonstration of stable combustion with ***high solar preheat*** is crucial for the development of this technology. The controllability of the solar-lab facility will allow the desired operating points to be investigated and the transient behaviour of the receiver-combustor system to be examined.

Finally, the ability to operate and ***test receivers under real-world conditions*** will allow the life of these components to be correctly assessed and improved designs proposed. The solar receiver is currently the life-limiting component of the hybrid solar gas-turbine, and their durability needs to be evaluated not only under steady normal operating conditions, but also during events such as generator trips and turbine overspeed. Improved receiver designs will allow higher temperature operation and increased conversion efficiencies for solar energy, reducing the overall costs.

For both receiver design and hybrid combustions, the results obtained will provide valuable input for the ***commercialisation of small-scale hybrid solar gas-turbines***, as well as the ***scale-up of the technology*** to industrial scales. Swedish industry is heavily involved in the supply of turbomachinery equipment for solar thermal power plants, and establishing core competencies in solar gas-turbine technology will allow this dominant position to be maintained when the market for hybrid solar gas-turbine power plants opens up.

On the small scale side, either parabolic dish or micro-tower systems, gas-turbines in the range 5 – 30 kW will form a ***cost competitive alternative*** to the expensive and unreliable solar photovoltaic panels and dish Stirling engines. In this power range, the Swedish gas-turbine company COMPOWER is already operating. A commercial small-scale hybrid solar gas-turbine power would be ideally suited to meeting electrification needs in rural and/or off-grid areas, and when coupled with polygeneration technologies, be capable of supplying power, heat, cooling and fresh water in these regions. The solar gas-turbine demonstration unit proposed in this work is of the correct size for this application, simplifying technology transfer towards a commercial product.

Concerning large scale hybrid solar gas-turbine power plants, it is expected that the optimum configurations will operate with units in the range of 20 – 50 MW, which matches well with the range of gas turbines supplied by Siemens Industrial Turbomachinery in Finspång. The technologies demonstrated in this project, along with projects funded through other Swedish research projects, will need to be scaled-up for application in these power plants, either through direct re-sizing or through series and/or parallel multiplication of the receiver/combustion units. Scale-up will also involve planning for ***commercialisation of the innovative solar components***, i.e. preparing manufacturing and industrialisation plans.

5. Method of Attack

As both the solar-lab facility and the COMPOWER micro gas-turbine are already in place at KTH, the work to be performed in this project will centre on the ***upgrade of the existing solar-lab*** to allow integration of the gas-turbine unit. This will include both physical changes to the facility in order to connect the solar receiver test units with the micro gas-turbine, as well as the reprogramming of the gas-turbine controller to allow hybrid operation.

The Division of Heat and Power Technology (KTH) has a large body of previously experience working with solar power systems, on both theoretical and practical aspects. Combined with the well-established knowledge in turbomachinery at the division, this will form the basis to pursue the proposed project. Furthermore, there is an established and well-functioning collaboration with the

R&D and Future Technologies department at Siemens Industrial Turbomachinery, which will help to ensure that the demonstration unit is of relevance to our key industrial partners.

The prosed project will proceed through a number of steps:

- Upgrade of the KTH solar-lab facility
    - Improvement of measurement system to provide sufficient data concerning the solar heat input to the gas-turbine controller
    - Installation of electrical equipment necessary to connect the gas-turbine generator
    - Increased capacity of the ventilation system to dissipate the additional heat

- Integration of the COMPOWER micro gas-turbine unit
    - Modification of gas-turbine combustor/recuperator to allow airflow extraction
    - Integration of connection piping between solar receiver and gas-turbine unit

- Update of the gas-turbine control strategy for hybrid operation

- Operation and testing of the solarised gas-turbine unit
    - Demonstration of stable operation
    - Validation of receiver and combustor interoperability
    - Measurement of efficiency, solar generation fraction and ramp rates

As the final stage of the project, a study will be launched to examine future research activities and project in which the solar gas-turbine test-rig can play a key role. This will ensure that the investment in the demonstration facility is used in the most effective manner to boost the solar turbomachinery industry in Sweden.

The main body of the solar-lab upgrade work will be performed by PhD students at the division, with support from supervisors (both internal and external) and a reference group. These persons were already involved in the construction of the initial solar-lab, allowing the project to proceed rapidly in its early phases. Frequent reference group meetings are suggested to keep a close collaboration with industry, OEM and utility representatives.

6. Project Plan

The work package description is given below. Within each work package associated milestones (M) and deliverables (D) are identified and correspond to the time plan given in section 7. The project leader will be Dr. Björn Laumert of the Division of Heat and Power Technology. The solar gas-turbine demonstration facility will be located at KTH, in the laboratory halls of the Division of Heat and Power Technology, where both the solar-lab and COMPOWER gas-turbine unit are currently installed.

WP 1 <u>Upgrade of Solar-Lab Facility</u>

The existing solar-lab facility at KTH will be upgraded to allow integration with the micro gas-turbine unit from COMPOWER AB. The required modifications to the facility are the following:

- Increase in the ventilation capacity of the solar-lab enclosure due to the additional heat generated by the hybrid operation of the gas-turbine.

- Upgrade of the electrical installation to accommodate the higher power requirement of the solar light source and the demands of the gas-turbine generator
- Upgrade of the measurement equipment to more accurately characterise the output of the solar receiver, and thereby provide the detail input required by the gas-turbine controller when operating in hybrid mode.

M 1: *Solar-lab ready for micro-turbine integration*

WP 2 Integration of the COMPOWER Micro Gas-Turbine Unit

The 3 kW_e micro gas-turbine unit from COMPOWER AB will be integrated with the upgraded solar-lab facility. Minor turbine modifications need to be made to allow the insertion of the solar air receiver into the gas-turbine circuit. This includes:

- Modification of the gas-turbine central casing to allow extraction of pressurised air after the recuperator, and allow re-insertion of this air before turbine combustor.
- Construction of high-temperature piping to transport the hot gases produced by the solar receiver and return them to the micro gas-turbine unit
- Pressure testing of the receiver circuit for operation with compressor air.

M 2: *Physical connection established and tested between gas-turbine and solar-lab facility*
M 3: *Gas-turbine fully integrated into solar-lab facility*

WP 3 Update of the Gas-Turbine Control Strategy for Hybrid Operation

The integration of solar heat into the gas-turbine circuit will change the operating characteristics of the turbomachinery unit, and thus requires modifications to be made to the control strategy of the unit. New control algorithms will be specifically developed for the hybridised solar gas-turbine, allowing stable operation to be maintained across the entire operating range.

The unit will progressively be tested, and operated on, with higher degrees of solar integration, up until full-load operation of the solar receiver is reached, in order to test the control strategies.

M 4: *New control algorithms implemented in gas-turbine controller*
M 5: *Control strategies tested in solar demonstration facility*

D 1: Report on control strategies for hybrid gas-turbine power plants
D 2: Scientific publication 1 (solar gas-turbine facility design)

WP 4 Operation and Testing of the Solarised Gas-Turbine Unit

Once the solar-lab and micro turbine unit have been connected and the control strategies implemented, testing of the solarised gas-turbine can begin. Within this demonstration project, testing will focus on validating the performance of the solar gas-turbine unit, and evaluating its controllability and flexibility. As such, the following tests are planned:

- Efficiency measurements (both fuel-electric and total conversion efficiency) as well as determination of the achievable solar production fraction.
- Flexibility measurements, including both turbine ramp rates, and response time of the solar air receiver unit
- Confirmation of the controllability during extreme events: load rejection, trip, overspeed

M 6: *Full operation of solarised gas-turbine in demonstration facility*
M 7: *Measure campaign completed*

D 3: *Scientific publication 2 (hybrid solar gas-turbine operation)*
D 4: *Final report on hybrid solar gas-turbine demonstration facility*

WP 5 Planning for Future Exploitation of Solar Demonstration Facility

Having completed construction of the solar demonstration facility, plans will be drawn up concerning future research activities and industrial exploitation of the results. This will ensure that the investment in the demonstration facility is used in the most effective manner to boost the solar turbomachinery industry in Sweden.

D 5: *Project plan for continuation of research activities*

7. Time Plan

The work to be performed is spread over 24 months (8 quarters) between 2013 and 2015. The expected work plan, including milestone and deliverable dates, is shown in the table below.

	2013		2014				2015	
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
WP1			M1					
WP2					M2	M3		
WP3						M4	M5, D1, D2	
WP4							D3	M6, D4
WP5								D5

8. Project Budget

The total project budget is 2.0 MSEK distributed over three years (though with two years total working time) according to the table below. The salary cost is related to the cost for the personnel involved in the upgrade and construction of the solar demonstration facility, as well as the elaboration of the new control routines for the gas-turbine. The costs for material and equipment include the items necessary for the upgrade of the solar lab, and initial testing of the solarised gas-turbine unit.

Project budget SOLDEMO (university) all in kSEK				
	2013	2014	2015	Total
Salary cost	75	300	75	450
Computer	20	20	0	40
Material	20	30	50	100
Equipment	350	300	40	690
Travel	0	20	20	40
Others	0	0	0	0
Overhead (max 35%)	240	350	90	680
SUM (kSEK)	705	1020	275	2000

9. Personnel

The work in the present project will be performed by experienced PhD students who were involved in the previous design of the solar-lab facility and are thus well established in the research field. Additional work (e.g. construction and installation of equipment) will be performed by laboratory technicians and research engineers. This will ensure a completion of the work with high efficiency and low risk. At the same time this project serves as a basis to establish a facility than can be used in future MSc. thesis and PhD projects, as well as for industrial research collaborations.

During the project, between 3 and 6 MSc. theses will be completed on topics related to solarised gas-turbines such system simulation, control system analysis, solar receiver design, etc. These thesis projects will both provide valuable input to the construction of the demonstration unit, as well as allow additional issues related to operation and design of solarised gas-turbines to be analysed. The MSc. thesis students can be drawn from the pool of available students within the university system, and these projects can thus be performed at no cost to TURBOPOWER.

The CSP group at KTH operates a close-knit working with regular meetings to disseminate on-going activities to all members (Seniors, PhD students and MSc. thesis students). The work is steered and monitored by a senior research leader who also will act as supervisor and project leader in this project.

In order to ensure the long-term industrial relevance of the demonstration unit, it is of vital importance for the success of the project that the industry, by active participation in the reference group, will dedicate time to the project.