Sizing of an integrated power supply system with an electrolyzer and a hydrogen-fueled gas turbine

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***Abstract*—This work aims at sizing a power supply system composed of a wind plant, an electrolysis plant, a compressor, a storage tank, and a hydrogen-fueled gas turbine power plant to deliver low-carbon electricity. This system offers the benefit to be a dispatchable power supply system, needed to deliver flexibility on the grid. For this Power-to-Power system, the sizing objective is to find the minimal functional sizes for all the components of the system. The sizing is done for the case of Germany in 2021. Two system plannings are considered: one in which demand is supplied solely by the gas turbine and the wind plant is dedicated to green hydrogen production, and a second one in which wind plant produces hydrogen and supplies demand while gas turbine completes balance. We also evaluate the capital and operational costs of the system, as well as its water usage and land footprint. Sizing results computed show that using an integrated approach in which planning is done to exploit the synergies between the wind plant and the gas turbine not only generates gains in costs, space and water usage, but also avoids over-sizing the system.**

***Index Terms*—Power-to-Power, power supply system, integration, renewables, hydrogen, gas turbine, electrolysis, storage**

I. Introduction

SECTOR integration is expected to be a key instrument in decarbonizing energy systems in an effort to address climate change. As a means to those ends, it is envisioned that future power systems be conceived in an integrated vision, that is, in a global approach that links energy-consuming sectors to the power grid and enhances the synergies between production and use of energy. One of the concepts that embrace this approach is *Power-to-Gas-to-Power*, or *Power-to-Power*. Power-to-Power can employ electrolysis to produce hydrogen from renewable resources such as wind and solar power. The hydrogen is then stored for future use and transformed back into electricity via fuel cells or hydrogen-fueled gas turbines. The latter, as an end-use application for hydrogen, has been gaining momentum in the wake of growing shares of variable renewable energy (VRE) into grids. Indeed, dispatchable power generation from conventional assets [1] along with short and long-term storage are needed to support VRE penetration. Thermal power stations that can be ramped-up and down quickly and operate at low output levels are of need [2] but have to be decarbonized. Gas turbine power plants (GTPP) in particular appear to be a promising solution for flexibility provision thanks to their modularity and cost-effectiveness [3]. Today, some hydrogen-only turbines are in the act of commercial rollout, but most commercially viable turbines require blending methane alongside hydrogen. Still regarding flexibility, the concept itself is evolving as providers are diversifying the assets they can leverage. In the broader sense, tools that have the potential to, when plugged into grids, reduce congestion and offer balancing, are looked upon favorably. Electrolyzers also stand out for that matter, along with gas turbines. Therefore, a key task to evolving towards power systems that are flexible and sustainable is studying integrated power supply systems in which multiple power generation means, fuels and storage systems are combined. The aim is to identify how systems that are traditionally designed to operate separately can improve their technical, economic and environmental performance when designed and planned jointly. That is where an integrated hydrogen production, storage, and power generation system may create value into a broader electricity system.

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A. Literature on power systems integration and contribution of this work

The integration of power systems has been addressed in literature. Focus is put on the modeling of such systems [4] or the evaluation of their performances to capture the benefits and drawbacks that come with the integrated approach [5].

Fuel cells and gas turbines (GT) are the main technologies addressed for Gas-to-Power integrated systems. Recent literature assigns about the same conversion rate to stationary PEM fuel cells as to GTPPs in Combined Cycle (CC) configuration, though the former entails higher system prices [6]–[8]. However, although fuel cells bear faster dynamic response and lower noise emissions [9], GTPPs can deliver inertial stability and higher electrical capacity to the grid.

In [10], an integrated power distribution system composed of a hydrogen-fired gas turbine co-located with an electrolysis unit is evaluated. Findings in that reference point to the advantage of systems with potential for storing large quantities of energy on long periods of time. In [11], conclusions suggest a feasible solution that integrates a GTPP with Power-to-Gas technology and the study provides detailed performance and economic analyses for two viable options. Next, an integrated power supply system co-locating a wind plant, an electrolysis plant and a GTPP is studied in [12] but with a time-based approach. That allows authors to effectively capture changing business opportunities on a hourly basis.

Finally, work focusing on structural interactions suggest that systems bridging a horizontal network connection (i.e. gas pipes), a vertical network connection (i.e. a GTPP), and a storage system can reach profitability by stacking value streams [13] (i.e. sales of electricity, hydrogen and ancillary services).

The aforementioned studies have all contributed to understanding the design and planning of integrated systems based on Power-to-Gas and Gas-to-Power. However, further research is required to put their evaluations in the context of various scenarios and case studies [14], [15]. Papers that combine both a techno-economic and environmental assessment are also less common. This paper contributes in applying the lessons learned in the modeling of integrated Power-to-Power systems to a concrete case study and evaluate its performance on the basis of component sizing, and economic and environmental metrics while using a time-based approach.

B. Aim and outline of this work

This work aims to size a renewables-based power supply system composed of an electrolysis plant powered by a wind plant and coupled to a compressor and a storage tank, which delivers green hydrogen used in a Combined Cycle Gas Turbine (CCGT) power plant to meet local grid electrical demand. The target is to determine the minimal feasible sizes for all the components of the system, meaning the sizes below which the system cannot deliver enough electricity, and above which the system would be oversized. Sizing results are computed by a sizing simulator developed for this study. We consider a case study in which the system is located in Germany, connected to a continental-type EU grid. Within this case study, the two scenarios shown in Fig. 1, and two configurations are considered, giving 4 sets of results to compare:

- **Sc1-B**: Baseload electrical demand from grid is only supplied by GTPP partly fueled with green hydrogen produced by wind plant and electrolysis.
- **Sc1-P**: Peaker electrical demand from grid is only supplied by GTPP partly fueled with green hydrogen produced by wind plant and electrolysis.
- **Sc2-B**: Baseload electrical demand from grid is supplied by both wind plant and GTPP partly fueled with green hydrogen produced by wind plant and electrolysis.
- **Sc2-P**: Peaker demand from grid is supplied by both wind plant and GTPP partly fueled with green hydrogen produced by wind plant and electrolysis.

The power supply approach described in Sc1-B and Sc1-P is the basic and intuitive approach that comes to mind when Power-to-Power process is mentioned. Sc1-B and Sc1-P are studied here as cases of reference for Sc2-B and Sc2-P.

The remainder of the paper is organized as follows: the system and the modeling of its components are described in section II. The German case study is then presented in section III, with a description of the data considered for the scenarios. Section IV presents the system planning and sizing methodology used to build our simulator. Section V provides results with some discussions and section VI concludes.

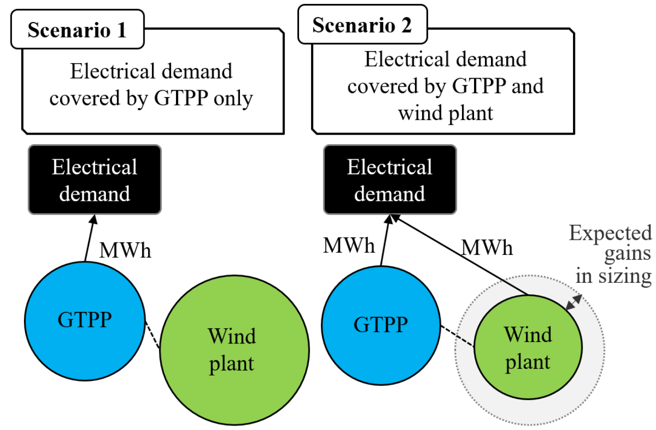


Fig. 1: Two different approaches to cover electrical demand: supply by GTPP only vs. supply by wind plant and GTPP.

II. SYSTEM ARCHITECTURE AND MODELING

The topology and modeling choices of the studied system, represented on Fig. 2, are detailed hereafter.

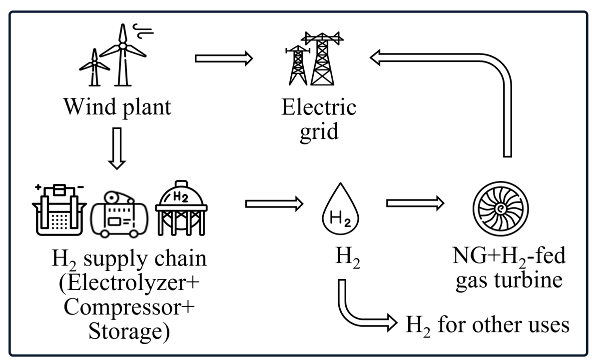


Fig. 2: Studied power supply system composed of a wind plant, an electrolysis plant and a GTPP.

a) Wind plant modeling: An onshore wind plant serves as the renewable energy supplier. The sizing parameter for the wind plant component is P_{wind} [MW], the nameplate capacity of the farm. For this component, the size is P_{wind}. We represent wind power availability by calculating a capacity factor c_f. c_f is obtained by calculating the power generated by the wind farm over an hour $Prod_{\text{wind}}$ divided by the installed capacity in the geographical location Cap_{wind}.

$$c_f = \frac{Prod_{\text{wind}}}{Cap_{\text{wind}}} \tag{1}$$

b) Electrolyzer modeling: The size of the electrolysis plant is the nominal power of the installation P_{elect} [MW], that can be built in a modular configuration and composed of multiple stacks [16]. Plant efficiency is materialized as a yield ratio r_{elect} [kWh-elec/kg-H_2], which is the electrical consumption required to produce 1 kilogram of hydrogen. p_{elect} [bar] and T_{elect} [K] respectively refer to the output pressure and output temperature of hydrogen. The mass of hydrogen produced hourly $\dot{m}_{\text{H2-prod}}$ [kg/h] is modeled following (2):

$$\dot{m}_{\text{H2-prod}} = \frac{P_{\text{elect}}}{r_{\text{elect}}} \cdot \Delta t \tag{2}$$

c) Hydrogen compressor modeling: End use applications such as gas turbines require the fuel to be at a high pressure. In practice, the compression step consumes part of the electrical power available for the hydrogen value chain, but at different rates depending on the wanted output pressure of the gas. For instance, for hydrogen, compression from 1 to 1000 bar requires twice as much work as compression from 30 to 1000 bar (4 kWh/kg-H_2-compressed and 2 kWh/kg-H_2-compressed, respectively [1]). Considering that, we use the parameter r_{comp} [kWh-elec/kg-H_2-produced] to represent the compressor's power needs. For simplification, we consider a single conservative value for r_{comp}. We calculate it using (3) considering a polytropic compression extracted from [17]:

$$\frac{\dot{W}_{\text{comp}}}{\dot{m}} = r \cdot \frac{n_v}{n_v - 1} \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{n_v - 1}{n_v}} - 1 \right] \tag{3}$$

- $\dot{W}_{\text{comp}}$ is the mechanical work [W].
- $\dot{m}$ is the mass flow rate of hydrogen though the compressor [kg/s] .
- r is the universal gas constant for hydrogen, 4124 J kg^{-1} K^{-1} [18].
- n_v is the polytropic factor, 1.41 for dihydrogen at 20°C.
- p_1 and p_2 are the inlet and outlet pressures of the compressor [bar].

As $\dot{W}_{\text{comp}}$ above is the mechanical work, we consider an electrical conversion efficiency η_{comp} as well. The size of the compressor component is noted P_{comp} [MW].

d) Hydrogen storage: After the compression stage, hydrogen is stored at 300 bar as compressed gas. The size for this component is Q_{sto} [metric tonnes], calculated by taking the maximum value reached over the period of study by $\dot{m}_{\text{H2-sto}}$ [kg/h], the mass present in the tank, and computed following (4). The amount of hydrogen that can be stored is limited by an upper and lower limit of pressure, $p_{\text{sto}_{\text{max}}}$ [bar] and $p_{\text{sto}_{\text{min}}}$ [bar] respectively. The existence of a lower pressure limit in the model infers that the storage cannot be emptied.

$$\dot{m}_{\text{H2-sto}} = \dot{m}_{\text{H2-sto}}(t - dt) + \dot{m}_{\text{H2-prod}} - \dot{m}_{\text{H2-cons}} \tag{4}$$

e) Gas turbine: For the Gas-to-Power process, the system relies on a gas turbine installed in a power plant and running on a hydrogen and natural gas (NG) blend. NG is assumed to be pure methane (CH_4). P_{GT} is plant's nominal power [MW] and η_{GT} is plant's LHV (Lower Heating Value) efficiency in percentage (%). Gas turbine component size in our model is P_{GT}. $\dot{m}_{\text{H2-cons}}$ [kg/h] is the hydrogen consumed hourly by the GT and is modeled following (5) and (6):

$$\dot{m}_{\text{H2-cons}} = \frac{hc \cdot \%H_2}{\%H_2 \cdot LHV_{H_2} + \%\text{CH}_4 \cdot LHV_{CH_4}} \cdot \Delta t \tag{5}$$

in which

$$hc = \frac{P_{\text{GT}}}{\eta_{\text{GT}}} \tag{6}$$

- hc is defined as the GT's heat consumption to produce electricity over an hour [MWh].
- $\%H_2$ and $\%CH_4$ and the volumetric portions of the respective gases.
- LHV_{H_2} and LHV_{CH_4} are the lower heating values of the gases, 33.33 kWh-LHV/kg and 13.9 kWh-LHV/kg respectively.

III. Case study: Implementing power supply system in Germany

The goal is to replace with our VRE-based power supply system a fully fossil power generation plant. We want to supply said power generation plant's demand while minimizing equipment sizing to reduce costs for economic reasons and physical space and water consumed for environmental reasons.

A. Definition of the case study

The power supply system is designed according to features found on a continental electric grid. The case of Germany is selected and the study is done over a year considering a hourly time step. The inputs data and parameters defined in section II are specified based on this case. That is the choice of the GTPP features, the choice to consider wind plant as the renewable source, the electrolyzer technology, the compressor type, the storage tank and the wind power availability.

B. Data considered

This section details the technology choice for the components and the assumptions made for remaining data.

1) Load factor profile: Data for hourly wind energy produced $Prod_{\text{wind}}$ has been collected from [19] and Cap_{wind} is taken to be 55797 MW (installed onshore wind capacity at the beginning of 2022 [19]). Fig. 3 shows the reconstructed wind load factor for the year 2021 in Germany based on (1).

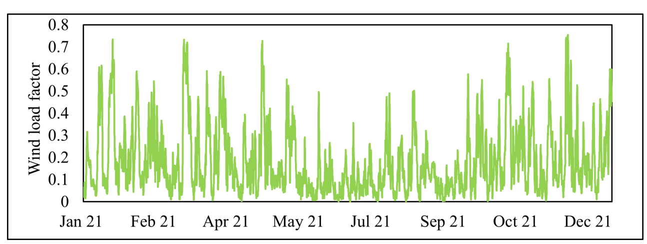


Fig. 3: Onshore wind load factor in Germany, 2021.

At any time step, capacity factor c_f will have to be factored in to the size of the plant to determine the wind power effectively generated in the system.

2) Baseload and Peaker scenarios: Peaker plants run only when there is a high demand for electricity, known as peak demand. Baseload plants however supply a dependable and consistent amount of electricity to meet the minimum demand. These two regimes will govern the demand profile to which the hydrogen-based power supply system has to deliver enough power for. They will be compared for the sake of this study.

For the Baseload regime, the demand profile is created on the basis of a number of operated hours nb_{hours} [hours] and a number of starts nb_{starts}. A Baseload plant is assumed to run 8000 hours at full load P_{GT}, spread over 50 starts. That is roughly 160 hours per GT run at full load, interspersed by 15 hours of stops at 0 MW. The load profile is shown in Fig. 4.

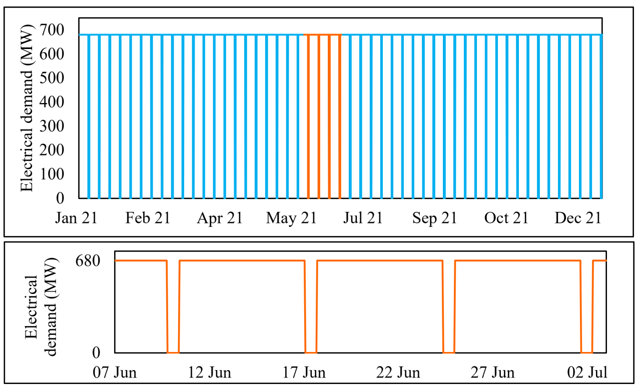


Fig. 4: Electrical demand profile for Baseload scenario - top graph is yearly profile and bottom graph is magnification over 1 month period.

Demand profile for the Peaker case is adapted from a real load profile extracted from a European GTPP that runs on Peaker regime. Fig. 5 shows the profile. We note that this profile is theoretical and does not include limits on GTPP start-up time.

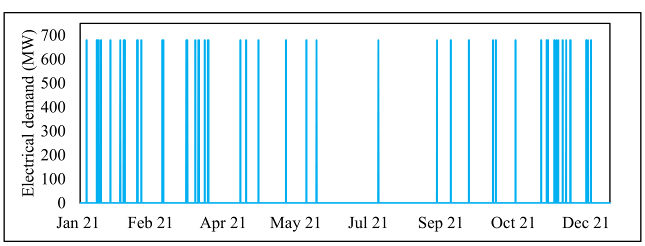


Fig. 5: Electrical demand profile for Peaker scenario.

3) Case study requirements: In this German case study, we consider a requirement that GTPP has to run with 20%-vol of hydrogen in its fuel mix. The requirement for the validity of a given sizing solution is that it must cover 100% of electrical demand profile.

4) Power supply system components:

a) Gas turbine: We consider for the case study a GE 9HA.01 machine in single shaft combined cycle configuration. The 9HA.01 is heavy-duty gas turbine frame that is suitable for delivering power on large grids such as Germany's. Its P_{GT} is 680 MW and η_{GT} is 63.7 % in CC [20]. This machine consumes 2.24 metric tonnes-H_2/hour when running with 20%-volumetric of hydrogen in fuel blend.

b) Electrolyzer: The electrolysis unit is modeled following a modular configuration. It consists of multiple modules of the McPhy McLyzer 3200-1 [21], which is an electrolyzer of Alkaline type. The nominal power of the stacks for a single module of this technology $P_{\text{elect}_{\text{stacks}}}$ is 16 MW. The yield ratio r_{elect} is 53 kWh-elec/kg-H_2-produced, p_{elect} is 30 bar and T_{elect} is 298.15 K. P_{elect} of the installation will be $P_{\text{elect}_{\text{stacks}}}$ multiplied by the number of modules nb_{mod}.

c) Compressor: In this case study, compressor's electrical efficiency η_{comp} is 97 %. r_{comp} to compress from 30 bar to 350 bar at this efficiency is 3.6 kWh-elec/kg-H_2-produced.

IV. System planning and sizing methodology

A. Planning and operation of the system

We identified two strategies for the planning of the system, based on the approaches presented in I (Fig. 1). For both, the simulation is carried out over one year on a hourly time step, beginning January 1$^{\text{st}}$ 2021 at 00:00:00 and ending December 31$^{\text{st}}$ 2021 at 00:00:00 (with 8760 steps). P_{load} [MW] hereafter is the electrical demand to supply.

In the first strategy detailed in Alg. 1, P_{load} is assumed to be covered only by GT (Case 1 in Fig. 1). We assume that hydrogen is produced during GTPP stops.

Algorithm 1 Demand is covered by GTPP fueled with hydrogen, wind plant and electrolyzer to only produce hydrogen.

$Prod_{\text{wind}} \leftarrow P_{\text{wind}} \cdot c_f$
Require: $P_{\text{elect}} \geq Prod_{\text{wind}}$
for t = 1:T **do** ▷ Every hour from 1 Jan. to 31 Dec.
  if $P_{\text{load}} = 0$ **then** ▷ H_2 produced during GTPP stops
    $Q_{\text{sto}} \leftarrow \dot{m}_{\text{H2-prod}}$ ▷ Storage filled with H_2 produced
    $\dot{m}_{\text{H2-cons}} \leftarrow 0$
  else if $P_{\text{load}} \neq 0$ **then** ▷ H_2 consumed when GTPP runs
    $\dot{m}_{\text{H2-cons}} \leftarrow$ Eq. (5)
    $Q_{\text{sto}} \leftarrow Q_{\text{sto}} - \dot{m}_{\text{H2-cons}}$
  end if
end for
Output: Q_{sto}

In the second strategy detailed in Alg. 2, both the wind plant and the GTPP participate in supplying the demand. The gap between wind energy production and electrical demand P_{curt} is first computed. If the value of P_{curt} is positive, it means more wind power is produced than needed to supply demand. P_{curt} becomes power curtailed from the wind plant. We can make use of it to produce hydrogen. If P_{curt} is negative, it implies no wind power is curtailed, wind plant supplies base demand up to its availability and GTPP needs to supply remaining balance using previously stored hydrogen.

It is ensured that Q_{sto} is valid if its corresponding computed p_{sto} is within the upper and lower bounds $p_{\text{sto}_{\text{min}}}$ and $p_{\text{sto}_{\text{max}}}$. The final hydrogen storage size is determined by taking the maximum value Q_{sto} reaches over the year of study.

Algorithm 2 Demand is covered by both hydrogen-fueled GTPP and wind plant.

$Prod_{\text{wind}} \leftarrow P_{\text{wind}} \cdot c_f$
Ensure: $P_{\text{elect}} \geq Prod_{\text{wind}}$
for t = 1:T **do** ▷ Every hour from 1 Jan. to 31 Dec.
  $P_{\text{curt}} \leftarrow P_{\text{load}} - Prod_{\text{wind}}$
  if $P_{\text{curt}} > 0$ **then** ▷ Surplus wind power
    $Q_{\text{sto}} \leftarrow \dot{m}_{\text{H2-prod}}$ ▷ Storage filled with H_2 produced
    $\dot{m}_{\text{H2-cons}} \leftarrow 0$
  else if $P_{\text{curt}} \leq 0$ **then** ▷ Insufficient wind power
    $\dot{m}_{\text{H2-cons}} \leftarrow$ Eq. (5) ▷ GT called
    $Q_{\text{sto}} \leftarrow Q_{\text{sto}} - \dot{m}_{\text{H2-cons}}$
  end if
end for
Output: Q_{sto}

B. Sizing methodology

The target for sizing is to identify the functional sizes of each component of the system P_{wind}, P_{GT}, P_{comp}, P_{elect} and Q_{sto}, in order to deliver electrical demand under the requirements specified in III-B3. Steps 4 and 5 in the methodology below are repeated iteratively in the sizing simulator.

- **Step 1**: Set Q_{sto} to infinite
- **Step 2**: Require $P_{\text{wind}} = P_{\text{elect}}$
- **Step 3**: Find minimal P_{wind} to cover demand
- **Step 4**: Gradually decrease P_{elect} to find minimal value
- **Step 5**: Gradually decrease Q_{sto} to find minimal value

The order of priority for sizing minimization has been chosen: wind plant size first, then electrolyzer size, and hydrogen storage tank size last. We consider Q_{sto} at $t = 1$ cannot be at zero to ensure first run. We also note that P_{GT} is not computed by the simulator: it is pre-determined following the case study.

V. Results

A. Sizing results

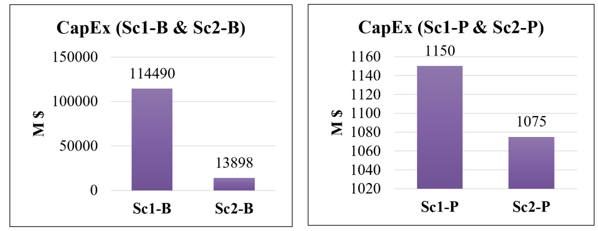
Based on the 2 algorithms proposed above, we deploy a simulation case. Table I shows the sizing results computed by the sizing simulator for the 4 scenarios presented in I-B.

TABLE I: Sizing results.

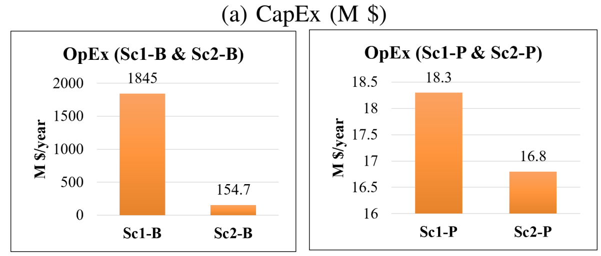
	P_{wind}	P_{elect}	P_{comp}	Q_{sto}
	MW	*MW*	*MW*	*metric tonnes*
Sc1-B	36000	20400	1386	22117
Sc2-B	2670	1600	102	16865
Sc1-P	270	80	6	164
Sc2-P	240	64	4.5	164

B. Techno-economic and environmental assessment

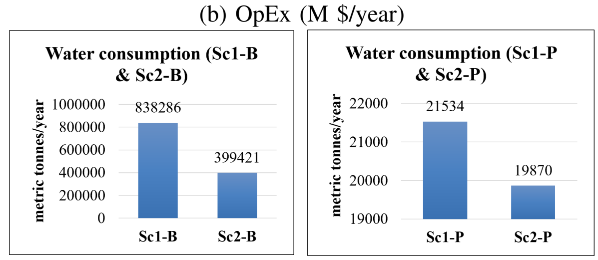
We conducted a techno-economic and environmental evaluation of the sizing results. We calculate the Capital expenditure (CapEx) [M \$], the Operational expenditure (OpEx) [M \$/year], the land footprint of the system [km²] and the water usage of the electrolysis plant [metric tonnes/year]. Assumptions are made with respect to data available in [22]. Results are presented in Fig. 6.



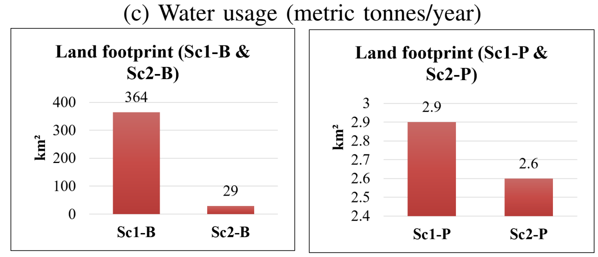
(a) CapEx (M \$)



(b) OpEx (M \$/year)



(c) Water usage (metric tonnes/year)



(d) Land footprint (km²)

Fig. 6: Capital costs, operational costs, water usage and land footprint of the 4 sizing solutions.

C. Discussion

We compare the two approaches 1 and 2, and the two regimes B and P in terms of size, costs and space.

Sc1-B and Sc2-B are the sizing results for Baseload demand. Sc1-B requires having 36000 MW of wind power to produce enough hydrogen when needed to deliver 680 MW over 8000 hours. When the planning is switched to allow the wind plant to cover demand (Sc2-B), sizing for all components is substantially decreased. The obtained hydrogen storage sizing for Baseload cases required ensuring that the hydrogen storage was not empty at the beginning of the year.

Figures for CapEx, OpEx, total land footprint of the system and electrolyzer's water usage also decrease, follow the same trend as the sizing. The results obtained for these criteria are to be taken with caution given the basic assumptions taken. Water consumption here refers to the stoichiometric quantity required for hydrogen production in the electrolysis process (9 L/kg-H_2-produced), excluding the needs for treatment and for the balance of plant. Land footprint data may not consider other uses and methodology to estimate space differs for power technologies. With those reserves considered, the better performing system is the one sized for Sc2-P given the minimal costs, space taken and water usage.

To sum up, as expected, for both Baseload and Peaker cases, sizing is decreased using the integrated approach in which system planning is done to allow both wind plant and GTPP to supply demand. GT size in this work is set following the selected machine, hence its constant value. The sizes obtained for storage suggest that it would be interesting to consider underground salt cavern storage given the large quantities. Results finally suggest the particular relevance that this system has for Peaker regimes instead of Baseload.

VI. Conclusion and Future Outlooks

In this paper, we developed an integrated power supply system composed of an onshore wind plant, an electrolysis plant, a hydrogen-fueled gas turbine, a compressor, and a storage tank. The case for Germany and the year 2021 have been considered to form a case study. The sizing objective was to achieve power supply requirements while designing the system with the minimal functional sizes for the components, meaning sizes below which system does not meet demand, and above which system is oversized. We studied a first theoretical "degraded" approach in which only the GTPP supplies demand with wind plant solely dedicated for hydrogen production, and a second integrated approach in which both wind plant and GTPP are planned to deliver electricity to the grid. Sizing results show that operating the system using the integrated approach not only generates gains in costs, space and water usage, but also avoids over-sizing the system. Results also point to the particular relevance of power systems combining a hydrogen-fueled GTPP and a wind plant in future grids to operate for Peaker-type demands instead of Baseload regimes.

This work shall be expanded on establishing an optimization method based on multi-objective and multi-criteria analysis. That would allow sizing results targeted to minimize costs, minimize environmental impact and maximize revenues from sales of electricity, hydrogen and ancillary services.

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