Exploration of the Trade-off between Short Term (Battery) and Long Term (Hydrogen) Storage for a Wind Powered Energy Community

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***Abstract*—As the share of renewable generation increases in energy communities arises the question of whether total cost (investment + operation) could be minimized by a proper combination of short term (battery) and long term (hydrogen) storage. Here we focus the study on a wind powered energy community with battery storage, grid connection (consumption/injection), and hydrogen (generation, storage and back to power). The main factors that impact the optimal operation and configuration, with particular focus on short and long-term storage, are identified for a general system. A sensitivity analysis is performed on those factors using two-stage optimization problems in a case study with 480 users to numerically quantify their interaction and influence on the solutions.**

***Index Terms*—wind, energy community, battery, hydrogen**

I. INTRODUCTION

The energy sector and its development is one of the key stones to a sustainable future. In this context, wind energy has become one of the most relevant energy resources in the so called energy transition [1]. Also these renewable generation technologies, as wind and photovoltaics, are allowing new forms of organization in the power systems, as the Renewable Energy Communities (REC). Here we focus the study in a wind powered REC, [2]. The proposed methodology could consider also photovoltaic generation, but the main results can be discussed considering just wind generation and also we have the limitations in the document length.

Wind generation poses significant challenges in the REC operation because of its characteristics, like limited predictability, short and long-term variability and availability, [3]. To cope with those challenges several solutions have been proposed [4], [5] as using battery storage [6], [7], hydrogen storage [8], [9] and/or demand side management.

Most of the previous works in the literature on REC deal with just one storage technology, either battery or hydrogen, and those that consider both do not address in depth the trade-off between the short-term and the long-term storage.

The main contribution in this work is to provide some insights on the trade-off between short-term (battery) and long-term (hydrogen) energy storage for a wind powered REC with grid connection (consumption / injection) under the objective of minimizing total cost (investment + operation). In particular to answer the questions: i) What are the main factors that impact on that trade-off, ii) To numerically quantify their interaction and impact for a case study, in which the decisions include the operation for a whole year on an hourly basis and the sizing of: grid connection, battery, wind turbine, hydrogen electrolyzer, hydrogen storage, and hydrogen turbine (back to electric power).

In the rest of the paper methodology is described in Sect. II, the case study (energy community of 480 users) in Sect. III, results are presented and discussed in Sect. IV, and finally conclusions are summarized in Sect. V.

NOTATION

Indices and Sets

t, T	Periods of time, $t \in T$.
ω, Ω	Scenarios for demand and prices, $\omega \in \Omega$.

Parameters

CAA, CAB	Amortization cost of storage of Hydrogen / Battery, (€$/kWh \cdot day$).
$CAPE, CATG, CAW$	Amortization cost of Electrolyzer / Hydrogen gas turbine / Wind turbine, (€$/(kW \cdot day)$).
CB, DB	Battery charge / discharge factor, (kW/kWh).
CTP	Cost of grid connection capacity, (€$/(kW \cdot day)$).
D_t	System power demand at period t, (kW).
FIP	Share of grid connection available for injection, $(p.u.)$.
PC_t, PV_t	Price of energy purchased from / sold to the grid at period t, (€$/kWh$).
W_{max}	Upper bound for the installed wind gen., (kW).
WA_t	Wind generation availability at period t, $(p.u.)$.
η_C, η_D	Battery charging / discharging efficiency, $(p.u.)$.
η_E, η_{GT}	Efficiency of hydrogen: Electrolyzer, Gas turbine, $(p.u.)$.
Δ_t	Lasting of time period t, (hours).

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Variables

a, b Rated capacity of storage: Hydrogen / Battery, (kWh).

cc, pe, pw, tg Rated power of: grid connection, electrolyzer, wind generation, hydrogen gas turbine, (kW).

$soc_t, soch_t$ State of Charge of storage at the end of period t: Battery, Hydrogen, (kWh).

$soc_0, soch_0$ State of Charge before starting operation of storage: Battery, Hydrogen, (kWh).

bd_t, br_t Power at t from battery to: Demand, grid, (kW).

hd_t, hr_t Power at period t from hydrogen storage to: Demand, grid, (kW).

rd_t, rb_t Power at t from grid to: Demand, battery, (kW).

$wb_t, wd_t, wh_t, wr_t, ws_t$ Power at t from wind turbine to: Battery storage, demand, hydrogen storage, grid, not used, (kW).

II. METHODOLOGY

The system under study, depicted on Fig. 1, is a wind powered energy community that consists of: users (demand), grid connection (injection / consumption), wind generation, battery storage, hydrogen storage, hydrogen electrolyzer and hydrogen turbine (back to electric power). The system is sized and operated to minimize the total cost (investment IC (1) + operation OC (2)) as stated in the objective function (3).

$$\begin{aligned} IC = {} & pw \cdot CAW + cc \cdot CTP + b \cdot CAB \\ & + pe \cdot CAPE + a \cdot CAA + tg \cdot CATG \end{aligned} \tag{1}$$

$$\begin{aligned} OC = \frac{1}{365} \sum_{t \in T} \Delta_t \cdot \big[& PC_t \cdot (rd_t + rb_t) \\ & - PV_t \cdot (wr_t + hr_t + br_t) \big] \end{aligned} \tag{2}$$

The decision variables are those described in the Notation. As general rule variables are in lower case and parameters in upper case or Greek. The investment cost IC (1) includes the amortization cost for: wind turbine pw, grid connection cc, battery b, electrolyzer pe, hydrogen storage a, and hydrogen turbine tg. Here we referred as "hydrogen turbine" the equipment required to burn the hydrogen and produce electricity.

The operation cost OC (2) is the sum of the cost for the energy purchased from the grid (at price PC_t) minus the energy sold to the grid (at price PV_t). Both IC and OC are in €/day.

In this context short-term means hours and long-term months. We consider the operation for a whole year on an hourly basis (8760 values for each variable), we avoid the use of scenarios (a few representative days for instance) to better capture the interaction between short and long-term storage. In what follows first the optimization problem for numerical evaluation is described, then the identification of the main factors in the trade-off between short and long-term storage is discussed.

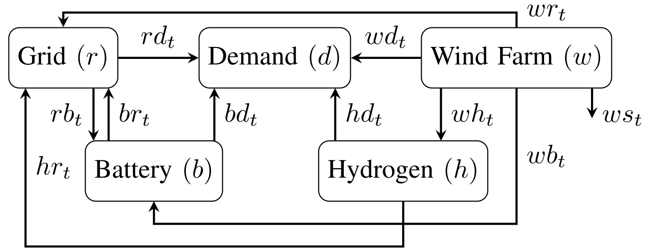


Fig. 1. System flow chart: components and power flows.

A. Optimization Problem for Numerical Computation

Optimal sizing and operation to minimize total cost (investment + operation) are computed using an optimization problem, (3)-(18), posed as a linear two-stage stochastic program. The objective function (3) is made of the investment cost IC, (1) plus the operation cost OC, (2), value z in €/day.

$$\min \{ z = IC + OC \} \tag{3}$$

$$rd_t + wd_t + bd_t + hd_t = D_t; \quad \forall t \in T \tag{4}$$

$$wr_t + wd_t + wb_t + wh_t + ws_t = pw \cdot WA_t; \ \forall t \in T \tag{5}$$

$$pw \leq W_{max} \tag{6}$$

$$\begin{aligned} soc_t = {} & soc_0 + \eta_C \cdot \Delta_t \cdot (rb_t + wb_t) \\ & - \frac{\Delta_t}{\eta_D} \cdot (br_t + bd_t) \, ; \quad t = 1 \end{aligned} \tag{7}$$

$$\begin{aligned} soc_t = {} & soc_{t-1} + \eta_C \cdot \Delta_t \cdot (rb_t + wb_t) \\ & - \frac{\Delta_t}{\eta_D} \cdot (br_t + bd_t) \, ; \quad t > 1 \end{aligned} \tag{8}$$

$$soc_{|T|} = soc_0 \tag{9}$$

$$wb_t + rb_t \leq CB \cdot b; \quad \forall t \in T \tag{10}$$

$$bd_t + br_t \leq DB \cdot b; \quad \forall t \in T \tag{11}$$

$$\begin{aligned} soch_t = {} & soch_{t-1} + \Delta_t \cdot \eta_E \cdot wh_t \\ & - \frac{\Delta_t}{\eta_{GT}} \cdot (hd_t + hr_t) \, ; \quad t > 1 \end{aligned} \tag{12}$$

$$\begin{aligned} soch_t = {} & soch_0 + \Delta_t \cdot \eta_E \cdot wh_t \\ & - \frac{\Delta}{\eta_{GT}} \cdot (hd_t + hr_t) \, ; \quad t = 1 \end{aligned} \tag{13}$$

$$soch_{|T|} = soch_0 \tag{14}$$

$$\eta_E \cdot wh_t \leq pe; \quad \forall t \in T \tag{15}$$

$$hd_t + hr_t \leq tg; \quad \forall t \in T \tag{16}$$

$$rd_t + rb_t \leq cc; \quad \forall t \in T \tag{17}$$

$$hr_t + br_t + wr_t \leq FIP \cdot cc; \quad \forall t \in T \tag{18}$$

Where: (4) is the power balance for demand; (5) is the power balance for wind generation; (6) is the upper bound for the wind generation that can be installed; (7), (8) are the energy balance for battery storage for $t = 1$ and $t > 1$ respectively; (9) states that the energy level in the battery at the end of operation is equal to the energy level just before starting operation (to avoid the use of free energy from the battery); (10) / (11) are the bounds for charging / discharging power from / to the battery; (12), (13) stand for the energy level in the hydrogen storage at $t > 1$ and $t = 1$ respectively; (14) sets the energy level in the hydrogen storage at the end of operation must have the same value as just before starting operation (to avoid the use of free hydrogen); (15) / (16) is the upper bound for the electrolyzer / hydrogen turbine output power, it links the rated capacity with the actual output (both are decision variables); (17) / (18) is the upper bound for the power consumed from / injected to the grid.

B. Identification of Main Factors in the Trade-off between Short-Term (Battery) and Long-Term (Hydrogen) Storage

In this section we assume the optimal values for the installed capacities and power flows are known (as in an ex-post analysis) to build a profitability condition for the short-term storage and also another one for the short-term storage, both of them on an yearly basis.

Let's say WES is the wind energy surplus (kWh/year), for instance the surplus during the windy season. We have two main options for that surplus: i) to sold it to the grid at the time it is produced (no storage required), let's say to an average price of $PWES$ (€/kWh), ii) to store it to be used at another time, for instance in the season with low wind, let's say at an average price of $PWEC$ (€/kWh). The storage has a cost related to the installation, the amortization cost: $a \cdot CAA + pe \cdot CAPE + tg \cdot CATG$. The profitability condition is that the net profit of using hydrogen storage must be greater than without storage, that is:

$$
\begin{aligned}
WES \cdot (\eta_E \cdot \eta_{GT} \cdot PWEC - PWES) \geq a \cdot CAA + \\
+ pe \cdot CAPE + tg \cdot CATG
\end{aligned}
\tag{19}
$$

Reasoning in similar terms for the battery we have:

$$
WES \cdot (\eta_C \cdot \eta_D \cdot PWEC - PWES) \geq b \cdot CAB \tag{20}
$$

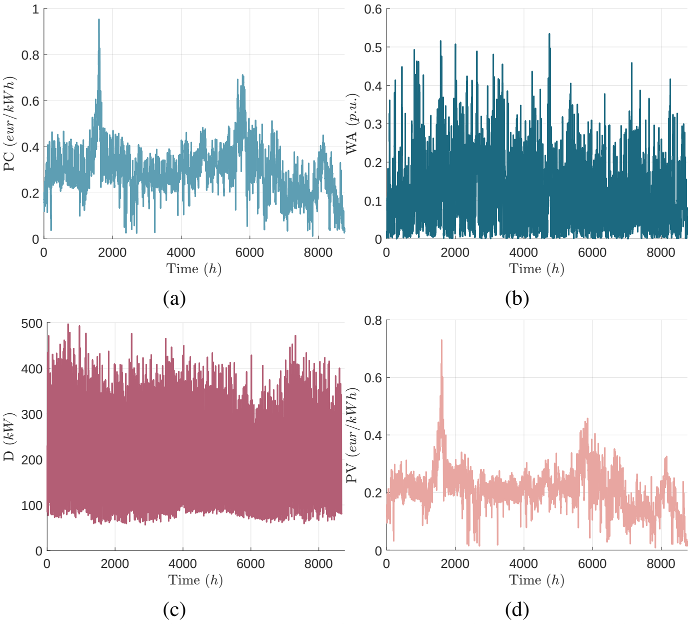
From (19) and (20) the main factors in the trade-off between short-term and long-term storage are:

1) The ratio between the wind generation and the demand, as the wind surplus WES depends directly on that ratio.
2) The efficiency of the hydrogen storage (η_E, η_{GT}).
3) The difference between the purchasing price PC_t and the selling price PV_t from/to the grid, as $PWEC$ depends on that difference and $PWES$ depends on PV_t.
4) The hydrogen amortization cost ($CAPE$, $CATG$). CAA is neglected because $a \cdot CAA$ is usually quite small compared to $pe \cdot CAPE$ and $tg \cdot CATG$.
5) The efficiency of the battery storage (η_C, η_D).
6) The battery amortization cost CAB.

The influence and interaction among these factors is summarized in the rate Φ, (21), where $PC - PV$ stands for a representative measure of the difference between the purchasing PC_t and the selling PV_t prices:

$$
\Phi = \frac{\eta_E \cdot \eta_{GT} \cdot (PC - PV)}{CAPE + CATG} \cdot \frac{CAB}{\eta_C \cdot \eta_D} \tag{21}
$$

The greater the value of Φ favours long-term storage respect to short-term storage. The factor Φ does not include the ratio between the wind generation and the demand because it is a common factor in (19) and (20), it is the same value in the numerator and also in the denominator of Φ.



(a) (b) (c) (d)

Fig. 2. (a) Price of energy purchased from the grid, (b) Wind availability on the rated wind capacity, (c) Demand, (d) Price of energy sold to the grid.

III. CASE STUDY

A wind powered energy community of 480 households is considered for the case study. It includes a grid connection (for consumption or injection), the users demand, wind generation, and the option to install electric battery storage and/or hydrogen (generation, storage and back to electric power). The operation for a whole year on an hourly basis (8760 values for each variable) is considered.

Grid energy prices correspond to the Spanish Market (domestic segment) for the year 2021, are available on [10], and depicted in Fig. 2a purchase price, and Fig. 2d selling price.

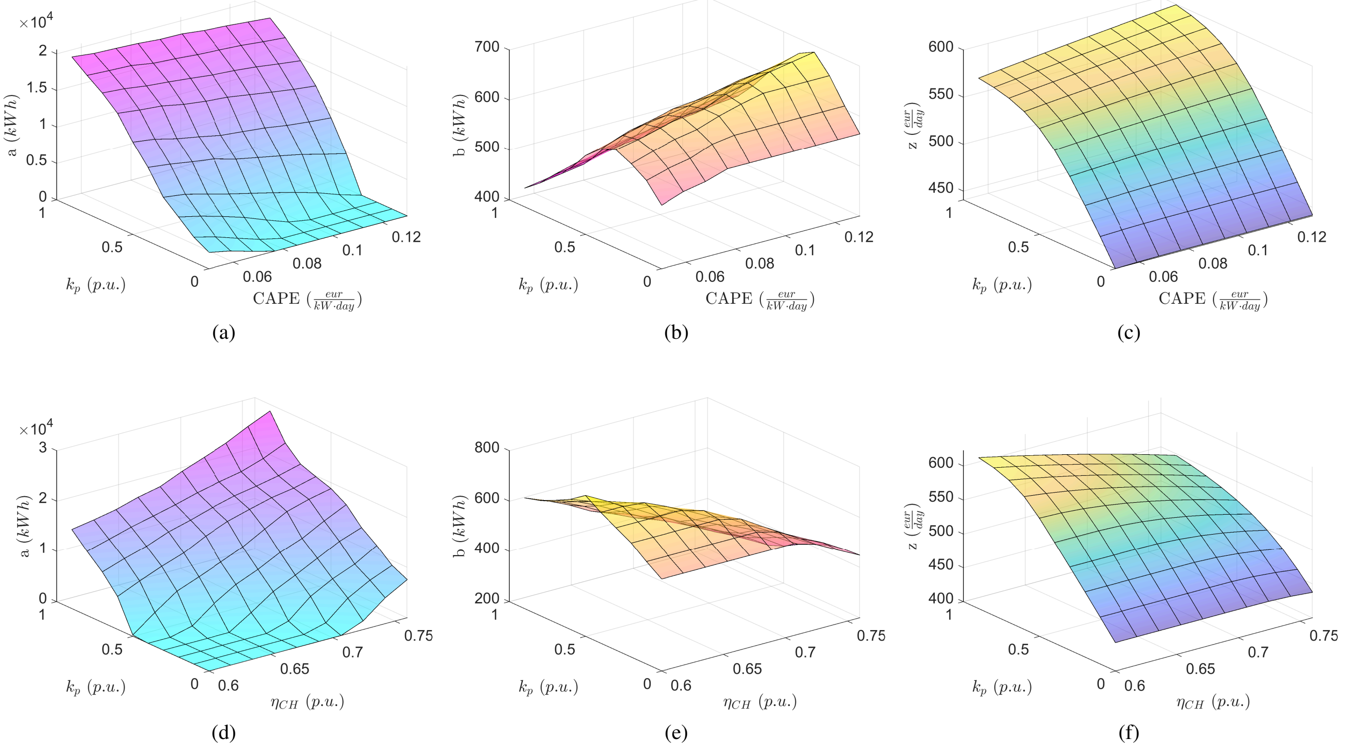
The wind availability, Fig. 2b, in per unit on the rated wind capacity installed corresponds to the hourly average value for measures of wind in the city of Ronda (Spain) during the years 2012-2017 with a resolution of 5 minutes.

The data for demand are built considering 32 original demand curves (hourly values for a whole year) from real households in the south of Spain. To get 480 users the data were replicated considering 15 groups of 32 users resulting the demand in Fig. 2c. The demand values are provided by the students enrolled in the course Power System Operation and come from the smart meters in each household.

The default values for the scalar parameters, as the amortization costs and the efficiency of each technology, are listed on Table I.

TABLE I
DEFAULT VALUES FOR PARAMETERS IN THE MODELS

	$€/(kW \cdot day)$			$p.u.$	
$CAPE$	0.138000	[9]	$CB = DB$	0.50	-
$CATG$	0.085000	[9]	$\eta_C = \eta_D$	0.90	[7]
CAW	0.129680	[9]	η_E	0.68	[9]
	$€/(kWh \cdot day)$		η_{GT}	0.45	[9]
CAA	0.000603	[9]	FIP	0.50	-
CAB	0.120000	-	W_{max} = 2000 kW		



(a) (b) (c)

(d) (e) (f)

Fig. 3. Sensitivity analysis on hydrogen amortization cost ($CAPE$, $CATG$) vs difference in purchasing and selling prices (k_p), results for: (a) Hydrogen storage a, (b) battery storage b, and total cost (investment + operation) z. Sensitivity analysis on the difference in purchasing and selling prices (k_p) vs hydrogen efficiency $\eta_{CH} \rightarrow (\eta_E, \eta_{GT})$, results for: (d) Hydrogen storage a, (e) battery storage b, and (f) total cost (investment + operation) z.

The upper bound for the wind rated capacity is set to W_{max} = 2000 kW, that is the value that makes the yearly wind generation lightly greater than the yearly demand. With this bound we keep the energy community operation in the range of self-consumption instead of operating as a net producer. We tested this on the simulations, but results with greater values of W_{max} are not included because of length limitations and to focus on the initial questions.

A. *Sensitivity Analysis*

In order to numerically quantify the influence and interaction of the main factors identified in Sect. II-B on the case study a sensitivity analysis is performed for each one of the five groups of parameters in Φ, (21). The five groups of parameters and the range of values (used in the figures) for each one are:

1) Hydrogen amortization cost: $CAPE \in$ [0.05, 0.13] €/(kW · day), $CATG \in$ [0.04, 0.08] €/(kW · day).
2) Hydrogen efficiency: $\eta_E \in$ [0.6, 0.76] (p.u.), $\eta_{GT} \in$ [0.40, 0.60] (p.u.).
3) Battery amortization cost: $CAB \in$ [0.015, 0.160] €/(kWh · day).
4) Battery efficiency: $\eta_C = \eta_D \in$ [0.85, 0.97] (p.u.).
5) Difference between the grid prices for purchasing and selling. In this case, we keep the value of the purchasing price PC_t and multiply the selling price PV_t for the scale factor $(1 - k_p)$ with $k_p \in$ [0.10, 1.00] (p.u.), thus the greater k_p the greater the difference.

In each sensitivity analysis the parameters in the same group change their value at the same time. Using an auxiliary parameter $s \in [0, 1]$ as an scale factor. For instance, in the group of hydrogen amortization cost it would be: $CAPE = 0.05 + s \cdot 0.08$, and $CATG = 0.04 + s \cdot 0.04$.

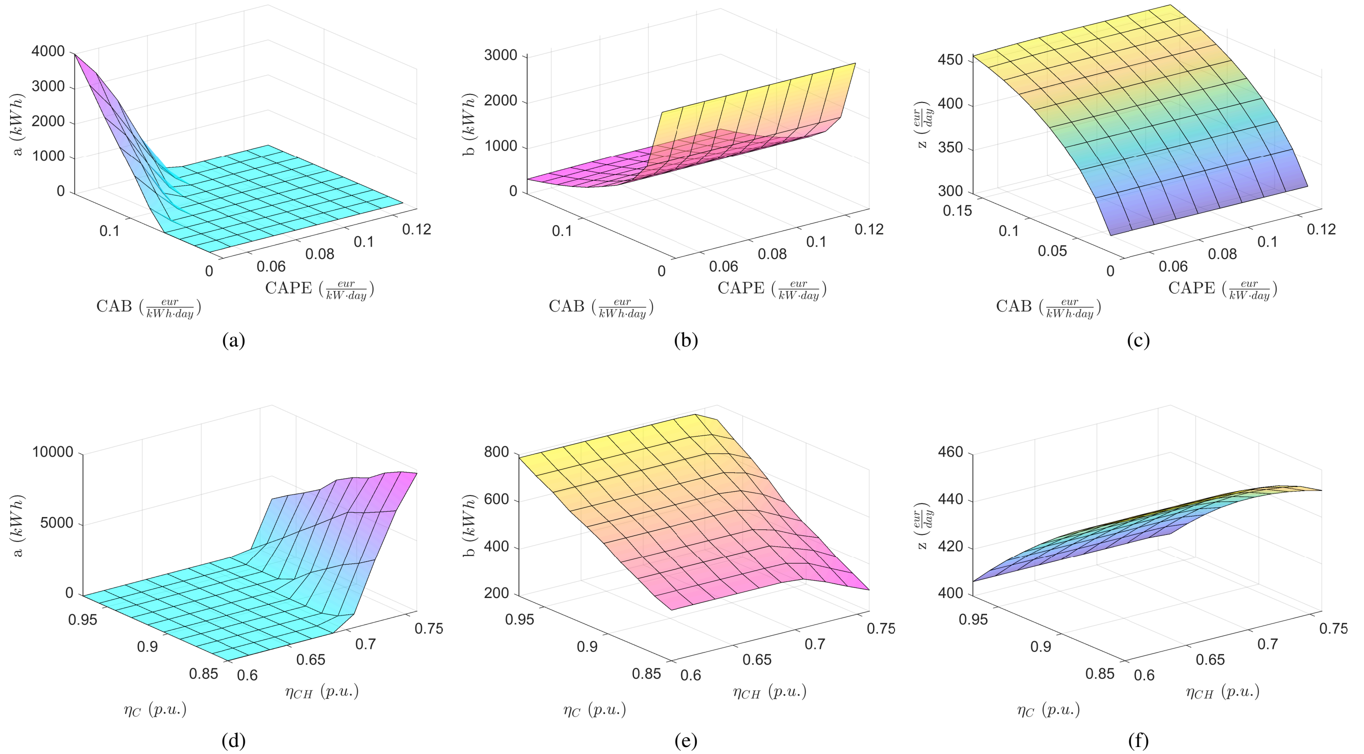
Optimization problems are solved using CPLEX under GAMS [11] in a computer with Windows 11, Intel(R) i7 Processor 1165G7@2.8GHz, and 16GB RAM. The computation time is up to 25.9 min. for each sensitivity analysis on two groups of parameters (mesh of 10x10 = 100 problems).

IV. RESULTS

With the aim to show the influence and the interaction among the five groups of relevant factors, Sect. III-A, the ten combinations that results from taking two elements in a set of 5 elements have been tested. For each combination we have a surface in three dimensions, Figs. 3 and 4, one for each group of parameters and the third for the result. Three results (one each column in Figs. 3 and 4) have been selected for each combination: hydrogen storage a, battery storage b, and total cost (investment + operation) z.

In all the ten combinations and all the problems in the sensitivity analyses the wind capacity installed was 2000 kW, that is exactly the upper bound W_{max}. That is because the energy community can get a positive net profit by installing more wind generation and acting as a net energy producer, but here we focus on self-consumption and not on this option.

With the current energy prices and technology amortization costs and efficiency, hydrogen is not profitable and it will not be installed in the case study with default parameters. But the sensitivity analyses show that the hydrogen technology is relatively close to the profitability frontier. The interaction



(a) (b) (c)

(d) (e) (f)

Fig. 4. Sensitivity analysis on battery amortization cost (CAB) vs hydrogen amortization cost ($CAPE$, $CATG$), results for: (a) Hydrogen storage a, (b) battery storage b, and total cost (investment + operation) z. Sensitivity analysis on battery efficiency $\eta_C \rightarrow (\eta_C,\, \eta_D)$ vs hydrogen efficiency $\eta_{CH} \rightarrow (\eta_E,\, \eta_{GT})$, results for: (d) Hydrogen storage a, (e) battery storage b, and (f) total cost (investment + operation) z.

of hydrogen efficiency and hydrogen amortization cost with the energy prices is shown in Fig. 3. For instance, seeing at Fig. 3d, an increase of around 5% over the current hydrogen efficiency, $1.15{\cdot}(\eta_E, \eta_{GT})$, or an increase of around 60% over the current purchase/selling prices, would do the hydrogen profitable. On the other hand, the required reduction in the amortization cost ($CAPE$, $CATG$) is quite drastic, of around 50%, Fig. 3a.

The interaction between hydrogen and battery is shown in Fig. 4. Battery and hydrogen are partially competing, an improvement in battery factors (reduction in amortization cost Fig. 4a, increase of efficiency Fig. 4d) leads to an increase in the hydrogen factors required to be profitable. And also hydrogen partially replaces battery, Fig. 4e.

V. CONCLUSIONS

The trade-off between short-term (battery) and long-term (hydrogen) storage is discussed for a wind powered energy community. Five groups of main factors are identified, their qualitative interaction is summarized in a fraction and, for a case study, their influence and interaction is numerically quantified. In the case study, hydrogen is not profitable but close to be. It can reach profitability by improving several factors, for instance by increasing efficiency around a 15% over the current value.

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