H2AEOLUS

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Dynamic Model for Hydrogen Production and Storage Plants

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Abstract: The current deliverable proposes models for hydrogen based storage plants to be studied and implemented within the EU-FCH 2 JU (European Union Fuel Cells and Hydrogen 2 Joint Undertaking) founded project HAEOLUS. The motivation for such advanced storage systems lies on the intermittent nature of wind energy combined with the (possible) penalty production deviations adopted in several electricity regulation markets. These facts explain the difficulty for clean energy (in particular wind) in playing a major role in the world energy system. So, coupling the wind farm with advanced energy storage systems represents, in principle, a good solution for boosting wind farm power supply. Within the HAEOLUS project, such hydrogen based storage concept will be tested and analysed.

The modeling part conducted in the current deliverable is preliminary for the development of ad hoc control strategies. To develop such models, constraints and limitations in terms of capital cost, response time, operational, maintenance and degradation issues of the equipments are taken into account.

Revision History

Date	Description	Author (organisation)
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1 Introduction

This deliverable addresses the problem of deriving dynamical and operational models for the hydrogen based energy storage system (ESS) developed under the EU-FCH JU project HAEOLUS −Hydrogen-Aeolic Energy with Optimized eLectrolyzers Upstream of Substation [1].

Specifically, the plant is modeled considering mixed-integer linear programming (MILP) constraints and switching dynamics for the hydrogen tank and the degradation dynamics. Also, depreciation costs are considered when switching among ON, OFF and STB (standby) operational states.

The models developed within this deliverable represent the backbone for the control algorithms to be derived in the further HAEOLUS activities and, therefore, they might be subjected to slight modification and particularization along the HAEOLUS development cycle.

The modeling activity is the preliminary stage for the control algorithms and the control architectures design. However, such design is outside the scope of the current deliverable and will be addressed in the next project's activities. Therefore, here it is only supposed the possibility of having a reference demand P_{ref} to be tracked with the available system power P_{avl}. Since such tracking is designed to be the most economical one, cost functions for the electrolyzer and the fuel cell are derived. The latter consider the operational cost and degradation cost of the equipment and will be then integrated in the control algorithms developed in the further projects activities.

2 Nomenclature

The forecasts, the parameters and the decision variables used in the proposed formulation are described, respectively, in Table 1, Table 2 and Table 3. The variable reported in Table 2 and the decision variable reported in Table 3 will be described in detail in Section 4.

3 System description

In the Haeolus project, both WP5 and WP6 investigates the wind-hydrogen system operations. However, while WP5 conduct techno-economic anaysis, WP6 investigates the run-time behaviour of the system and perform control action. For this reason, WP5 and WP6 can be seen as complementary workpackages. Once WP5 establish the most profitable size and operational scheme of the plant (studying the net profit value of the overall system and the price per ton of the produced hydrogen), WP6 propose control algorithms that actually operate the designed system in runtime taking care of its physical constraints and the degradation and operation costs it experiences according to its operating conditions.

A conceptual block diagram of the system is shown in Figure 1. The red solid lines denote energy flows, green solid lines denote hydrogen flows, and blue dashed lines denote data flows. The wind power is the main energy source of this energy plant. When required, the produced electricity is delivered to the load. Excess power from the wind turbines can be shunted to the electrolyzer for hydrogen production with the help of energy storage control algorithms. The produced hydrogen from the electrolyzer is stored in a hydrogen tank. In case of insufficient

Table 1: Parameters.

Parameters	Description
OM_e	Operational and maintenance cost of the electrolyzer
OM_f	Operational and maintenance cost of the fuel cell
$H^{\max}$	Maximum Level of the hydrogen storage unit [Nm^3/Wh]
$H^{\min}$	Minimum Level of the hydrogen storage unit [Nm^3/Wh]
$P_e^{\max}$	Maximum power level of the electrolyzer [kW]
P_e^{STB}	Standby power of the electrolyzer [kW]
$P_e^{\min}$	Minimum power level of the electrolyzer [kW]
$P_f^{\max}$	Maximum power level of fuel cell [kW]
$P_f^{\min}$	Minimum power level of fuel cell [kW]
P_f^{STB}	Standby power of the fuel cell [kW]
η_e	Efficiency for the electrolyzer
η_f	Efficiency for the fuel cell
P_w	Wind power production [kW]
Cycles_e	Number of life cycles of the electrolyzer
Cycles_f	Number of life cycles of the fuel cell
NH_e	Number of life hours of the electrolyzer
NH_f	Number of life hours of the fuel cell
HY_e	Number of per year life hours of the electrolyzer
HY_f	Number of per year life hours of the fuel cell
T	Simulation horizon [h]
T_s	Sampling period [h]
ζ_e	Electrolyzer hydrogen production rate [Nm^3/kW][1]
ζ_f	Fuel cell hydrogen consumption rate [kW/Nm^3]
$S_{\mathrm{rep},e}$	Electrolyzer stack replacement cost [€/kW]
$S_{\mathrm{rep},f}$	Fuel cell stack replacement cost [€/kW]

Table 2: Forecast powers over the simulation horizon $\mathbb{T}$.

Forecasts	Description
P_w	Wind power production [kW]
P_{ref}	Electrical load demand [kW]

Table 3: Real and logical decision variables.

Variables	Description
δ_e^{ON}	On state of the electrolyzer
δ_e^{OFF}	Off state of the electrolyzer
δ_e^{STB}	Standby state of the electrolyzer
δ_f^{ON}	On state of the fuel cell
δ_f^{OFF}	Off state of the fuel cell
δ_f^{STB}	Standby state of the fuel cell
P_e	Electrical power of the electrolyzer [kW]
P_f	Electrical power of the fuel cell [kW]
P_{avl}	Available system electrical power [kW]
H	Stored level of the hydrogen [Nm^3].

wind, the fuel cell uses the stored hydrogen for re-electrification purpose, thus playing the role of a backup power source that continues to deliver electricity.

We remind to the reader that P_{ref} and P_{avl} have been introduced in order to derive the power balance equation for the system depicted in Figure 1. The particularization of the models for specific control objectives will be addressed in the related project's deliverables, since it is outside the scope of this document.

4 System modeling

The system has been modeled via a mixed dynamic and logic (MDL) formulation, where both continuous state and discrete (logic) states concur in the model definition.

The three logic discrete state, for both the electrolyzer and fuel cell, are ON (the unit is producing/consuming hydrogen), OFF (the unit does not produce/consume hydrogen and does not absorb any power) and STB (the system does not produce/consume hydrogen but absorbs

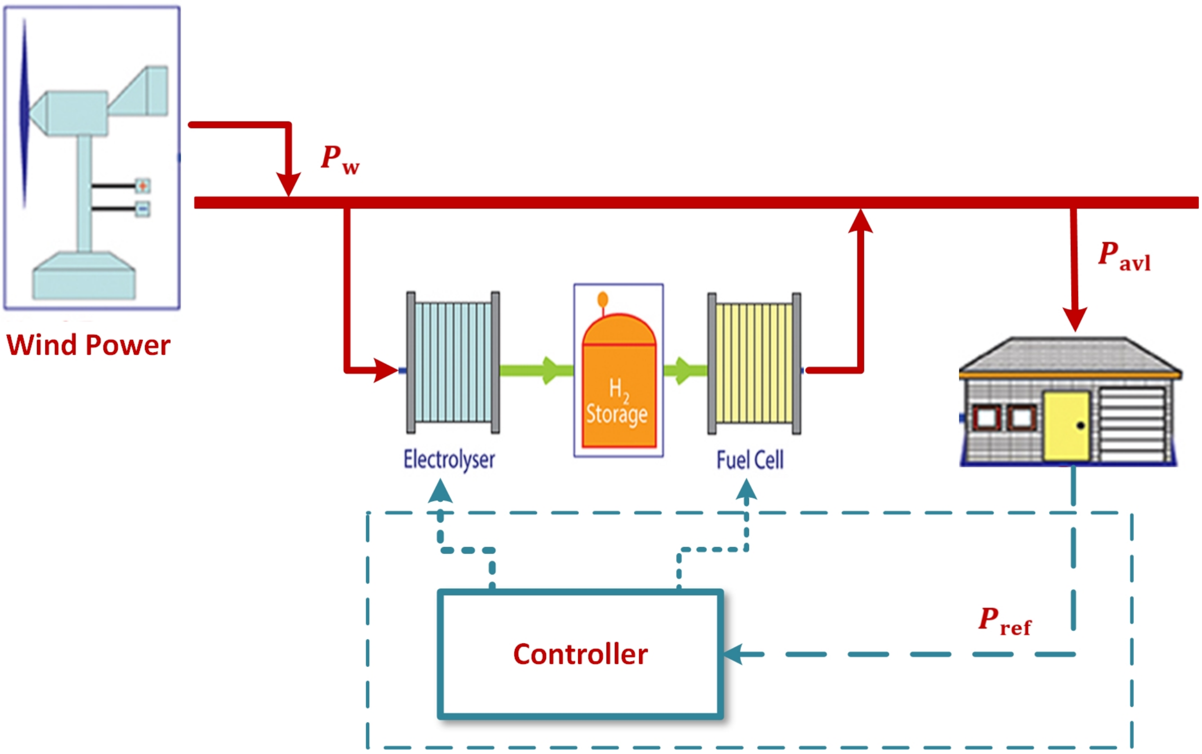

Figure 1: HAEOLUS' hydrogen based storage system modeled in this deliverable. P_e, P_f and P_w are the electrolyzer power, the fuel cell power and the wind power, respectively. Also, P_{ref} is the reference demand and P_{avl} is the available power.

a power P_i^{STB}, with $i \in \{e, f\}$). The consumption/production of the hydrogen implies the unit degradation.

All the equations are derived in a discrete time fashion. We denote with k the discrete time. The (physical) continuous time t can be immediately obtained via $t := kT_s$, with T_s being the sampling time. In this deliverable, the sampling time is supposed to be of one hour and all the parameters in the equations are computed according to such sampling time. Since the control architecture is not addressed here, a different sampling time (and related equations' parameters) may be considered in the future deliverables, according to the timescale of the control loop. In that case, a simple rescaling of the parameters and the equations will be adopted.

4.1 Discrete Operational States of the Electrolyzer and the Fuel cell

The discrete operational states of the devices are presented in this section. The three discrete operational modes ($\mathrm{ON}/\mathrm{OFF}/\mathrm{STB}$) for both the electrolyzer and the fuel cell characterize our models. The latter have been modeled with three mutually exclusive binary variables, δ_i^{ON}, δ_i^{OFF}, and δ_i^{STB}, with $i \in \{e, f\}$. Figure 2 shows the allowed state transitions of the electrolyzer and the fuel cell from one state to the other. The automaton is so characterized by three operational modes to which we will associate the three binary decision variables and other six additional binary variables denoting the state transitions, respectively.

The operational states and switching of the devices have been modeled and discussed in the two following subsections.

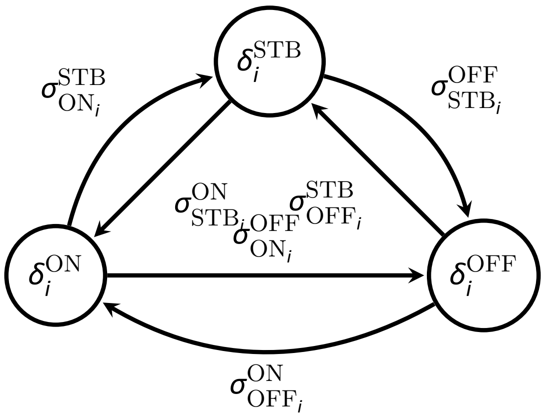

Figure 2: Operational modes automaton.

4.1.1 Mathematical Model and MLD Constraints Formulation of the States

The three discrete states $\delta_i^{\mathrm{ON}}(k)$, $\delta_i^{\mathrm{OFF}}(k)$ and $\delta_i^{\mathrm{STB}}(k)$ of both devices are characterized by the operating power of the devices themselves at any time k. Specifically, the logical $\delta_i^{\mathrm{ON}}(k)$ occurs when the devices power value is between $P_i^{\min}$ and $P_i^{\max}$. On the other hand, when the devices are in stand by, i.e., $\delta_i^{\mathrm{STB}}(k) = 1$, the power value is P_i^{STB}. Finally, the devices will go to their $\delta_i^{\mathrm{OFF}}(k)$ state when their power value is at zero. In other words, for $i \in \{e, f\}$

$$\begin{cases} P_i^{\min} \le P_i(k) \le P_i^{\max} & \iff \delta_i^{\mathrm{ON}}(k) = 1, \\ P_i(k) = P_i^{\mathrm{STB}} & \iff \delta_i^{\mathrm{STB}}(k) = 1, \\ P_i(k) = 0 & \iff \delta_i^{\mathrm{OFF}}(k) = 1. \end{cases} \tag{1}$$

These logical states are, as modeled in Figure 2, mutually exclusive and each device is always in one and only one mode. In order to cope with an optimal control framework, the cases above need further manipulations to derive MILP constraints. For this reason, as intermediate step, we introduce the following six auxiliary variables defined as

$$z_i^{\ge 0}(k) = \begin{cases} 1 & P_i(k) \ge 0, \\ 0 & P_i(k) < 0, \end{cases} \tag{2a}$$

$$z_i^{\le 0}(k) = \begin{cases} 0 & P_i(k) > 0, \\ 1 & P_i(k) \le 0, \end{cases} \tag{2b}$$

$$z_i^{\ge P_i^{\mathrm{STB}}}(k) = \begin{cases} 1 & P_i(k) \ge P_i^{\mathrm{STB}}, \\ 0 & P_i(k) < P_i^{\mathrm{STB}}, \end{cases} \tag{2c}$$

$$z_i^{\le P_i^{\mathrm{STB}}}(k) = \begin{cases} 0 & P_i(k) > P_i^{\mathrm{STB}}, \\ 1 & P_i(k) \le P_i^{\mathrm{STB}}, \end{cases} \tag{2d}$$

$$z_i^{\ge P_i^{\min}}(k) = \begin{cases} 1 & P_i(k) \ge P_i^{\min}, \\ 0 & P_i(k) < P_i^{\min}, \end{cases} \tag{2e}$$

$$z_i^{\le P_i^{\max}}(k) = \begin{cases} 0 & P_i(k) > P_i^{\max}, \\ 1 & P_i(k) \le P_i^{\max}, \end{cases} \tag{2f}$$

By using the transformations defined in [2], the above formulas can be expressed with the following boolean inequalities

$$\begin{aligned} P_i(k) &< M z_i^{\ge 0}(k), \\ -P_i(k) &\le M(1 - z_i^{\ge 0}(k)); \end{aligned} \tag{3a}$$

$$\begin{aligned} -P_i(k) &< M z_i^{\le 0}(k), \\ P_i(k) &\le M(1 - z_i^{\le 0}(k)); \end{aligned} \tag{3b}$$

$$\begin{aligned} P_i(k) - P_i^{\mathrm{STB}} &< M z_i^{\ge P_i^{\mathrm{STB}}}(k), \\ -P_i(k) + P_i^{\mathrm{STB}} &\le M(1 - z_i^{\ge P_i^{\mathrm{STB}}}(k)); \end{aligned} \tag{3c}$$

$$\begin{aligned} -P_i(k) + P_i^{\mathrm{STB}} &< M z_i^{\le P_i^{\mathrm{STB}}}(k), \\ P_i(k) - P_i^{\mathrm{STB}} &\le M(1 - z_i^{\le P_i^{\mathrm{STB}}}(k)); \end{aligned} \tag{3d}$$

$$
\begin{aligned}
P_i(k) - P_i^{\min} &< M z_i^{\geq P_i^{\min}}(k),\\
-P_i(k) + P_i^{\min} &\leq M(1 - z_i^{\geq P_i^{\min}}(k));
\end{aligned} \tag{3e}
$$

$$
\begin{aligned}
-P_i(k) + P_i^{\max} &< M z_i^{\leq P_i^{\max}}(k),\\
P_i(k) - P_i^{\max} &\leq M(1 - z_i^{\leq P_i^{\max}}(k)),
\end{aligned} \tag{3f}
$$

where M is a sufficiently large positive number. The auxiliary variables codified by inequalities (3) are then adopted to model the MLD linking the discrete logical states of each device with its operating power, according to (1). Namely, for $i \in \{e, f\}$, the following constraints are derived

$$(1 - \delta_i^{\mathrm{ON}}(k)) + z_i^{\geq P_i^{\min}}(k) \geq 1, \tag{4a}$$

$$(1 - \delta_i^{\mathrm{ON}}(k)) + z_i^{\leq P_i^{\max}}(k) \geq 1; \tag{4b}$$

$$(1 - \delta_i^{\mathrm{STB}}(k)) + z_i^{\geq P_i^{\mathrm{STB}}}(k) \geq 1, \tag{4c}$$

$$(1 - \delta_i^{\mathrm{STB}}(k)) + z_i^{\leq P_i^{\mathrm{STB}}}(k) \geq 1; \tag{4d}$$

$$(1 - \delta_i^{\mathrm{OFF}}(k)) + z_i^{\geq 0}(k) \quad \geq 1, \tag{4e}$$

$$(1 - \delta_i^{\mathrm{OFF}}(k)) + z_i^{\leq 0}(k) \quad \geq 1; \tag{4f}$$

$$\delta_i^{\mathrm{ON}}(k) + \delta_i^{\mathrm{OFF}}(k) + \delta_i^{\mathrm{STB}}(k) = 1. \tag{4g}$$

4.1.2 Mathematical Model and MLD Constraints Formulation of the State Transitions

Each transition is the result of the state change, and can be defined with the help of the six following expressions

$$\sigma_{\mathrm{ON}_i}^{\mathrm{OFF}}(k) = \delta_i^{\mathrm{ON}}(k-1) \wedge \delta_{\mathrm{i}}^{\mathrm{OFF}}(k), \tag{5a}$$

$$\sigma_{\mathrm{OFF}_i}^{\mathrm{ON}}(k) = \delta_i^{\mathrm{OFF}}(k-1) \wedge \delta_{\mathrm{i}}^{\mathrm{ON}}(k), \tag{5b}$$

$$\sigma_{\mathrm{ON}_i}^{\mathrm{STB}}(k) = \delta_i^{\mathrm{ON}}(k-1) \wedge \delta_i^{\mathrm{STB}}(k), \tag{5c}$$

$$\sigma_{\mathrm{STB}_i}^{\mathrm{ON}}(k) = \delta_i^{\mathrm{STB}}(k-1) \wedge \delta_{\mathrm{i}}^{\mathrm{ON}}(k), \tag{5d}$$

$$\sigma_{\mathrm{STB}_i}^{\mathrm{OFF}}(k) = \delta_i^{\mathrm{STB}}(k-1) \wedge \delta_i^{\mathrm{OFF}}(k), \tag{5e}$$

$$\sigma_{\mathrm{OFF}_i}^{\mathrm{STB}}(k) = \delta_i^{\mathrm{OFF}}(k-1) \wedge \delta_i^{\mathrm{STB}}(k). \tag{5f}$$

A cost will be later associated with each of the transitions defined above. To cope with MILP constraints, each expression of the (5) is equivalently converted into three inequalities, thus resulting in the 18 following formulas

$$
\begin{aligned}
-\delta_i^{\mathrm{ON}}(k-1) + \sigma_{\mathrm{ON}_i}^{\mathrm{OFF}}(k) &\leq 0,\\
-\delta_i^{\mathrm{OFF}}(k) + \sigma_{\mathrm{ON}_i}^{\mathrm{OFF}}(k) &\leq 0,\\
\delta_i^{\mathrm{ON}}(k-1) + \delta_i^{\mathrm{OFF}}(k) - \sigma_{\mathrm{ON}_i}^{\mathrm{OFF}}(k) &\leq 1;
\end{aligned} \tag{6a}
$$

$$
\begin{aligned}
-\delta_i^{\mathrm{OFF}}(k-1) + \sigma_{\mathrm{OFF}_i}^{\mathrm{ON}}(k) &\le 0, \\
-\delta_i^{\mathrm{ON}}(k) + \sigma_{\mathrm{OFF}_i}^{\mathrm{ON}}(k) &\le 0, \\
\delta_i^{\mathrm{OFF}}(k-1) + \delta_i^{\mathrm{ON}}(k) - \sigma_{\mathrm{OFF}_i}^{\mathrm{ON}}(k) &\le 1;
\end{aligned} \tag{6b}
$$

$$
\begin{aligned}
-\delta_i^{\mathrm{ON}}(k-1) + \sigma_{\mathrm{ON}_i}^{\mathrm{STB}}(k) &\le 0, \\
-\delta_i^{\mathrm{STB}}(k) + \sigma_{\mathrm{ON}_i}^{\mathrm{STB}}(k) &\le 0, \\
\delta_i^{\mathrm{ON}}(k-1) + \delta_i^{\mathrm{STB}}(k) - \sigma_{\mathrm{ON}_i}^{\mathrm{STB}}(k) &\le 1;
\end{aligned} \tag{6c}
$$

$$
\begin{aligned}
-\delta_i^{\mathrm{STB}}(k-1) + \sigma_{\mathrm{STB}_i}^{\mathrm{ON}}(k) &\le 0, \\
-\delta_i^{\mathrm{ON}}(k) + \sigma_{\mathrm{STB}_i}^{\mathrm{ON}}(k) &\le 0, \\
\delta_i^{\mathrm{STB}}(k-1) + \delta_i^{\mathrm{ON}}(k) - \sigma_{\mathrm{STB}_i}^{\mathrm{ON}}(k) &\le 1;
\end{aligned} \tag{6d}
$$

$$
\begin{aligned}
-\delta_i^{\mathrm{STB}}(k-1) + \sigma_{\mathrm{STB}_i}^{\mathrm{OFF}}(k) &\le 0, \\
-\delta_i^{\mathrm{OFF}}(k) + \sigma_{\mathrm{STB}_i}^{\mathrm{OFF}}(k) &\le 0, \\
\delta_i^{\mathrm{STB}}(k-1) + \delta_i^{\mathrm{OFF}}(k) - \sigma_{\mathrm{STB}_i}^{\mathrm{OFF}}(k) &\le 1;
\end{aligned} \tag{6e}
$$

$$
\begin{aligned}
-\delta_i^{\mathrm{OFF}}(k-1) + \sigma_{\mathrm{OFF}_i}^{\mathrm{STB}}(k) &\le 0, \\
-\delta_i^{\mathrm{STB}}(k) + \sigma_{\mathrm{OFF}_i}^{\mathrm{STB}}(k) &\le 0, \\
\delta_i^{\mathrm{OFF}}(k-1) + \delta_i^{\mathrm{STB}}(k) - \sigma_{\mathrm{OFF}_i}^{\mathrm{STB}}(k) &\le 1.
\end{aligned} \tag{6f}
$$

4.2 Model of the Hydrogen Storage Dynamics

The hydrogen storage dynamics are defined as a function of the hydrogen level at the previous time step $H(k)$ and the $\zeta_e(k)$ and $\zeta_f(k)$, respectively the hydrogen production and consumption rates. Notice that the $\zeta_i(k)$ are time varying functions which incorporate the efficiency degradation of both devices.

$$\zeta_e(k+1) = \left(1 - \frac{d}{P_e^{\max}\mathrm{HY}_e} P_e(k)\delta_e^{\mathrm{ON}}(k)\right)\zeta_e(k), \tag{7a}$$

$$\zeta_f(k+1) = \left(1 - \frac{d}{P_f^{\max}\mathrm{HY}_f} P_f(k)\delta_f^{\mathrm{ON}}(k)\right)\zeta_f(k), \tag{7b}$$

$$H(k+1) = H(k) + \zeta_e(k)P_e(k)\delta_e^{\mathrm{ON}}(k)T_s - \frac{P_f(k)\delta_f^{\mathrm{ON}}(k)T_s}{\zeta_f(k)}, \tag{7c}$$

where d is the degradation rate when the unit is working at a constant maximum power and over the number of yearly life hours. According to what discussed during the project meeting in Bilbao (September 2018), the degradation is assumed to be linearly increasing with respect of the power. Notice that, according to (7) the electrolyzer produces hydrogen only in the ON mode. Similarly, the fuel cell consumes hydrogen and produces power only in the ON mode. Both the STB and OFF mode are not associated to hydrogen production and consumption. However, the STB mode will be associated with a power consumption needed to keep the active stack warm.

4.3 Electrolyzer and Fuel cell Cost Functions

The cost incurred in operating the electrolyzer and the fuel cell are summarized in the two respective cost functions derived in this section. Both of them are expressed as a summation of different cost related to the component depreciation, the reduction in the number of life cycles and the energy spent in keeping the units warm during the stand by mode. More in details, the manufacturers of the electrolyzers and the fuel cells defined the life cycles of the devices as a function of number of working hours. It has been noticed in many studies [3, 4, 5, 6, 7] that the fluctuating loads and the operating cycles can seriously affect these devices in a number of ways. Therefore, in order to tackle such outlined problems, we propose the following cost functions

$$
\begin{aligned}
\mathrm{J}_e(k) = &\left(\frac{S_{\mathrm{rep},e}}{\mathrm{NH}_e} + \mathrm{Cost}_e^{\mathrm{OM}}\right)\delta_e^{\mathrm{ON}}(k) \\
&+ \mathrm{Cost}_{\mathrm{OFF}_e}^{\mathrm{ON}}\sigma_{\mathrm{OFF}_e}^{\mathrm{ON}}(k) \\
&+ \mathrm{Cost}_{\mathrm{ON}_e}^{\mathrm{OFF}}\sigma_{\mathrm{ON}_e}^{\mathrm{OFF}}(k) \\
&+ \mathrm{Cost}_{\mathrm{ON}_e}^{\mathrm{STB}}\sigma_{\mathrm{ON}_e}^{\mathrm{STB}}(k) \\
&+ \mathrm{Cost}_{\mathrm{STB}_e}^{\mathrm{ON}}\sigma_{\mathrm{STB}_e}^{\mathrm{ON}}(k) \\
&+ \mathrm{Cost}_{\mathrm{STB}_e}^{\mathrm{OFF}}\sigma_{\mathrm{STB}_e}^{\mathrm{OFF}}(k) \\
&+ \mathrm{Cost}_{\mathrm{OFF}_e}^{\mathrm{STB}}\sigma_{\mathrm{OFF}_e}^{\mathrm{STB}}(k) \\
&+ c(k)P_e^{\mathrm{STB}}\delta_e^{\mathrm{STB}}(k),
\end{aligned} \tag{8a}
$$

$$
\begin{aligned}
\mathrm{J}_f(k) = &\left(\frac{S_{\mathrm{rep},f}}{\mathrm{NH}_f} + \mathrm{Cost}_f^{\mathrm{OM}}\right)\delta_f^{\mathrm{ON}}(k) \\
&+ \mathrm{Cost}_{\mathrm{OFF}_f}^{\mathrm{ON}}\sigma_{\mathrm{OFF}_f}^{\mathrm{ON}}(k) \\
&+ \mathrm{Cost}_{\mathrm{ON}_f}^{\mathrm{OFF}}\sigma_{\mathrm{ON}_f}^{\mathrm{OFF}}(k) \\
&+ \mathrm{Cost}_{\mathrm{ON}_f}^{\mathrm{STB}}\sigma_{\mathrm{ON}_f}^{\mathrm{STB}}(k) \\
&+ \mathrm{Cost}_{\mathrm{STB}_f}^{\mathrm{ON}}\sigma_{\mathrm{STB}_f}^{\mathrm{ON}}(k) \\
&+ \mathrm{Cost}_{\mathrm{STB}_f}^{\mathrm{OFF}}\sigma_{\mathrm{STB}_f}^{\mathrm{OFF}}(k) \\
&+ \mathrm{Cost}_{\mathrm{OFF}_f}^{\mathrm{STB}}\sigma_{\mathrm{OFF}_f}^{\mathrm{STB}}(k) \\
&+ c(k)P_f^{\mathrm{STB}}\delta_f^{\mathrm{STB}}(k),
\end{aligned} \tag{8b}
$$

where $\mathrm{Cost}_e^{\mathrm{OM}}$ and $\mathrm{Cost}_f^{\mathrm{OM}}$ denotes the operating and maintenance cost of the electrolyzer and the fuel cell, $c(k)$ is the power spot price. $\mathrm{Cost}_{\mathrm{OFF}_i}^{\mathrm{ON}}$, $\mathrm{Cost}_{\mathrm{ON}_i}^{\mathrm{OFF}}$, $\mathrm{Cost}_{\mathrm{STB}_i}^{\mathrm{ON}}$, $\mathrm{Cost}_{\mathrm{ON}_i}^{\mathrm{STB}}$, $\mathrm{Cost}_{\mathrm{STB}_i}^{\mathrm{OFF}}$, and $\mathrm{Cost}^{\mathrm{STB}}_{\mathrm{OFF}_i}$ describe the startup, shutdown and standby cost of the electrolyzer and the fuel cell, respectively choosing $i \in \{e, f\}$. These cost are payed any time a mode switch occurs, since any complete sequence of switching accounts for a working cycle and, therefore, reduces the components' life. The adoption of these costs within the control cost function allows to properly take into account such degradation and, therefore, help to drive the system in the most profitable way. Estimating such costs may be difficult in practice. At the moment, literature based values have been selected but more suitable values may come during the WP3 activities according to the real plant working data. We wish to emphasize, for the sake of clarity, that shifting from OFF to ON (cold start) presents usually a higher cost than from STB to ON (warm start). On the other hand, devices in OFF mode do not absorb any power, while this is not true in STB mode. The $S_{\mathrm{rep},e}$ and $S_{\mathrm{rep},f}$ represents the stack replacement cost of the electrolyzer and the fuel cell, respectively.

The electrolyzer and fuel cell cost functions represent the operational and depreciation cost in running the two equipment. Such cost functions will be integrated in suitable optimal control objectives to enforce that the overall plant operates in the most profitable way.

The development of the control algorithms is outside the scope of this deliverable and will be presented in later documents.

4.4 Power balance equation

Denoting with P_{ref} the load demand and with P_{avl} the available power that can be provided by the HAEOLUS hydrogen based storage system, the power balance equation is given by

$$P_{\mathrm{avl}}(k) = P_w(k) - P_e(k)\delta_e^{\mathrm{ON}}(k) + P_f(k)\delta_f^{\mathrm{ON}}(k). \tag{9}$$

It can be clearly seen from the given formula that the system power P_{avl} depends on the available wind power P_w and the balancing action of the hydrogen storage system.

4.5 Physical and operating constraints

Physical constraints are given by the maximum and minimum power allowed for the electrolyzer and the fuel cell and the maximum and minimum hydrogen level in the storage tank.

These constraints are given in what follows

$$P_e^{\mathrm{min}} \le P_e(k) \le P_e^{\mathrm{max}}, \tag{10}$$

$$P_f^{\mathrm{min}} \le P_f(k) \le P_f^{\mathrm{max}}, \tag{11}$$

$$H^{\mathrm{min}} \le H(k) \le H^{\mathrm{max}}. \tag{12}$$

Ramp rates for P_e and P_f are also given as

$$|P_e(k+1) - P_e(k)|\delta_e^{\mathrm{ON}} \le R_e, \tag{13}$$

$$|P_f(k+1) - P_f(k)|\delta_f^{\mathrm{ON}} \le R_f, , \tag{14}$$

where R_e and R_f are the maximum power rate for the electrolyzer and the fuel cell, respectively.

5 Model parameters

The model developed in the previous sections is given in a parametric way. The values of the parameters have to be assigned according to the ones of the plant actually installed.

According to the current HAEOLUS project status, the parameters for the equipments to be installed are given in Table 4. Current missing data have been assigned through the literature [8, 9, 10]. Notice that the value of the parameters may be subjected to variations in further model releases according to the equipment that will actually be installed and possible parameters estimation thorough diagnostic and prognostic algorithms (both system construction and diagnostic and prognostic activities in the HAEOLUS project are not yet due).

The efficiency degradation of the electrolyzer and the fuel cell is taken as two percent per year at maximum power and the devices stack replacement cost is considered as 2/3 of the 40 % of the Capex_i of the devices, as reported in the following formula

$$S_{\mathrm{rep},i} = \left.\frac{2 \times \mathrm{Capex}_i \times 0.4}{3}\right|_{i\in\{e,f\}}, \tag{15}$$

The Capex_i value and the size of both devices are given in Table 4. Also the considered initial values for hydrogen production rate ζ_e and hydrogen consumption rate ζ_f are 0.23 $\mathrm{Nm}^3/\mathrm{kW}$ and 1.320 $\mathrm{kW}/\mathrm{Nm}^3$, respectively.

6 Conclusions

The current deliverable develops models for operating, with optimal control strategies, the HAEOLUS hydrogen based energy storage system to be coupled to the wind power generation. The models both encode discrete logical states representing operating device modes and continuous dynamics. The models take into account the cost that each device introduces any time it switches between logical states, thus degradating the number of life cycles and the loss of efficiency along the working conditions. Furthermore, the other physical constraints and cost, such as the power consumption in standby mode, are considered.

The cost related to each device and the models developed will then be included in suitable control algorithms and implemented withing the EU-FCH 2 JU project HAEOLUS [1]. Along the project's development cycle, timescales, control algorithm and model parameters may be further particularized according to the other deliverables outcomes.

All the models reported in this deliverable have been implemented in MATLAB. The optimizations have been performed through YALMIP.

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Table 4: Parameters and cost factor values for the system's components.

PEM Electrolyzer Parameters	
$\mathrm{Cost}_e^{\mathrm{STB}}$ = 0.0042 €	NH_e = 40000 hours
$\mathrm{Cost}_e^{\mathrm{ON}}$ = 0.123 €	$\mathrm{Cost}_e^{\mathrm{OFF}}$ = 0.0062 €
$\mathrm{Cost}_{[\mathrm{deg},e]}$ = 0.05 €	Capex_e =1.55 €/kW
$\mathrm{Cost}_e^{\mathrm{OM}}$ = 0.002 10 €/h	$P_e^{\max}$ = 3000 kW
$P_e^{\min}$ = 300 kW	P_e^{STB} = 1 kW
NY_e= 8000 hours	
PEM Fuel cell Parameters	
$\mathrm{Cost}_f^{\mathrm{STB}}$ = 0.003 €	NH_f = 40000 hours
$\mathrm{Cost}_f^{\mathrm{ON}}$ = 0.01 €	$\mathrm{Cost}_f^{\mathrm{OFF}}$ = 0.005 €
$\mathrm{Cost}_{[\mathrm{deg},f]}$ = 0.01 €	Capex_f = 1.55 €/kW
$\mathrm{Cost}_{\mathrm{OM}}^f$ = 0.01 €/h	$P_f^{\max}$ = 132 kW
$P_f^{\min}$ = 12 kW	P_f^{STB} = 1 kW
NY_f= 8000 hours	
Hydrogen Tank Parameters	
Volume = 10 Nm^3	Pressure = 30 bar

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