Sizing study of a hydrogen electrolyzer-gas turbine system

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***Abstract*— The aim of this paper is to determine a sizing methodology of a hybrid architecture composed of a power plant, an electrolyzer with hydrogen compressor; a high-pressurized gaseous storage, and a gas turbine. The purpose of such system is to replace a CO_2-emitting electrical production provided by a natural gas fired turbine in Germany operating as a peaker by the hybrid architecture which also mitigates the intermittent power of a wind-only system. The proposed sizing methodology aims to determine range of power and capacity of each component, and associated operation profiles studied on an hourly basis.**

Keywords—electrolysis, gas turbine, hydrogen, Power-to-power

TABLE I. NOMENCLATURE

Symbol	*Definition*	Unit
t	Time	s
ΔP	Power available/required	W
P_{elc}	Electrolyser power	W
p_{elc}	Electrolyser outlet pressure	Pa
T_{elc}	Electrolyser outlet temperature	K
ψ_{elc}	Electrolyser specific electricity consumption	J/kg_{H_2}
$P_{comp_{it}}$	Compressor isothermal power	W
$P_{comp_{elec}}$	Compressor electrical power	W
$\dot{m}_{H2}$	Hydrogen mass flow produce or consumed	kg/s
r_{H2}	Hydrogen specific constant	$J.kg^{-1}.K^{-1}$
m_{str}	Hydrogen mass inside the storage	kg
p_{str}	Pressure inside the hydrogen storage	Pa
V_{str}	Hydrogen storage volume	m^3
P_{GT}	Gas turbine nominal gas power	W
LHV_{H2}	Hydrogen lower heating value	J/kg
η_{turb}	Gas turbine LHV efficiency	/
η_{isth}	Compressor isothermal efficiency	/
η_{elec}	Compressor electrical efficiency	/

I. INTRODUCTION

Renewable wind and solar energy have seen their deployment accelerated due to decarbonization goals [1]. Some countries, such as Germany, are developing ambitious environmental strategies for developing renewable energy by 2050 [2], [3]. Realistically, these renewable energies will not be enough to ensure future electricity demand by themselves. Those sources require a back-up system or an energy storage system to provide on-demand power because they are inherently intermittent [4]. Battery technology is not suitable to store and provide large energy capacities over prolonged periods of time [5], so dispatchable power production sites are still needed. Combining green hydrogen production and gas turbine technology is a way to provide electricity on-demand plus hydrogen gas.

In their work, Öberg, Odenberg and Johnsson [6] highlight competitive potential of such systems in future energy networks where intermittent renewable energies comprise a large share. In addition, the presence of thousands of turbines on the European continent in particular paves the way for retrofits from natural gas to hydrogen fuel.

Several papers studied similar systems while focusing on the electricity and heat production potential [7], the thermodynamic efficiency [8], and economic potential [9]. The work of Thomas, Tobias, and Manfred [10] demonstrated the potential economic viability for an on-site hydrogen production system coupled with a hydrogen-fired gas turbine. Conditions of economic viability include cheap renewable electricity and high hydrogen demand. The focus of the present work is to analyze the operating profile of such system components for a given sizing methodology.

II. CONCEPT AND METHODOLOGY

This paper proposes a sizing methodology of a hybrid architecture based on a 100% hydrogen-fired gas turbine and hydrogen production chain (electrolyzer, compressor, high-pressure gaseous hydrogen storage) coupled with wind power. Fig. 1 describes its operation to meet yearly electrical demand on an hourly basis with a yearly renewable production. Two operational cases were considered for the hybrid architecture, based on wind turbine production relative to electricity production.

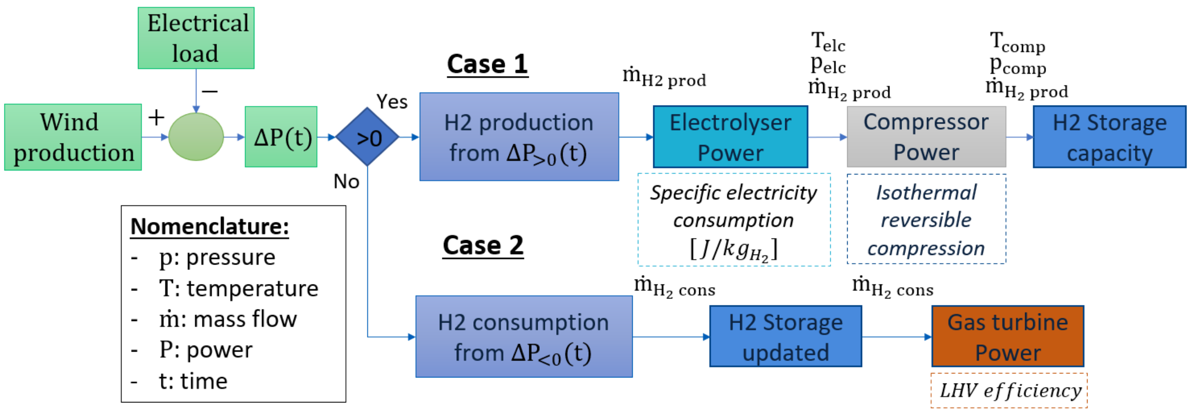

Fig. 1 Hybrid Architecture operation concept

- Electricity produced from wind is greater than or equal to electrical load demand. In this case, wind production supplies the electrical load, and excess production is used to produce hydrogen by electrolysis. The hydrogen is then compressed to a high pressure and stored. The gas turbine does not operate.
- Wind turbine production is not sufficient to meet electrical demand. Gas turbines operating with hydrogen fuel fill the gap between wind production and electrical demand. The electrolyzer and hydrogen compressor do not operate.

The main assumptions hereafter have been considered:

- The electrolyzer and the compressor are both fed by the renewable power during hydrogen production phases (1).

$$\Delta P(t) = P_{elc}(t) + P_{comp}(t) \quad (1)$$

- Hydrogen is assumed to be an ideal gas. Isothermal reversible compression is assumed for the compressor. This compression minimize the mechanical work and it's considered as an ideal case. It makes it possible to understand the orders of magnitude involved while remaining in an ideal case, not too far from a real case in view of the pressure ranges studied [11], [12]. An isothermal efficiency (η_{ist}) and an electrical efficiency (η_{elec}) are considered, while r_{H_2} is the gas specific constant (2).

$$P_{comp_{elec}}(t) = \dot{m}_{H_2}(t).\, r_{H_2}.\, T_{elc}.\ln\left(\frac{p_{str}(t-dt)}{p_{elc}}\right)/\eta_{ist}/\eta_{elec} \quad (2)$$

- Supplier's data are used to model electrolyzer and gas turbine performances. A specific electricity consumption $\psi_{elc}[J/kg_{H_2}]$ is used for the electrolyzer (3), LHV efficiency (η_{turb}) for the gas turbine (4).

$$P_{elc}(t) = \dot{m}_{H_2}(t).\, \psi_{elc} \quad (3)$$

$$P_{GT}(t) = \dot{m}_{H_2}(t).\, LHV_{H_2}.\, \eta_{turb} \quad (4)$$

- The hydrogen mass hydrogen production can be deduced as (5), based on (1), (2) and (3). As well, starting from (4) the hydrogen consumption can be determined (6).

$$\dot{m}_{H_2}(t) = \frac{\Delta}{\psi_{elc} + r_{H_2}.T_{elc}.\ln\left(\frac{p_{str}(t-dt)}{p_{elc}}\right)/\eta_{ist}/\eta_{elec}} \quad (5)$$

$$\dot{m}_{H_2}(t) = \frac{P_{GT}(t)}{LHV_{H_2}.\eta_{turb}} \quad (6)$$

- The hydrogen storage is considered as one unique volume with no impact due to the outside environment. The inside compression, due to the mass accumulation (7), is considered as isothermal. Hydrogen ideal gas pressure can be calculated as (8).

$$m_{str} = m_{H_2}(t) + m_{str}(t - dt) \quad (7)$$

$$p_{str}(t) = \frac{m_{str}(t)*r_{H_2}*T_{str}}{V_{str}} \quad (8)$$

The following computational process is applied to determine components' sizing:

- Initialize the components' values: Unlimited storage is assumed with a minimum pressure to maintain; gas turbine nominal power is fixed at maximum electrical demand power; gas turbine is assumed to be able to operate between 0 and 100% nominal power without restriction (in reality, NOx, and CO emissions if not 100% H_2 fuel blend, would limit minimum power output the gas turbine can deliver which is typically around 35% of the nominal power) and to operate at a constant efficiency independently of the power output; electrolyzer nominal power is assumed to be the same as the available renewable power; electrolyzer is assumed to be able to operate at part-load; renewable nominal power is set at the gas turbine power; if there is two different sources (wind and solar) then it's the addition of their power which is considered as the nominal renewable power.
- Run simulation over the year. Check if the hybrid system meets 100% of the electricity demand at every hour. With each iteration, increase or reduce the renewable nominal power until it reaches a value where the system can no longer meet the electrical

demand. The renewable nominal power is fixed at the lowest value where the hybrid system can still supply the electricity demand.

- The electrolyzer nominal power is decreased to the lowest value so the entire system can still meet 100% of electrical demand, for the fixed renewable nominal power selected.
- The hydrogen storage tank volume is determined based on the selected electrolyzer power.

III. Case study

The case study is based on a consumption profile to be answered with the hybrid system, this profile will be called "baseline". This baseline under consideration is a GE 9E.04 gas turbine (147 MW; 39.6% LHV efficiency, based on GE catalog available at https://www.ge.com/gas-power/products/gas-turbines) powered by natural gas, located in Hamburg, Germany. Northern Germany was chosen to have a continental framework, with gas turbines already present and renewable energies already well established, and under development, in the electricity grid [13], [14].

A "peaker" year type profile is assigned to it, based on seasonal winter operation. This profile consists of 50 runs of 4 hours at full load, see Fig. 2. This operation corresponds to high demands in winter, due to increased heating demand. High demand is therefore recorded between the months of November and April. This operation, applied to our hybrid system, makes it a seasonal storage. The choice of this kind of operation is based on several studies which have shown the importance of such storage in electrical networks with renewable energy injections of up to 100% [15], [16], [17]. In their work, Elberry, Thkur and Veysey, in particular, validate the role of seasonal hydrogen storage in Finland's energy transition [18], which also has to face an increase in electricity consumption during the winter.

To power the hybrid system, intended to replace the baseline, the case study is based on a year onshore wind production profile, with the same location as the baseline. This profile, see Fig. 3, was extracted from [19] considering a 2 MW Vestas V90 2000 turbine model with 80 meters hub height, and the 2019 year. The hybrid architecture is also based on an identical gas turbine, an electrolyser consuming 56 kWh_{elec}/kg_{H_2}, compressor with 79.6% isothermal and 97% electrical efficiencies, and a gas pressure tank at 300 bar storage with a single volume and a minimum pressure of 35 bars.

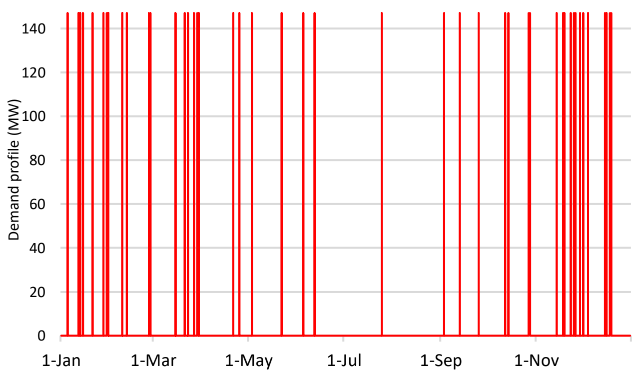

Fig. 2 Electricity demand profile

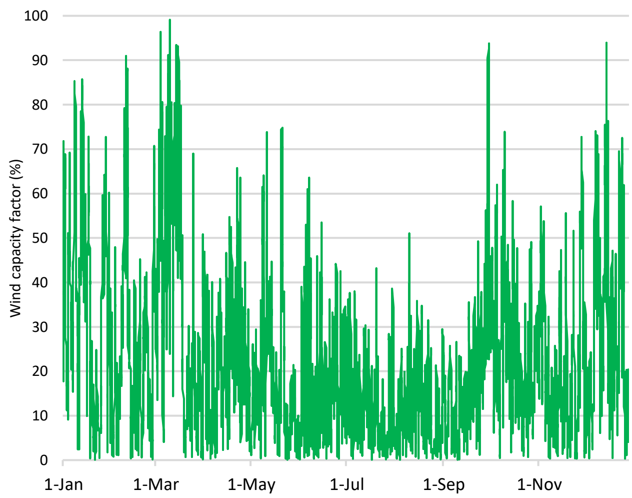

Fig. 3 Wind production profile

IV. Results

Applying the methodology to the case study, the sizing presented in Table II was obtained. They correspond to equipment size to be considered for the system to meet the electrical demand.

A. *Hydrogen mass storage*

Fig. 4 showing the useful hydrogen, *i.e.*, hydrogen that can be used in the gas turbine to produce work while maintaining a safe minimum pressure in the storage tank. It can be observed that, in period 1 in Fig. 4, the storage reaches its minimum capacity. This is due to a high electricity demand in this period. This period, which represents only 5.6% of the year, is the only time when the hydrogen production chain is used to its full capacity. Periods of hydrogen production stoppage are observed between the end of June and September, period 2 in Fig. 4. The system has the capacity to produce more hydrogen, but this is not necessary to meet electrical demand 100% of the time. One can see a possible improvement, which is to utilize hydrogen for other purposes rather than having production stoppage periods.

B. *Gas turbine production*

The proposed architecture involves sharing the response to electrical demand between the renewable power available, non-controllable, and the gas turbine, controllable The Fig. 5 highlights this phenomenon where we notice that the turbine works in part load mode at all these calls. Part-load operation results in a reduction in the efficiency of a gas turbine [20], [21], [22]. The effects of this efficiency reduction should be integrated in this method to improve it.

If the turbine never falls below the minimum power that has been set in this particular case, this could happen in other less favorable cases. The possibility of the turbine not functioning due to reaching its minimum power should be taken into account in future operating strategies for such a hybrid architecture.

TABLE II. Dimensionnal results

	Renewable power	**Electrolyzer power**	**Compressor power**	**Hydrogen storage (useful)**
Sizing	85 MW	58 MW	1.05 MW	302 tons

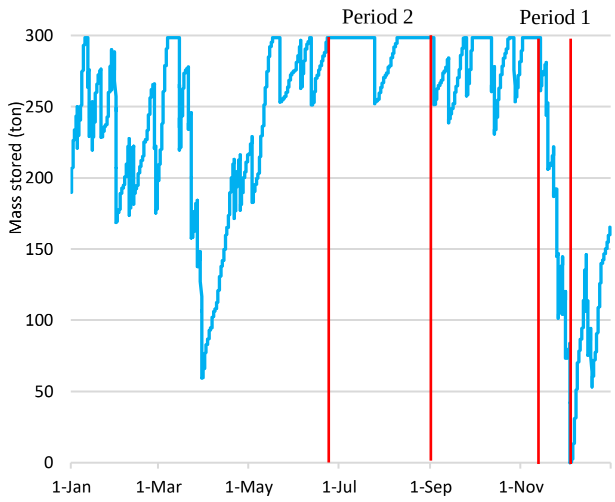

Fig. 4 Useful hydrogen mass storage analysis

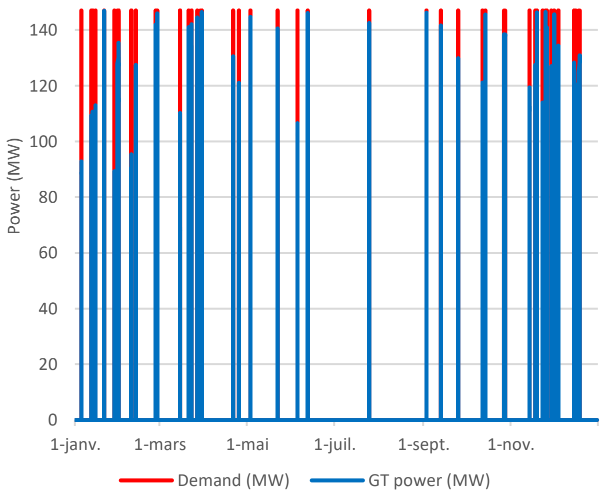

Fig. 5 Gas turbine production compared to demand

C. Electrolyzer operation profile

The electrolyzer operation profile, see Fig. 6, shown a vast period where the electrolyzer operates in part load mode, which corresponds to the “period 2” seen in Fig. 4. This period corresponds to summer when the winds are less powerful. The electrolyzer, being directly powered by wind production, is therefore based on the power available. As for the gas turbine, this implies a drop in efficiency during such operation. Alkaline technology is particularly subject to this, which is less the case with PEM (Proton Exchange Membrane) technology [23], [24].

The choice of operating strategy will be decisive in overcoming this problem. The technologies already available couldn’t reach the kind of power requested in our case. So, assembling several smaller devices will certainly be chosen. The control of these devices could decrease the impact of the part-load operation by the by operating only a limited number of devices but at full power.

D. Compressor operation profile

The compressor also has periods when it works in part load mode, see Fig. 7. These periods are influenced by the filling rate of the hydrogen tank and by the hydrogen production capacity directly dependent of the renewable power available. In our case, the choice of a single reservoir leads to a gradual increase in the compressor ratio. Operation at different discharge pressure required to adapt the compressor [25], [26].

In cases where storage is composed of several small tanks, the compressor could operate at the same pressure discharge for most of the operating time. This will have an impact on the energy available for the electrolyzer. Determine a filling strategy will be required to know the compressor parameters of operation (mass flow, temperature, pressures). These parameters could impact the work required for the compression [27], [28].

As for the electrolyzer, the compressor would be composed of several smaller devices to reach the power required. The operation strategies should also determine the optimal number of devices in operation at full load.

As explained in equation (5), the model is based on isothermal compression according to the ideal gas law, which is an ideal case. The power dedicated to the electrolyzer is therefore underestimated, to put it in a more unfavorable case, and closer to reality, it would be necessary to switch to isentropic compression based on a real gas law.

E. CO_2 abatement

One of the targets of this hybrid solution is to provide a decarbonized solution. IPCC data shows emissions between 350 and 490 g_{CO_2eq}/kWh_{elec} [29] due to natural gas combustion in gas turbine.

Switching to hydrogen would decrease those direct emissions by 100%. The rest of lifecycle emissions would need to be evaluated although they are expected to be lower than natural gas value chain emissions if hydrogen is produced through electrolysis powered by renewables [30], [31], [32].

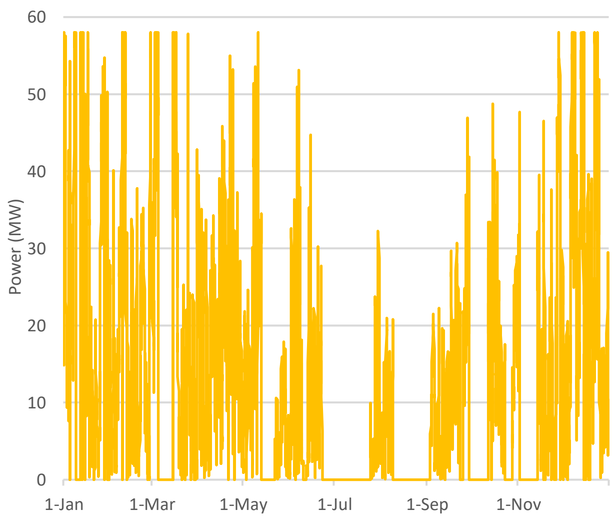

Fig. 6 Electrolyzer power profile

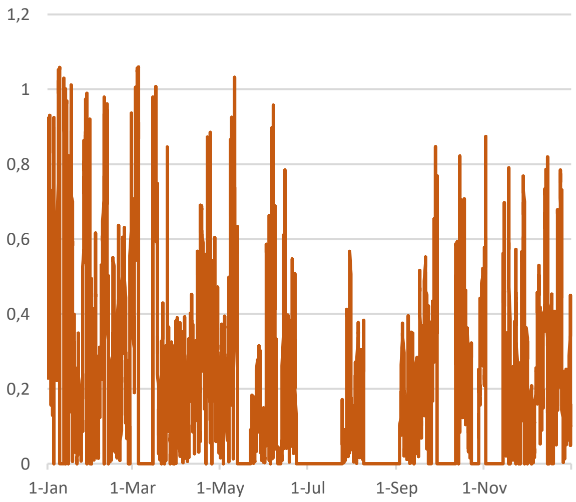

Fig. 7 Compressor demand profile

F. Grid support

This paper focuses on the use of a hybrid system aiming to ensure that electrical demand is met 100% of the time; however, there are other grid characteristics that will require support as more variable renewable power is added to the electrical grid. This system could potentially provide additional grid support. Specifically, short-term dynamics based on frequency regulation will be addressed in a future collaborative work aiming to understand their impact on the hybrid system.

V. Conclusion and Future Works

In this work, a methodology to size a low carbon hybrid power generation system was developed and applied. This system aims to replace a former natural-gas power plant in Germany and to meet its electrical production profile. The hybrid system consists of renewable electricity production, gas turbine electricity production, an electrolyzer, a compressor, and hydrogen storage. Switching from a 147 MW gas-fired plant to this hybrid system requires a wind production of 85 MW, an electrolyzer of 58 MW, a compressor of 0.91 MW and 302 tons of hydrogen storage capacity. The sizing result shows components' power and capacities for the minimal wind power required as constructed. This work also makes it possible to obtain the operating profiles of the various components of the system over the year of operation.

We note final sizing was built aiming to only meet the electrical demand 100% of the time. This objective is well fulfilled although other factors, such as seeking maximum efficiency during component operations or reducing component deterioration would impact the final results. Periods of hydrogen non-production can be observed because the hydrogen storage is full while intermittent electricity would be available to feed the electrolyzer. Also, the components of the system work most of their operation times at part-load. This implies a reduction of their efficiencies and possibly has an impact on required service and maintenance.

Future work will consist in improving the model accuracy by switching from isothermal compression according to the ideal gas law to isentropic compression by equation of real gases. The work will then investigate power island operating cycles, such as startup, shutdown, and determine operation strategies to reduce components fatigue and optimize component cycles. Last, a constrained optimization will be applied for the sizing based on these additional factors. This methodology will also be applied on an isolated-grid type of system to understand how conclusions could be affected. Besides, parallel work is addressing economics of such hybrid system which is an important aspect for decision makers.

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