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## **THERMAL STEAM POWER PLANT FIRED BY HYDROGEN AND OXYGEN IN STOICHIOMETRIC RATIO, USING FUEL CELLS AND GAS TURBINE CYCLE COMPONENTS**

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### **ABSTRACT**

This proposal fully complies to the demands of a zero emission power plant since only hydrogen and oxygen as obtained from splitting water are provided as fuel in a working gas cycle of pure water. Distributed power plants based on solar radiation, solar heat, wind power and water power from river flow, tidal flow and even wave motion should drive electrolyzers producing hydrogen and oxygen. The units are connected with a pipeline system delivering hydrogen and oxygen at high pressure into respective storage tanks in the vicinity of the proposed power plant. So periods of generation of hydrogen and oxygen can overlap and these fuel gases are available to produce peak power according to demand.

The proposed plant is an hybrid plant incorporating SOFC fuel cells into an innovative power cycle with steam as working fluid. Twelve fuel cells of 2.5 MW power produce electricity and heat up working fluid from 600 to 800°C. In a succeeding combustion chamber the fuel cell surplus hydrogen as well as the gas turbine hydrogen demand is burned with pure oxygen leading to a working gas (steam) of 1550°C and 40 bar. The working gas is expanded in an innovative cycle producing additional 109 MW of electrical energy. So an overall output of 139 MW can be achieved with a thermal efficiency of 73.8 % based on fuel taken from the storage tanks for hydrogen and oxygen at 60 bar.

### **INTRODUCTION**

International concerns lead to climate conferences in which the danger of a world-wide climate change due to the emission of human-generated CO<sub>2</sub> is widely discussed. We feel that the necessary counter-measures are taken up too slow and with insufficient work and technical input. Therefore our proposal

aims at a zero emission power system using only energy provided by the sun [1].

A zero emission power plant is presented which uses hydrogen and oxygen as obtained from splitting water as fuel in a cycle with a working gas of pure water. Fuel cells as well as an innovative power cycle work together in this hybrid plant, similar to [2,3]. Primary heat input for the process of water-splitting is envisaged by solar radiation, solar heat, wind power from land and off-shore sites and water power from river flow, tidal flow and maybe even sailing ship-generated water flow [4].

In a certain vicinity all these plants operating at different time periods in different locations should be united by a hydrogen/oxygen collection system via pipelines. We propose respective electrolyzers to be installed in all these solar-power-driven local primary power plants. These plants and electrolyzers are to be connected in delivering the two gases hydrogen and oxygen from water-splitting at high pressures (50 – 100 bar) into the respective storage tanks in the vicinity of the power plant.

So periods of high generation of hydrogen and oxygen according to solar heat input over time give an input to be stored in high-pressure tanks (60 bar). Of course also wind and water flow allow an harvest of power to be stored. It can then be used for peak power according to the demand of the specific electricity customer supply system.

### **FUEL CELL**

To date, high temperature SOFC fuel cells with electrical powers up to 250 kW<sub>el</sub> were successfully built and operated [5,6] and an increase of unit power up to 2500 kW<sub>el</sub> seems feasible. Therefore in this proposal of a hybrid power plant 12

fuel cells of 2.5 MW<sub>el</sub> are arranged in parallel delivering 30 MW<sub>el</sub>. This power output is chosen in order to obtain reasonable size of turbomachines.

The SOFC fuel cell model assumes 85 % fuel utilization, a stack temperature rise of 200°C (600°C inlet/800°C outlet), and a voltage of 0.63 V, while operating at a pressure of 40 bar; except for the pressure, not particularly challenging operating conditions for today's SOFC.

Based on [7] a temperature increase up to 300°C represents state of the art. A higher cell voltage would also be possible and would improve the efficiency of the proposed cycle. But on the other hand, a cell voltage of 0.63 V as published e.g. by Westinghouse with air as oxidant [8] allows the operation at higher current density and leads to a smaller size of the fuel cells and thus to considerably lower investment costs.

The electrical power of a fuel cell operating with hydrogen and oxygen can be calculated with following Eqs. (1) and (2):

$$P_{el} = U \cdot I \quad (1)$$

$$I = n \cdot F \cdot (\dot{m} / M \cdot \eta_{fu}) \quad (2)$$

with U as cell voltage, I as current, n as the number of electrons transferred in the reaction (2), F as the Faraday constant (96485 As/mol), M as molar mass of hydrogen,  $\eta_{fu}$  as fuel utilization and m as the fuel mass flow. The term within the parentheses in Eq. (2) corresponds to the rate of consumption of the reactant.

For the chosen cell voltage the electrical power is about half of the energy content of the utilized hydrogen, so that the difference heats up the steam flow through the fuel cell as well as the reactants hydrogen and oxygen.

## THERMODYNAMIC LAYOUT

All thermodynamic simulations were performed using the commercial software IPSEpro by SIMTECH Simulation Technology [9]. This software allows to implement user-defined fluid properties to simulate the real gas properties of the cycle medium as well as to add new models to the model library as the fuel cell.

The efficiencies and losses of the components of the power cycle are listed in Table 1.

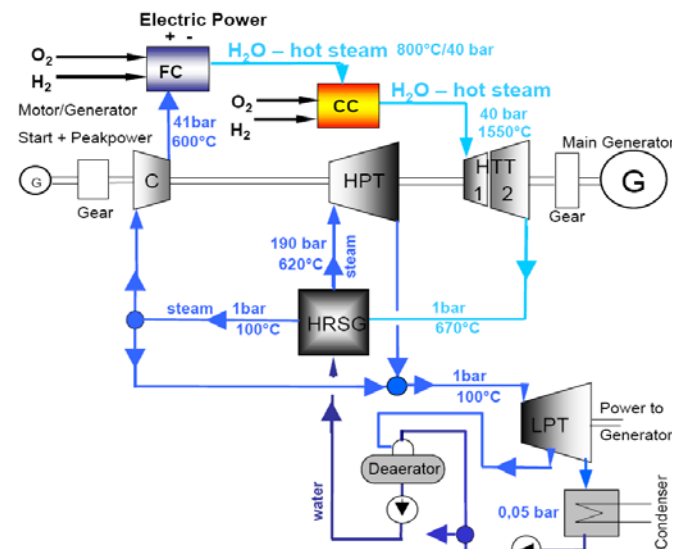
## PROCESS DESCRIPTION OF HYBRID PLANT

Figure 1 shows the principle flow scheme of the hybrid cycle, Fig. 2 shows the plant with the arrangement of fuel cells and turbomachinery. The plant is based on a proposal by Jericha [10] and consists basically of a high-temperature and a low-temperature cycle – a combined cycle. The high-temperature part consists of the fuel cells, the combustion chamber, the high-temperature turbine (HTT), the high-pressure turbine (HPT), the compressor and the heat recovery steam generator (HRSG). The low-temperature steam loop consists of the low pressure steam turbine (LPT), the condensate and the feed pump, the deaerator as well as the high pressure steam supply to the HPT and the low pressure steam

supply to the steam compressor feeding the fuel cells. The

**Table 1:** Component efficiencies and losses used in the thermodynamic simulation

Fuel	pure hydrogen
Combustor pressure	40 bar
Pressure loss FC/Combustor	1 bar
Oxygen excess	0 %
DC/AC converter efficiency	97 %
Turbine efficiency	HPT: 92 %, HTT: 90%
Compressor efficiency	89 %
Pump efficiency	70 %
HRSG pressure loss	10 bar cold, 0.1 bar hot side
Condenser pressure	0.05 bar
Mechanical efficiency	99 %
Generator efficiency	98.5 %



**Fig. 1:** Principle flow scheme of the hybrid cycle

detailed flow sheet used for the thermodynamic simulation can be found in the appendix (Fig. 6) and gives mass flow, pressure, temperature and enthalpy of all streams.

Steam (in the following called working gas) is compressed by a high-speed (22432 rpm) turbo compressor to 41 bar, 600°C starting from 1 bar, 100°C near saturation line. From there the working gas stream supplies several fuel cells and acts as cooling medium in the fuel cells to limit the temperature increase to 200°C. The fuel cells are arranged in parallel providing together a 30 MW DC electrical output delivered after the DC/AC conversion directly to the electrical grid. To the fuel cells 0.58 kg/s of pure hydrogen and oxygen in stoichiometric ratio are fed at 41 bar to deliver the electrical

output as well as to heat up the working gas to 800°C. Fig. 3

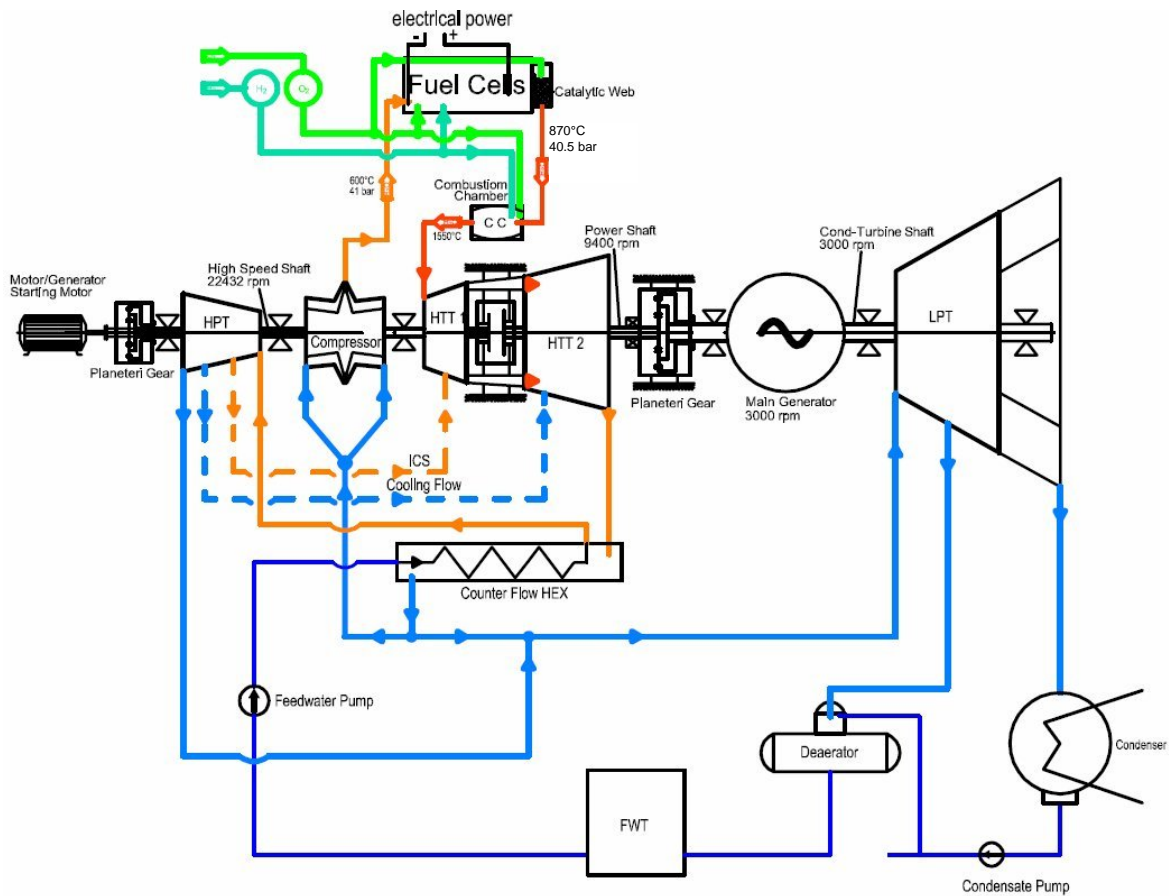


Fig. 2: Hybrid Plant with Arrangement of the Fuel Cells and the Turbomachinery

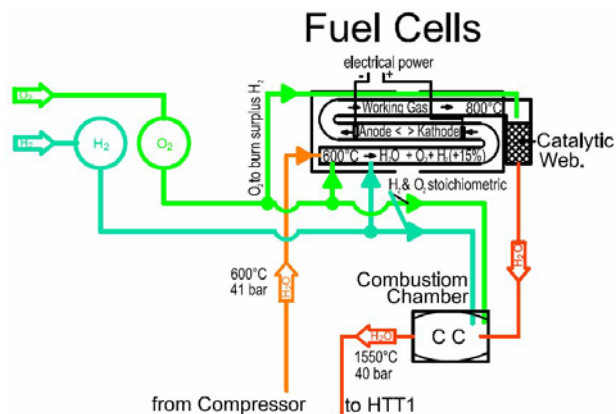


Fig. 3: Flow of fuel cell and combustion chamber

shows the internal relation of fuel cells and gas turbine combustion chamber in detail. The combustion water created by the hydrogen/oxygen combustion ( $H_2 + \frac{1}{2} O_2 = H_2O$ ) both

for electricity and heat production is added to the working gas flow – also pure steam. A surplus of 15 % of the total hydrogen and oxygen input (directly to fuel cells) which is required for the chemical reaction given above is first transported on with the working gas. To be certain with proper effective combustion a catalytic burner is arranged just behind the fuel cells [11] increasing the steam temperature to approximately 870°C. This is only a security measure to provide complete combustion since it is secured that any part of unburned hydrogen leaving the fuel cells and passing through the high temperature zone of the gas turbine combustion chamber is completely burned [12]. A high steam temperature of 870°C is possible at the combustion chamber inlet, because steam as cooling medium is provided.

The SOFC fuel cells proposed need an ignition temperature of 600 °C but can go up in temperature high above. The value of limit temperature of 800 °C was selected following design requirements of the plant cycle since the output flow of the fuel cells has to be delivered to the gas turbine combustion chamber. The steam with a temperature of 870°C after the catalytic burner is transferred by several tubes which can be operated at

this temperature without extreme high-temperature tube material providing only special internal insulations.

The high temperature turbine HTT is fed by the outflow of the combustion chamber at 40 bar and 1550°C. Here blade cooling sets in, since the high temperature requires effective measures in design. So in the first row of nozzles internal cooling is provided which reduces the mean blade inlet temperature to 1533 °C. This stage is to be built as a transonic stage using the innovative cooling system ICS which was developed within the EU research project DITTUS at Graz University of Technology in cooperation with GE Nuovo Pignone, Italy [13].

This first gas turbine stage HTT1 and the compressor are arranged on a very-high-speed shaft (22432 rpm) together with the high pressure turbine HPT to be described in consequence. After the first stage HTT1 the following stages of HTT2 power turbine are arranged on a somewhat slower running shaft (9400 rpm). At the outlet of the HTT2 we obtain steam at 1.1 bar and 670°C containing sufficient heat to feed a heat recovery steam generator producing high-pressure steam (190 bar) for the high pressure turbine HPT. After the HRSG about two-third of the 1 bar steam mass flow is sent to the compressor and further on to the fuel cells.

The HPT is running with the high speed shaft of 22432 rpm being directly coupled to compressor and first gas turbine stage (see Fig. 2). The inlet pressure of 190 bar is high for the mass flow and the power output of this relatively small steam turbine. So high speed and high number of stages are necessary. Steam is extracted in order to cool the high-temperature turbine (HTT1 and HTT2). The HPT expands to 1.1 bar close to saturation. The stream is then mixed with the remaining 1 bar steam coming from the HRSG and delivered to the low-pressure turbine.

There the working steam expands to condensing conditions at 0.05 bar in the condenser (maximum wetness being 12 %). Condensate pump, deaerator and feed water pump follow conventional practice. After the condensate pump the combustion generated water is extracted to maintain the cycle mass balance. The feed pump compresses the water to 200 bar and delivers it to the HRSG. Some water is led to the compressor inlet and outlet for quenching in order to obtain the optimal conditions at the fuel cell inlet.

## LAYOUT OF TURBOMACHINERY

The design and arrangement of the turbomachinery is shown in Fig. 4. The compressor design is envisaged as a double flow rotor with two axial stages on each side connected to a central radial disk. The disk is built in one piece together with the axial shaft parts which carry the above mentioned axial stages on both sides. So the general arrangement of the rotor is symmetric which allows inflow at low pressures from both sides and is creating an optimal flow situation in the radial diffuser leading the compressed working gas to the fuel cells. The axial stages contribute about half of the compressor pressure head. The first axial stages are checked for the admissible maximum tip Mach number of 1.4 as learned from

the development work at Darmstadt University [14], having designed and tested an industrial transonic compressor stage.

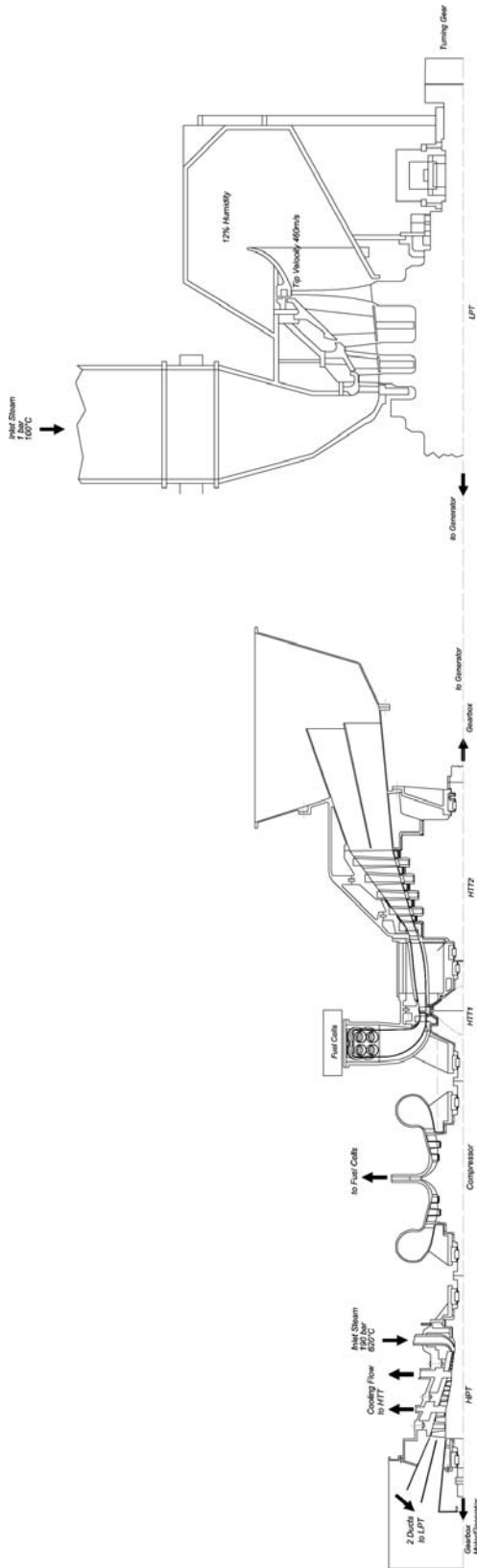


Fig. 4: Design details of the main turbomachinery

As mentioned before, the compressor is arranged together with the first gas turbine stage HTT1 and the high pressure turbine HPT on a very high speed shaft (22432 rpm). This high rotational speed is necessary to achieve a reasonable enthalpy drop for the HTT1 and especially for the HPT despite their small dimensions as a result of the low volume flow. The rotational speed is also limited by the tip Mach number of the first axial stages of the compressor running at the same speed.

After the first stage HTT1 the following stages of HTT2 power turbine are arranged on a somewhat slower shaft running with 9400 rpm. This speed leads to a reasonable stage number of five at bearable disk stresses at the same time. Fig. 4 shows the drawing of these five stages on a solid rotor design with blade lengths from 90 mm to 350 mm attached in fir-tree roots on small elongation disks on the rotor drum.

For the cooling of the HTT compressor turbine (HTT1) and power turbine (HTT2) the innovative cooling system ICS is applied. It consists of hollow rotor blades with radial slits on the pressure side from which a supersonic flow of cooling medium adhering to the surface is created. These coherent films starting on the pressure side go in both directions. The first slit row releases cooling steam flowing in the same direction as the main flow, whereas the second slit row creates a film which flows also partly against the main flow around the leading edge and then all along the suction side to the trailing edge. This system was tested in several arrangements in cascade and turbine test facilities and presented to ASME and other scientific organizations [15, 16] proving the feasibility and the cooling improvements of this novel design method [17]. Several papers on transonic stages and ICS cooling have been published in the wake of this development, pointing out the specific design advantages of such a stage [18].

The total cooling mass flow of the HTT turbine is estimated to 8 kg/s which corresponds to 13.7 % of the total inlet mass flow. This amount is taken from previous investigations on Graz Cycle high temperature turbines [19] and considers that the heat radiation of a working fluid of pure steam is less than of a working fluid containing also CO<sub>2</sub>.

The power turbine is connected by a planetary gear to the main generator delivering the main power output. On the other side of the generator the low pressure steam turbine LPT is attached in the form of a conventional low-pressure three-stage turbine (see Fig. 5). The mean radius of the last stage is 1134 mm and the last blade length is 660 mm carrying conventional water droplet impingement protection (maximum wetness being 12 %). The speed is 3000 rpm, the turbine is contributing about 14 MW to the power output.

The design of the high pressure turbine HPT requires some further deliberations (see Fig. 4). Part load can be managed by lowering entry conditions, so that a control stage is not necessary. High efficiency is needed there, so that the design decision was made for a 50 % reaction blading and multiple stages at low rotor diameter. In a partly undivided casing rotor and attached blade carriers are axially mounted. In between the carriers taps are arranged to deliver cooling flow to the HTT. A balance piston is needed and is to be built in the usual way.

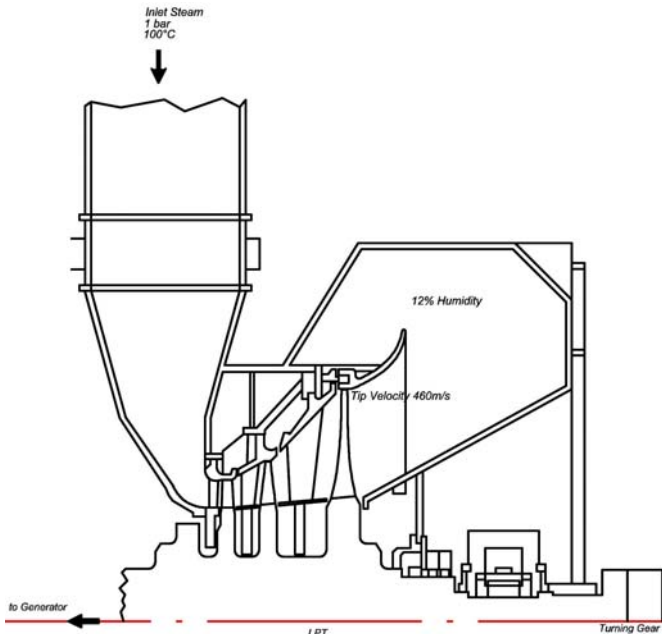


Fig. 5: Design details of the low-pressure steam turbine

## POWER BALANCE

Based on the thermodynamic layout of the hybrid power cycle a power balance of the process is given in Table 2. Input of 1.568 kg/s hydrogen and the stoichiometric mass flow of oxygen are fed to the fuel cells and the combustion chamber resulting in a total heat input of 188 MW. The HTT – a gas turbine - is the most powerful turbine of the plant and delivers 123.1 MW. The power of HPT and LPT are 22.4 MW and 14.3 MW, respectively. The total turbine power of 159.8 MW is opposed to a total compression power of 48.5 MW, resulting in a generator power of 109.6 MW. Additionally, 29.1 MW of AC electrical power is provided by the fuel cells, so that the net electrical power of this plant is 138.7 MW. This results in a remarkably high net efficiency of 73.8 % showing the advantage of incorporating fuel cells into a gas turbine power plant.

If a higher share of fuel cell power could be achieved, the total efficiency of the hybrid cycle would even be higher. But in the current design the steam mass flow leaving the combustion chamber is the minimum mass flow which still allows to obtain feasible turbomachinery dimensions. So a higher share of fuel cell power can only be achieved by increasing the fuel cell power and at the same time allowing a higher temperature increase in the fuel cell. If the turbomachinery mass flow is maintained and a fuel cell temperature increase of 300°C is allowed, the fuel cell power can be raised to 47 MW and the total efficiency from 73.8 % to 76.2%. But in this investigation it was intended to limit the number of fuel cells, because of the expected difficulties of building a 2.5 MW fuel cell and of arranging them in parallel in front of a combustion chamber.

Table 2: Power Balance

Fuel input	1.568 kg/s H <sub>2</sub> , 12.44kg/s O <sub>2</sub>
Total heat input	188 MW
HTT power	123.1 MW
HPT power	22.4 MW
LPT power	14.3 MW
Compressor power	47.8 MW
Total pump power	0.7 MW
Generator power	109.6 MW
Fuel cell DC power	30 MW
Fuel cell AC power	29.1 MW
Net electrical power	138.7 MW
Net efficiency	73.8 %

## SUMMARY AND CONCLUSIONS

With considerable development of fuel cells to higher power and electric efficiency and with the use of turbomachinery development to which the Institute for Thermal Turbomachinery and Machine Dynamics, Graz University of Technology, is proud to have contributed, a hybrid power plant is presented with advanced and beneficial features. It combines fuel cells with an advanced power cycle using steam as working fluid.

Electrolysers powered by solar and solar-derived energy produce hydrogen which is fired in the fuel cells as well as in the combustion chamber with pure oxygen. The working gas steam allows a highly efficient power cycle with a peak temperature of 1550°C and heat extraction at ambient temperature. This results in an efficiency of 73.8 % for this hybrid power cycle.

In order to assess the merits of this new hybrid cycle, also an economic evaluation would be necessary. Due to the high costs of fuel cells high specific plant costs are expected, but since some components as the HTT have to be newly developed, it is not possible to obtain reliable investment costs at this time. An economic evaluation would also need a comparison with an alternative plant using hydrogen and oxygen as fuel.

The main source of energy for this power plant is the sun whose radiation is used directly or via transformation to energy contained in moving air and water. Thus applying this power cycle in a future energy system the world could reap the following beneficiary effects [1]:

- no generation of CO<sub>2</sub> at all
- use of water as working medium in fuel generation as well as in power generation
- possible improvement of the world's climate situation, certainly the task of the future.

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APPENDIX

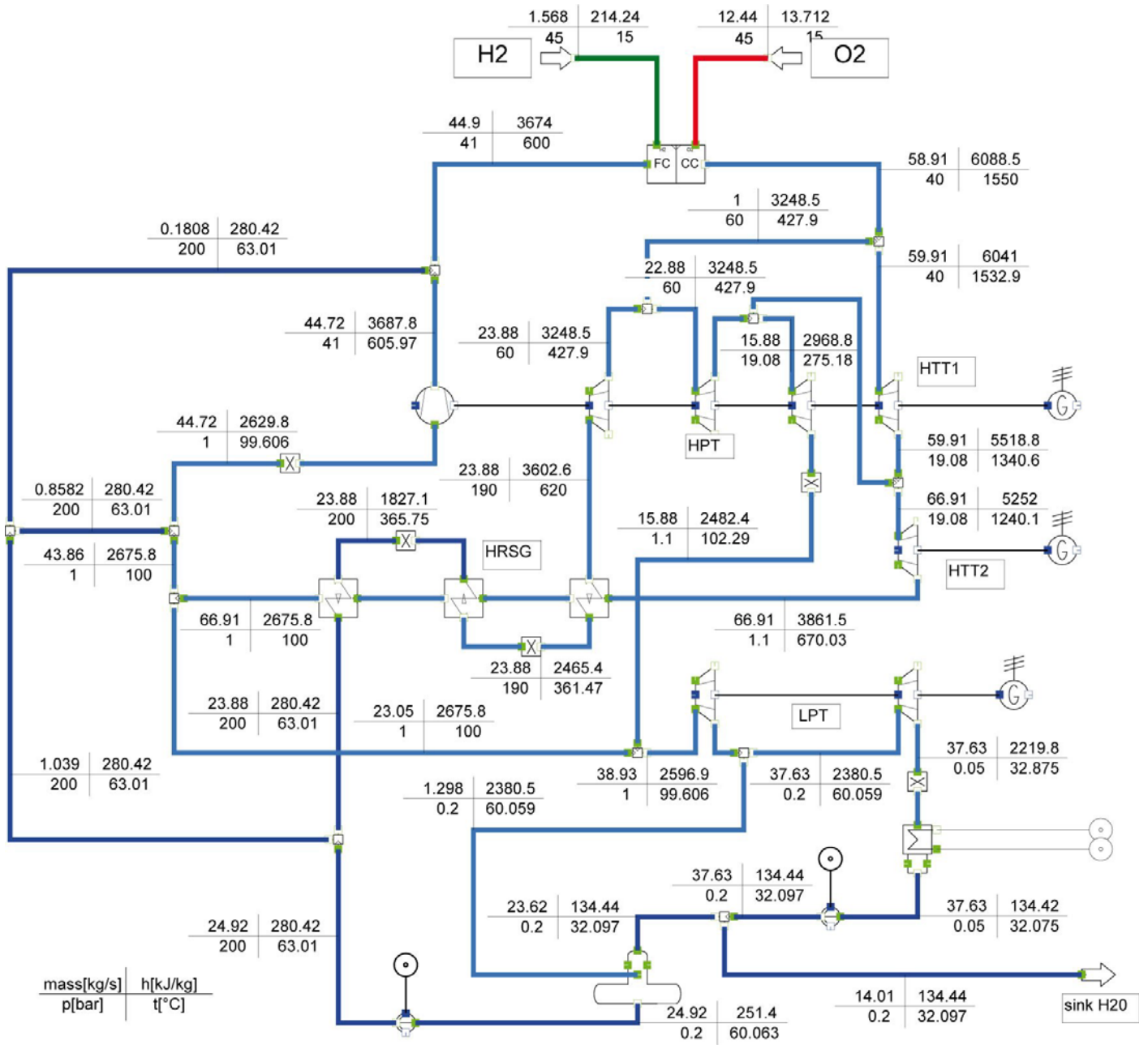


Fig. 6: Detailed thermodynamic cycle data of the fuel cell/gas turbine hybrid plant