Feasibility of hydrogen-air energy storage gas turbine system for the solar power plant in Yakutsk region

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Abstract. For the solar power plants unsteady power generation is one of the main drawbacks, which must be taken into account. The hydrogen-air energy storage gas turbine system is considered in this paper for the Yakutsk region in Russia. This place with no centralised electrical grid has enough solar insolation level to supply the power the settlement of several households with the average power consumption of 3 kW. The calculations show that 52 photovoltaic panels of the specific type are optimal number from the power balance data. It is supposed that in the months with the surplus of solar power the system works in generation mode and in the other months in storage mode. Also some reserve is planned for the supply during night in the storage mode by the gel batteries. After that the volumes and masses were determined for the reservoirs containing air, hydrogen and oxygen for the energy storage. The air reservoir for the compressed air energy storage (CAES) has the biggest volume 121 m³ according to the calculations. The gas turbine (GT) of 5 kW suits the system in the power generation mode. The special hydrogen-air combustion chamber is required for the GT unit.

1. Introduction
The problem of the energy storage for the solar power stations has already been demonstrated in different papers. The use of hydrogen produced by the extra generated electricity by a rooftop solar power generation unit was analyzed for producing the required electrical power at night [1]. Two concentrated photovoltaic thermal modules integrated with organic Rankine cycle were proposed to generate electricity during the day with the extra power being utilized in an electrolyser to produce hydrogen. At night the required electrical power for the house is supplied by the fuel cell system using the hydrogen produced during the day.

Another experimental study [2] was carried out with the greenhouse at the farm in Valenzano (Bari, Italy). The equipment was installed there to produce electricity by solar photovoltaic source. It supplied the power for electrolyser which produced hydrogen from water. The produced hydrogen was stored in special pressure tank, and then it was used for greenhouse electricity demands by a fuel cell system at night or overcast sky. The electricity produced was used for heating system of 48 m² greenhouse.

The case study concerning a plant for hydrogen production and storage was performed for four different technical solutions [3]. The plant was located in Romania with the average hydrogen yield of 100 kg/day. The results showed that a system of producing hydrogen by the electrolysis of vapor...
produced by concentrated thermal solar systems and electricity generation using concentrated photovoltaic systems (hybrid system) were preferable.

As for the compressed air storage in the field of the solar power the theoretical analysis was made [4] for floating photovoltaic systems. The authors suggest using the pipes for the buoyancy of the modular raft structure as a compressed air reservoir. Such a system can be considered as an isothermal compressed air energy system (ICAES) because of the very large thermal bath formed by the water basin. The system needs some improving in compressor system, but the quantity of stored energy is still enough to provide the day-night autonomy of the floating PV pontoon.

Due to the need in enhancing of the energy performance of historical buildings the simulation and experimental investigation was made [5] for the compressed air energy storage (CAES) of the solar energy which was produced by the photovoltaic tiles on the roof of the building in Italy. The integration of the PV system with CAES system had the goal of exploiting the surplus energy produced by the PV system, which was not consumed by the appliances of the building. The compressed air was expanded in the quasi-turbine for producing energy when the PV generation was not enough. The small-sized CAES system was located in the unoccupied basement of the building. The authors’ simulation for the CAES showed that it covered 21.9 % of the residential energy demand at 30 bar, and the CAES covered 26 % of the residential energy demand for the building at 225 bar compression section.

Several configurations of the hybrid system which combines hydrogen energy storage and CAES were theoretically analyzed [6]. The simplest configuration consisted of the compressor, turbine, air storage and hydrogen storage as main components. The part of the electrical power was used to drive the compressor, and so the working fluid was pumped in the reservoir. The rest of the electrical power was used to produce hydrogen in electrolyser. But the authors neglected the effects of the air reservoir size. They considered that the volume of the reservoir is enough to assume that the temperature and pressure are constant within the reservoir. It was concluded that for a simple hybrid storage system the introduction of hydrogen storage in a CAES had a positive effect. For regenerated system the combination of hydrogen system and CAES always improved the efficiency. And when a multistage system was considered, the efficiency grew by increasing in number of stages in the compression and expansion phases. But in the last case the marginal efficiency has to be balanced as the costs increase too with more stages.

Iranian scientists conducted a theoretical study [7] for applying high solar power potential in the south of the Iran to reduce the fuel consumption of the GT power plants which are the major energy technology used in Iran. The power generation system was supposed to electrify 500 households. Hybrid system was considered which consisted of electricity and compressed air storage technologies, molten carbonate fuel cells, gas turbines, photovoltaic modules, thermal energy storage system, lead/acid batteries. The isobaric system using an auxiliary water reservoir for the CAES has been seldom addressed in other research works before. The difference in height between the pressurized air vessel and water reservoir creates a constant pressure in the air vessel during charging and discharging process because the water reservoir has a large area and low height. Consequently the pressure fluctuations during charging and discharging processes could be neglected.

In this paper it is modelled the combined hydrogen-air energy storage gas turbine unit [8] for the solar power plant. The solar power plant supplies a small remote workers’ settlement consisting of several houses in Russia with the electrical energy. The workers’ settlements are very often located in the areas with no centralised electrical grid, but the solar radiation levels there could be rich enough.

2. Location of the study and the energy storage system layout

Yakutsk region in the Russian Federation was used for the modelling of the power production by the power plant. The precise coordinates 62° N 129° E of the settlement located at some distance to the west from Yakutsk were used for the insolation data in the area with the absence of the centralised electrical grid. Also these coordinates are more convenient for the software used. The chosen area is
plentiful for the solar resources according to the insolation data [9]. The average power consumption is slightly more than 3 kW here.

The novelty of the storage system in this paper is a gas turbine system and a combustion chamber. The main goals of the chamber construction must be ensuring of the stoichiometric component ratio in the process of the most complete combustion of hydrogen in oxygen and the smooth air heating to avoid the formation of nitric oxides.

The principle of work of the storage system calculated in this paper is showed in figure 1. The solar plant 1 supplies the settlement 14 with the electricity, and when there is a surplus of the generated energy in the electrolyser 6 a process of hydrogen and oxygen production occurs using the energy produced by the solar power plant. Hydrogen and oxygen are pumped then in hydrogen reservoir 7 and oxygen reservoir 8. The air compression in charging mode takes place in the compressors driven by engine-generator 4. The compressor unit consists of a medium part 2 and a high-pressure part 3. Also there are two air coolers 9 for intermediate air cooling. The heat excess from the coolers is accumulated in the heat storage 10. After cooling the air is compressed into the air reservoir 11.

And in the power generation mode the compressed air from the reservoir is directed through the regenerative air heater 13 where it is heated by the gas-turbine 5 exhaust gas. After that the air is fed to the combustion chamber 12 where the former is heated by the energy of burning hydrogen in oxygen. In the chamber the hydrogen is precombusted in oxygen what leads to mixing of the generated high-temperature steam with the air. Consequently the air is heated to the required temperature, and in this process the formation of any harmful substances (NOx) is excluded.

![Figure 1](image)

**Figure 1.** Schematics of hydrogen-air storage gas turbine system for the solar power plant.

The chosen hydrogen-air storage gas turbine system is thoroughly described in [8] including the equations for the calculating of the main parameters. The characteristics of the PV module Hevel HVL-380/HJT used in this paper are showed in table 1.
Table 1. The characteristics of the chosen PV modules.

|                        | PV |        |
|------------------------|----|--------|
| Nominal power          | 380 W |        |
| Efficiency, $\eta_{PV}$| 19 % |        |
| Surface area, $S_{PV}$ | 2.0 m²|        |

The climatological data-base for the Russian Federation software [9] is applied in this paper for the initial data for monthly insolation level. The advantage of chosen program is the availability of the daily insolation data for the optimally oriented surface which is one of the most popular and cost effective way of installing the PV panels. In figure 2 there are the daily insolation data for the optimally oriented surface for coordinates of the Yakutsk region.

![Daily solar insolation on the optimally oriented surface of the PV panel in Yakutsk region.](image)

We can conclude from figure 2 that the solar power plant for the chosen place can generate effectively from March till September. From November till January the storage system is an essential component. And February and October can conventionally divide these two modes, but for this particularly case we will include February and October in generation mode. For the following calculations the equation (1) for electrical energy $E$ produced by the PV panels if it is assumed that they supply the electrical network which can consume all the produced electrical energy for the period of time [10] is used

$$E = \eta_{PV} \overline{Q}_d S_{PV} N$$

where $\eta_{PV}$ is the efficiency of the PV panel, $\overline{Q}_d$ is the daily solar insolation on the surface of the PV panel kWh/(m²·day), $S_{PV}$ is the surface of a PV panel m² and $N$ is the days’ quantity in the selected period of time.

What for the power consumption of the settlement the theoretical load schedule for comparable size inhabited locality may be used for our calculation [11]. Having collected all the necessary information in table 2, we also should calculate the surplus of the generated energy which the storage system can accumulate. The conditions for the solution were that the sum of the energy surplus from March till September has to be more that the energy shortage from October till February, and that some reserve should be made for the surplus of energy because we should take in account the efficiency of the
storage system as well as the solar insolation uncertainty. And then it makes it possible with the numerical method to determine the optimal quantity of the PV panels needed from energy balance calculation.

### Table 2. Energy balance for determining of the optimal PV panels quantity.

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Gen. per hour, kWh | 0.92 | 2.36 | 4.23 | 5.58 | 5.9 | 6.43 | 6.19 | 5.16 | 3.51 | 2.45 | 1.33 | 0.63 |
| Gen. per month, kWh | 574 | 1331 | 2641 | 3371 | 3865 | 3222 | 2121 | 1530 | 804 | 393 | -347 | -1216 |
| Consum. per month, kWh | 3712 | 3120 | 2335 | 2243 | 1920 | 1447 | 1535 | 1821 | 1800 | 1877 | 2020 | 3039 |
| Surplus (shortage-) per month, kWh | -3138 | -1789 | 306 | 1128 | 1764 | 2438 | 2330 | 1401 | 321 | -347 | -1216 | -2646 |

To obtain this balance we took 52 PV panels as optimal quantity because it can be seen from the table 2 that generation Surplus$_{Mar-Sep}$ > Shortage$_{Oct-Feb}$ by 551 kWh which is enough to meet both conditions above. For comparison if we used for the same scale of storage only gel batteries Haze HZY 12-230, where 12 V is the voltage and 230 Ah is the capacity, it would be necessary to have more than 3500 batteries. In figure 3 the calculated surplus or shortage from table 2 of power generation can be seen for generation and storage modes already mentioned above.

![Figure 3. Power generation surplus or shortage for the solar power plant during the year, kWh.](image)

Finally according to the [8] we will calculate other necessary parameters for the storage system. The minimum pressure in the reservoirs is taken as the minimum pressure at the gas turbine inlet (1.5 MPa), and the maximum pressure is determined by the maximum pressure in the reservoir (12 MPa). The air reservoir needs more space than other reservoirs, but it is quite comparable in scale order to the area needed for the solar panels.

The gas turbine with the power of 5 kW is enough for this case. For the reserve in the generation mode period we should foresee the batteries for night power supply nevertheless. For the average July consumption it will need about 10 kWh power reserve which we can supply by the same type of gel batteries in the quantity of 4 only. We suppose that the electrolyser works all the storage period, but...
Compressor accumulates air only in the months with the most surplus of the solar energy yield. It is the period from April till August according to table 2. Finally we gather the equipment parameters for the accumulation system in table 3.

| Table 3. The characteristics of the reservoirs of the storage system equipment. |
|---------------------------------------------------------------|
| Symbol      | Value       |
| m_{air}, kg | 13562       |
| m_{H2}, kg  | 76          |
| m_{O2}, kg  | 603         |
| V_{air}, m^3| 121         |
| V_{H2}, m^3 | 9.66        |
| V_{O2}, m^3 | 4.63        |
| Gas turbine power, kW | 5           |
| Electrolyser power, kW | 0.5         |
| Compressor power, kW | 3.0         |

3. Conclusion
In the first chapter it was demonstrated that there is no single solution to the problem of energy storage for the solar power plants. Some authors offer compressed air storage systems. Hydrogen storage system using fuel cells is also very popular. In the second chapter the feasibility of hydrogen-air energy storage gas turbine system for the solar power plant in Yakutsk region was investigated for the particular case and energy demand. First the solar insolation potential was analyzed for the chosen coordinates. Also the principle layout for the storage system was described. Allowance was made for the load schedule of the settlement. It made it possible to compile the energy balance for the storage system. Then the optimal quantity of the PV panels was calculated with the numerical method, and after that other main energy characteristics of the system and the volumes of the reservoirs were determined. Some of the conclusions are listed below.

- The solar insolation level in the described region of Yakutsk allows for the solar power plant to supply the settlement with the electrical energy from March till September effectively, but in the other months effective storage system is essential.
- 52 PV panels are enough for the load schedule even considering some reserve.
- The chosen hydrogen-air energy storage gas turbine system can be effectively used for described case, and the reservoirs sizes are not oversized for the small settlement’s conditions. The gas turbine with the power of 5 kW suits the system.
- Nevertheless, 4 batteries are foreseen for the night power reserve.
- In the following studies the economic assessment of the equipment costs may be of great value.

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