Application to the Research Program TURBOPOWER

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CSP ROADMAP WP1

Gas Turbines for High-Penetration Renewable Markets

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Executive Summary

This research project is aimed at establishing the competitiveness of industrial gas turbines in electricity markets with a high penetration of non-dispatchable renewable energy sources. Both open- and combind-cycle gas-turbine technology is already well established on the market, but the growing penetration of renewable generation technologies will require these units to operate in a non-conventional manner. At the same time, the emerging solar hybrid gas-turbine technology is likely to form an important cornerstone of both short-term and long-term renewable energy development as it combines low CO_2 energy production with proven dispatchability and reasonable electricity costs. The proposed project seeks to analyse future market roles and operational requirements for both conventional and hybrid gas-turbine configurations. The project will build on results obtained in the TURBOPOWER Phase I Addendum in which a number of promising hybrid gas turbine power plant configurations were analysed and shown to be both economically and environmentally competitive. In the present proposal the objectives are threefold: firstly to identify relevant gas-turbine power plant configarions for different electricity markets, secondly to identify the optimal mix of plant configurations for a given market and thirdly to identify performance requirement for optimal gas-turbine power plant configurations. At the same time relevant boundary conditions (e.g. electricity pricing and plant loading) will be obtained, allowing detailed evaluation of the technical and economic performance of the gas turbine concepts when connect to the electricity grid. This will allow the industry to correctly focus their development on the next generation of machines to be competitive under these conditions. As in Phase I, 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.

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1. Background

As our awareness of the dangers of global climate change grows, the development of new renewable energy technologies is of primary importance in the effort to reduce emissions of carbon dioxide and other greenhouse gases. Rapid increases in the price of oil and worries about the stability and security of the extraction of fossil fuels have lead to renewed interest in the development of local energy sources, thereby reducing dependence on foreign sources. However, with the growing penetration of renewables into electricity markets in many countries (e.g 13% in Sweden, 18% in Spain, 27% in Denmark) changes are beginning to be felt in the operation of the electricity grid [1]. The boundary conditions for power plants operation are changing and, as such, an improved understanding of the varying loads and prices on the electricity grid is required to confirm the performance of emerging gas turbine (GT) concepts and to further optimise their design for these new markets.

Concentrating solar power (CSP) has been shown [2] to be one of the more promising solutions for meeting the growing demand for energy, especially in the Sun-belt regions of the world. CSP plants convert the Sun's energy first to a high temperature heat source, before further conversion of this heat to useful work. The thermal conversion step allows the integration of energy storage and the possibility for increased flexibility through hybrid operation, making these systems controllable and dispatchable. Due to their high conversion efficiencies and low water consumption, GT-based CSP systems are expected to grow in importance in coming years. KTH's previous work on hybrid solar gas turbines has identified a number of promising and competitive design concepts [3-6].

Variability in supply from non-dispatchable renewables such as solar photovoltaics (PV) and wind result in greater fluctuations as well as an increased need for flexibility in conventional power plants which must compensate for these variations. GT based power plants are ideally positioned to respond to the demands for flexible reserve power: due to their low inertia, simple-cycle gas turbiness are able to respond quickly and efficiently to changes in demand. Combining GT technology with concentrated solar energy allows back-up power and spinning reserve to be provided with very low carbon emissions.

In recent years, the efficiency of simple cycle industrial GTs (such as the SGT-750) has risen dramatically, and when combined with bottoming steam-cycles, combined cycle power plants provide the highest conversion efficiencies. When these systems are supplemented with energy from CSP systems, carbon emissions can be reduced below the levels achievable by any other technology, whilst still maintaining a fully dispatchable power supply.

2. Objectives and Goals

The overall goal of the proposed project is to investigate the role of the GT in markets with both large solar resources and a high penetration of renewable energy in the electricity grid; the Iberian electricity grid has been selected for study as a typical example of this kind of market [7]. The projects aims to investigate both the utilisation of the GT-based power plants to produce power using both fuel and concentrated solar energy, but also the role of the GT as spinning reserve for grids with large inputs of non-dispatchable and fluctuating renewable electricity, such as wind and solar PV. The goal is to find viable, i.e. cost effective and competitive, GT-based power plant solutions for these electricity markets.

In order to reach this overall goal, a flexible tool for power plant dispatch and electricity grid modelling will be developed including transmission constraints and reserve power requirements.

The tool will be flexible in the sense that it can be set up to simulate any configuration of electricity grid, by defining the mix of technologies, the structure of the transmission network, pricing schemes, etc. In order to be able to take into account the interaction of the GT power plants with other units in the grid, the simulation tool will include all conventional power generation technologies on the market.

In more precise terms, the tool will be able to determine for each simulated market scenario:

1. The hourly evolution of the electricity price as well as the overall cost of electricity production (in ¤/MWh_e)
2. The hourly mix of the different power generation technologies dispatched for electricity production (in % of electricity generation by source)
3. The hourly evolution of CO_2 emissions from electricity generation (in $kgCO_2/MWh_e$)

Using this tool, the operation of the different GT concepts (both fossil-fired and solar hybrid) will be analysed and the most economically viable configurations identified, along with the market roles for different technologies. The boundary conditions in terms of dispatching and load cycling will also be determined, in order to provide input for the design of the next generation of GT units. Finally, a SWOT (Streangth Weakness Oportunities and Threats) analysis for the role of GTs for the high-penetration renewable market situation will be performed.

The objectives need to be managed within the time frame of the TURBOPOWER program and thus a 1 year project is proposed, which will identify promising GT plant configurations for a first high-renewable market (the Iberian market is suggested) while setting the basis and objectives for a potential continuation.

3. Scientific Benefit

The focus of the study is the analysis of GT power plant concepts for different electricity markets with large renewable energy shares. The analysis of markets from the point of view of a specific power generation technology is a new scientific angle, which will involve the establishment of models of the different electricity grids for which the GT power plants are designed. Grid simulation will allow the establishment of real-world boundary conditions for the analysis of future GT power plants. Furthermore the work will involve the establishment of relevant, new and innovative hybrid solar GT power plant configurations, with the market boundary conditions being used to evaluate their techno-economic relevance.

This research will be valuable both for policy makers as well as the GT industry and utilities to understand the market position of GT based power plants in electricity markets that are moving towards ever higher renewable mixes. This research will furthermore identify viable and innovative GT plants that are adapted to potential changes in market conditions.

4. Industrial Relevance

The relevance of this project for the industry is twofold:

Firstly, GT-driven industry will receive decision making tools and information for the identification of business opportunities in electricity markets with growing shares of renewable energy sources with large solar resources. It will also enable the industry to analyse and adapt their technology offers for different markets with different mixes of renewable energies. Furthermore, it will enable the industry to analyse and discuss the impact of potential policy changes with the relevant policy makers and to identify the market scenarios which make a certain GT technology competitive

Secondly, the industry will receive relevant GT power plant configurations based on already existing machines that are competitive in different renewable energy market scenarios. The study will also provide potential new and innovative cycle and GT configurations for optimum use of solar energy in markets with a growing renewable energy mix.

Finally, the demands (in terms of loads, capacity factors and ramp rates) placed on GTs operating in electricity grids with a high-penetration of non-dispatchable renewables will be identified, allowing gas turbine industries to focus their development on identifying/adapting machines to be competitive under these condtions.

5. Method of Attack

The work will centre on the development of the new simulation tool: EDGESIM (for Electiricity Distribution and Generation SIMulator) and the application of the tool to the analysis of a high-potential solar power and renewable energy market: the Iberian penisula. The Division of Heat and Power Technology (KTH) has previously established an effective working tool (DYESOPT) for the analysis and optimisation of power plants under different boundary conditions. Combined with the well established knowledge in turbomachinery and CSP technology this will form the basis to pursue the proposed project. The power plants shall be based on available industrial gas turbines but also consider potential new hybrid solar gas turbine systems in which concentrated solar energy is used to supplement heat provided in the conventional combustion chamber

Furthermore, there is an established and well functioning collaboration with the R&D and Future Technologies department at Siemens Industrial Turbomachinery that will facilitate the identification of viable gas turbine plant configurations to be applied in the different market situations.

The project will proceed through a number of steps:

- Establishment of linerised models of the solar gas turbine power plants in order to examine dispatching and unit commitment problems
    - Optimal planning of gas turbine operation under varying electricity demand/pricing
    - Electricity pricing provided from electricity grid simulation, operation data (esp. loading) to be provided to the thermoeconomic models.

- Quanitification of the value of dispatchability/regulation services, especially from dispatchable compared to non-dispatchable renewable generation sources
    - Improved/optimal gas turbine designs for CSP and spinning reserve requirements will be proposed
    - Cost-functions and gas turbine performance to be cross-validated with data from industrial partners wherever possible.

- Trade-off studies to analyse the impact of changed market conditions on the cost-effectiveness and environmental impact of the different plant configurations.

As the final stage of the project, a study will be launched to examine further ways to harness the tools and results developed in this project, with a view to performing additional analyses and extending the study to other gas turbine based renewable energy concepts and energy markets in a potential project extension.

Frequent reference group meetings are suggested to keep a close collaboration with industry, OEM and utility representatives.

One senior PhD student is intended to perform the main body of the work as part of a post-doctoral study with support from supervisors (both internal and external) and a reference group. The choice to involve a senior PhD student rather than start with a new student is to be able to quickly build-up the electricity grid and market models at the beginning of the project in an efficient manner as they form the basis of this study.

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 work plan has been established with the assumption that one postdoctoral researcher works for 1 year at 100% on the project. The project leader is Assistant Professor Dr. Björn Laumert of the Department of Energy Technology, KTH.

The EDGESIM tool will be based on linear programming models of the different power plant concepts, which are then used to simulate the process of plant dispatch in an electricity market. The tool will be able to simulate different interconnected regions of demand and production, with any number and combination of power plant types being located in any number of regions.

WP 1.1 Elaboration of Linear Programming Power Plant Models

The following plants types will be modelled: solar PV and hybrid CSP, natural-gas open- and combined-cycle, coal, nuclear and wind. The models will be flexible with respect to plant size, efficiency and, for CSP, storage capacity, so that different technologies can be modelled.

M 1.1: Power plant models established

WP1.2 Elaboration of Plant Dispatch Routines

Simulation routines for economic plant dispatch will be elaborated, taking into account the electricity demand to be met, transmission constraints between regions and well as the requirement to provide reserve power for variable renewables (PV/wind).

M 1.2: Plant dispatch and grid transmission model available and validated

WP1.3 Integration into Optimisation Algorithms

The power plant and dispatch models will be integrated into an optimisation algorithm, allowing the optimum dispatch to be determined, in terms of electricity costs as well as overall CO_2 emissions from electricity production.

M 1.3: Optimised plant concepts identified and evaluated

D 1.1: Beta version of EDGESIM software package
D 1.2: Scientific publication 1

WP 1.4 Analysis of High-Potential Solar Energy Markets

The EDSEIM tool will then be used to analyse the deployment of relevant GT technologies in an initial market with a strong solar resource. Analysis will determine the market roles of the different power plants and the degree of CSP penetration that is achievable in the market as well as the mix of GT technologies that gives lowest electricity costs as well as lowest overall CO_2 emissions from the power sector.

The first study will consider the Iberian market, which has a dense electricity grid and an overall overcapacity in terms of existing power generation infrastructure. Additionally, the Iberian market has a large pre-existing wind capacity, which may pose a challenge, but, equally, presents an opportunity for GT-based CSP plants to provide grid balancing services.

M 1.4: Boundary conditions established for GT operation
M 1.5: Value of dispatchability and regulation services established

D 1.3: Scientific publication 2

WP 1.5 SWOT Analysis and Project Plan for Continuation

Based on the results obtained from the EDGESIM tool, a SWOT analysis will be performed. R&D objectives will be identified and the needs for competence build-up will be identified based on the project outcomes and the SWOT analysis.

Finally, a project plan will be establish for an eventual continuation based on identified R&D objectives and need for competence build-up

D 1.4 SWOT report
D 1.5 Project plan for continuation

Evaluation for eventual continuation with reference group and steering committee

7. Time Plan

	2012	**2013**										
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
WP1.1				M1.1								
WP1.2						M1.2						
WP1.3								M1.3 D1.1				
WP1.4									M1.4	M1.5		
WP1.5												D1.4 D1.5

8. Project Budget

The total project budget is 1.00 MSEK distributed over two years according to the table below.

Project budget CSP-GT Optimisation (university) all in kSEK	2012	2013	Total
Salary cost	50	572	**622**
Computer	4	36	**40**
Material			
Equipment			
Travel	4	36	**40**
Others	4	36	**40**
Overhead (max 35%)	20	238	**259**
SUM (kSEK)	**82**	**918**	**1000**

The salary cost is related to the cost for a first year post-doc and senior support and supervision. The cost Others is related to license costs for necessary software programs.

9. Personnel

The work in the present project will be performed by an experienced post doc who is well established in the research field. 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 senior research position in the field. The CSP-Turbomachinery group operates a close-knit working with regular meetings to disseminate ongoing activities to all members (Seniors, PhD students and MSc. thesis students). The work is steared and monitored by a senior research leader who also will act as supervisor and project leader in this project.

It should also be noted that 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.

10. References

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[3] Spelling J., Russ M., Laumert B. et al., *"A Thermoeconomic Study of Hybrid Solar Gas-Turbine Power Plants"*, Proceedings of the International SolarPACES Conference, Granada, 2011

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[5] Spelling J., Favrat D., Martin A. et al., *"Thermoeconomic Optimization of a Combined-Cycle Solar Tower Power Plant"*, Energy, In Press (Corrected Proof), Available Online: 29 April 2011

[6] Spelling J., Laumert B., Fransson T., *"Optimal Gas-Turbine Design for Hybrid Solar Power Plant Operation"*, GT2012-68054, ASME Turbo Expo, Copenhagen, 2012

[7] Operador del Mercado Ibérico de Energía, *"Resultados de Mercado"*, www.omie.es (accessed 2nd February 2012)