Modeling of a Hydrogen Storage Wind Plant for Model Predictive Control Management Strategies

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Outline

- **Renewable Energy and hydrogen as an Energy Storage system**
- **HAEOLUS Project**
  - HAEOLUS project
  - Consortium
- **Energy Storage Modeling and Control**
  - HAEOLUS dynamic modeling
    - Multi-layer plant modeling
    - Discrete operational states of the electrolyzer and the fuel cell
    - State space model of the hydrogen storage tank
    - System's operating & physical constraints formulation
  - Multiple objective optimization model
    - Smoothing the power production
    - Forecasted power demand satisfaction
- **Numerical Results**
- **Conclusions**

Renewable Energy Storage

Challenges of today's electrical grid

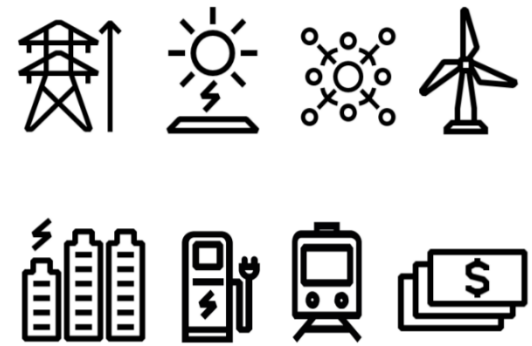
- Electricity consumption on the rise
- Growth in renewables
- Proliferation of smart grid technology
- Coal plant retirements
- Tax and regulatory incentives
- **Wind and PV renewables are not programmable sources**

Energy storage benefits for the grid and the industry

- Providing smooth grid integration of renewable energy
- Storing renewable generation peaks for demand peaks
- Flattening demand peaks, for grid equipment stress reduction
- Decreasing the power fees related to short time peak loads
- Maintaining generation and demand balance

Goals

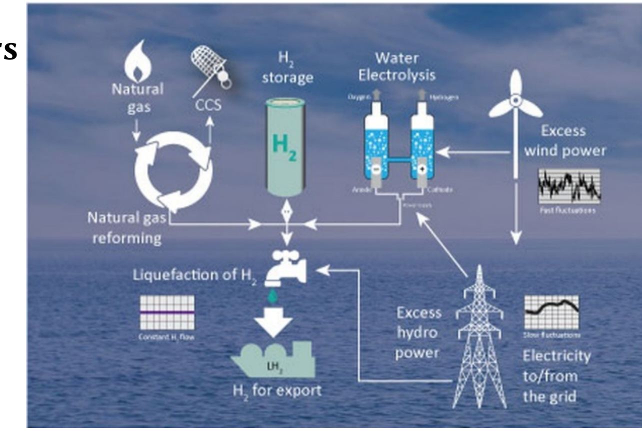
- Load Levelling
- Peak Shaving
- Frequency regulation
- Power Quality



Renewable Energy Storage

Hydrogen for electrical energy storage

- Conversion of excess renewable power in hydrogen via **electrolysers**
- **Storage of hydrogen** in gas cylinder, tanks or underground
- Re-electrification of the hydrogen through a **fuel cells**
- **Hydrogen combustion in**
- **Ideal for long-term energy storage** (remote locations)



Hydrogen for power to gas and gas to power

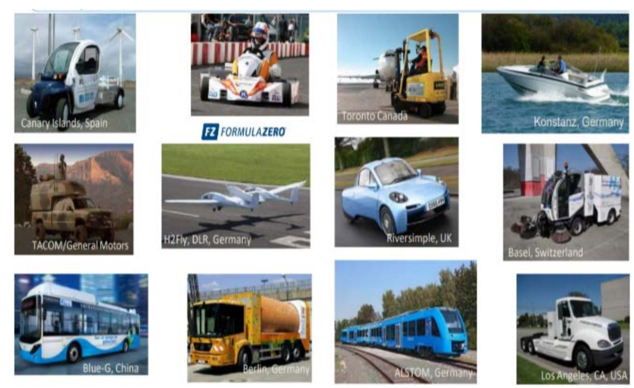
- Hydrogen may be burnt in gas turbines or backup generators
- Hydrogen may be added up to 10% directly to the methane grid
- Hydrogen may be converted into methane or ammonia

Hydrogen for industry

- Hydrogen can be sold as chemical product as it is or converted into ammonia (green electrolysis from renewables vs classical hydrocarbon extraction)
- Employed in steel production, mining ore processing

Hydrogen as fuel for mobility applications

- Hydrogen can be produced directly at refueling stations and used for cars, trucks and boats



HAEOLUS Project

- The Raggovidda wind park in Varanger peninsula (Norway):
  - 45 MW built of 200 MW concession
  - Bottleneck to main grid 95 MW
  - Total Varanger resources 2000 MW
  - Capacity factor 50%
  - Local economy based on fishing

- HAEOLUS – Hydrogen-Aeolic Energy with Optimised eLectrolysers Upstream of Substation (2018-2021) is a FCH2 JU and EU-H2020 research project with a total 5 M€ founding.
- It aims to evaluate a carbon-free, hydrogen-based solutions for wind farms
- 2.5 MW electrolyser within the wind farm fence
- Develop MW-scale PEM technology, benchmark against FCH2 JU targets
- Enable remote operation, minimise maintenance requirements, remote diagnostic and prognostic
- Produce 120 tons of hydrogen over 2.5 years
- Demonstrate multiple control systems:
  - Electricity storage
  - Mini-grid
  - Fuel production

www.haeolus.eu

HAEOLUS Consortium

SINTEF

Project coordinator

tecnalia

Techno-economical analysis and impact

University of Sannio

Control algorithms

UBFC
UNIVERSITÉ BOURGOGNE FRANCHE-COMTÉ

Remote diagnostic and prognostic

VARANGER KRAFT

Operator of the wind park and grid

HYDROGENICS
SHIFT POWER | ENERGIZE YOUR WORLD

Electrolyser and fuel cell supplier

KES
Knowledge Environment Security Srl

Middleware developer for remote monitoring and control

Norway

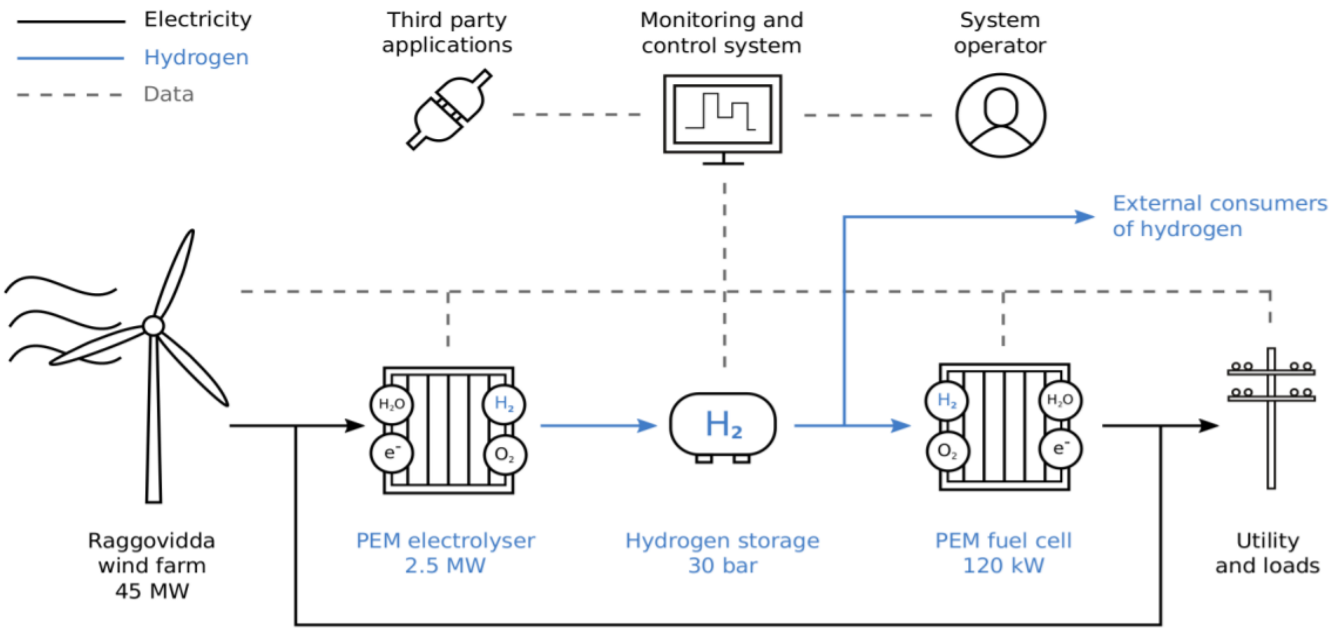
France

Spain

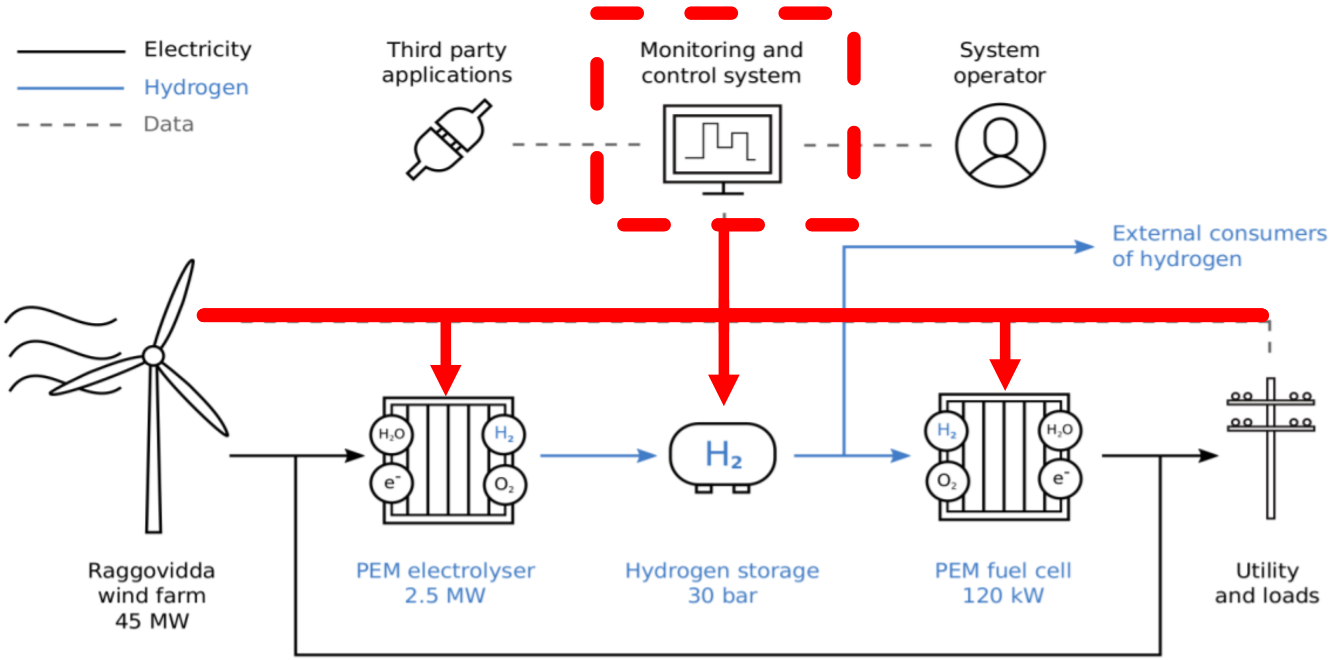
Belgium

Italy

Block Diagram of the HAEOLUS plant



Block Diagram of the HAEOLUS plant



HAEOLUS Dynamic Modeling

Dynamic Plant Model

- Logical and physical modeling for the development of ad-hoc control strategies
- The HAEOLUS dynamic model has been designed and developed to implement multi level controllers (at the moment, we are considering two levels)

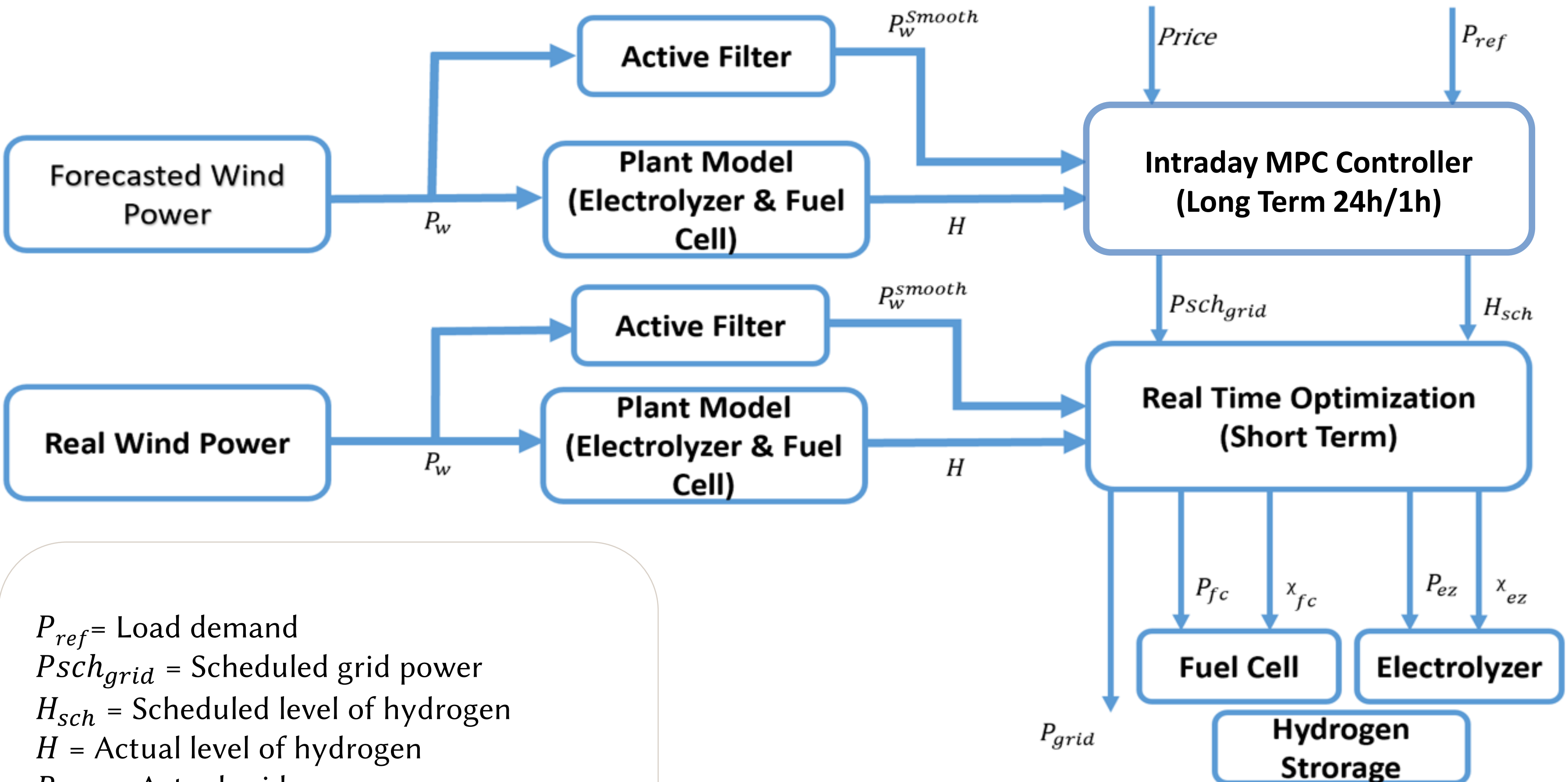
Multi-level control

- To address the problem of solving different time scales of the electricity markets
- Markets ranging from daily horizon schedule (24 hour ahead) to real time load sharing (seconds)

Features

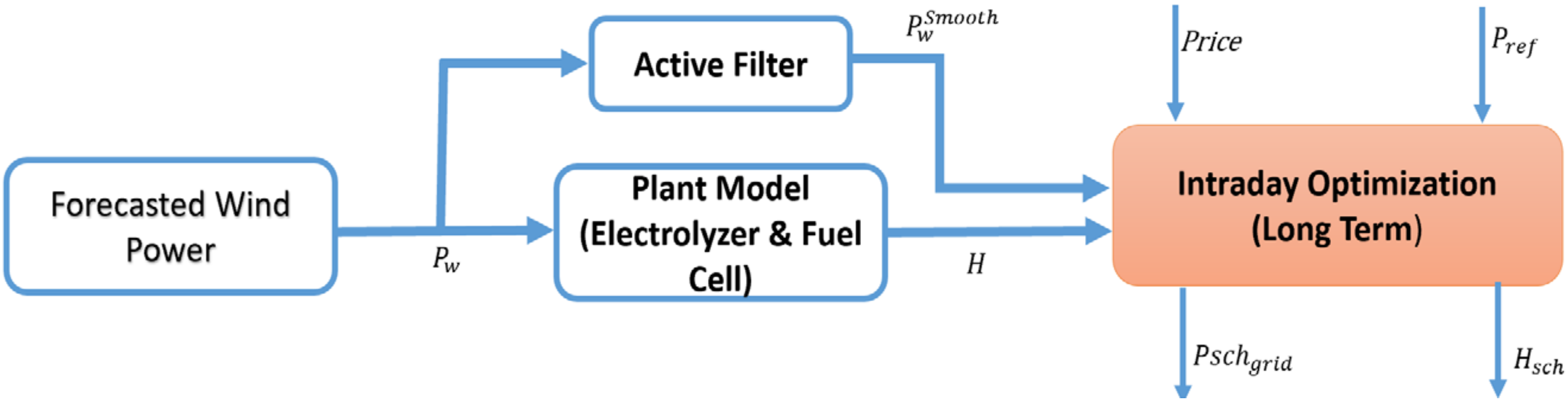
- Multi level & multi timescale control hierarchy
- Constraints and limitations of the energy system
- Capital cost, response time, operational, maintenance and degradation issues of the equipment

Two Levels Control Architecture



P_{ref}= Load demand
$Psch_{grid}$ = Scheduled grid power
H_{sch} = Scheduled level of hydrogen
H = Actual level of hydrogen
P_{grid} = Actual grid power
Price= Power spot price
P_w^{smooth}=smooth power output
P_{elz} = Electrolyzer power

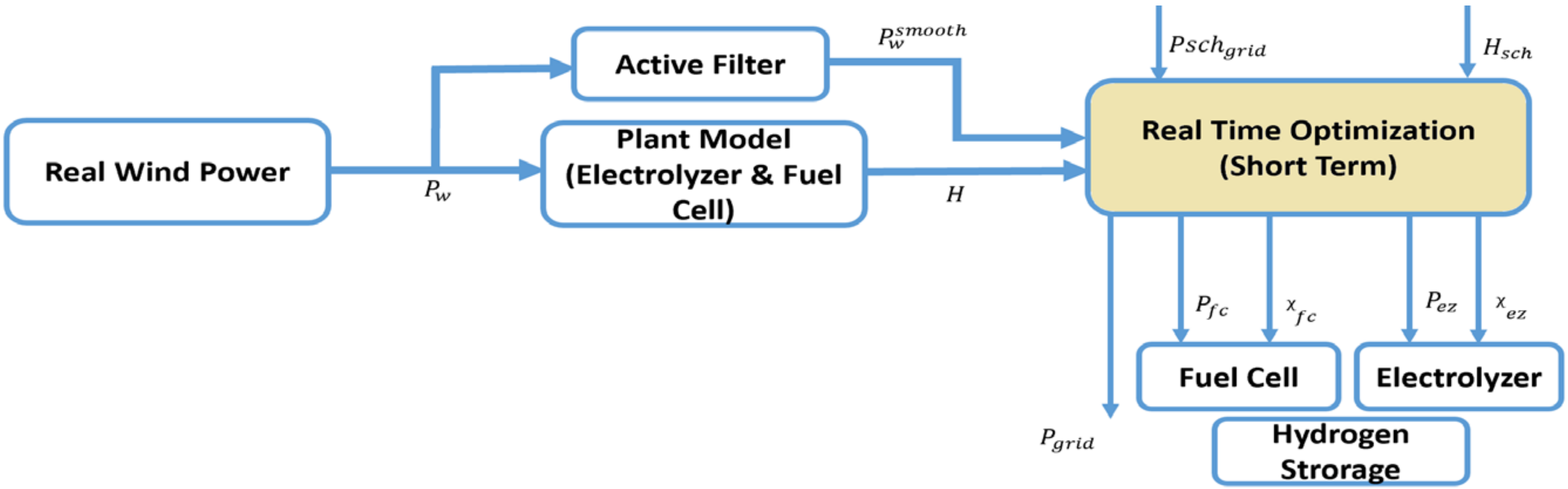
Higher Level Control (HLC)



Higher Level Control

- **The purpose of the intraday MPC is to handle electricity transactions for the following day**
- The control goal is:
  - Find the optimal power schedule profiles for the electrolyser and the fuel cell so as to deliver power to the grid, minimize operational cost and maximize power sold revenues

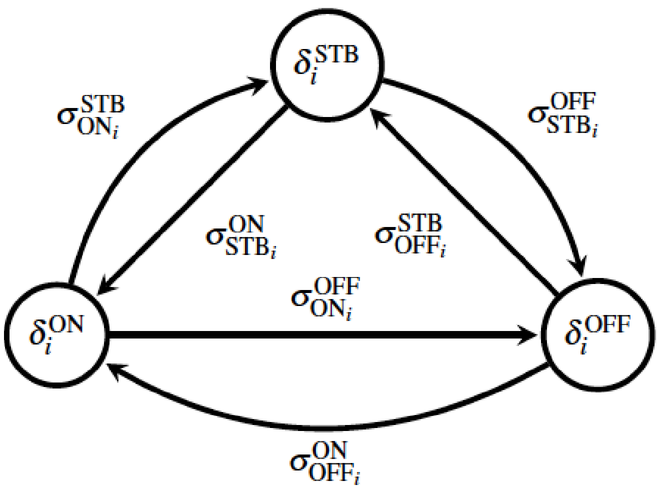
Lower Level Control (LLC)



Lower Level Control

- **The purpose of the lower level control is to track the higher level control references**
- The LLC will execute every 1 min to track the reference set by the intraday optimization (from the HLC)
- The control goals are:
  - Output power smoothing
  - Tracking the requested power while minimizing the operational cost

HAEOLUS Higher Level Mathematical Model

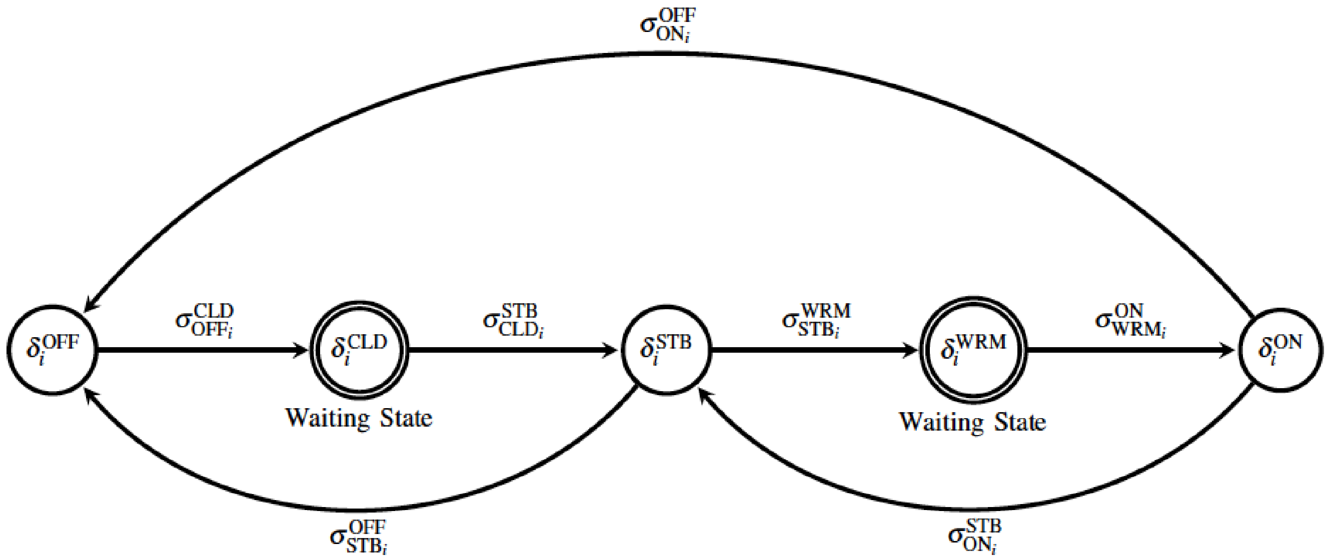


Operational modes automaton for the electrolyser and the fuel cell

Higher Level Modeling

- **The higher level control model is characterized by**
  - Three operational modes ON/OFF/STB of devices
  - **At ON state**
    - Hydrogen production and consumption
    - Power value is between $P_i^{\min}$ and $P_i^{\max}$
    - Corresponding logical variable $\delta_i^{ON}(k) = 1$
  - **At Standby state**
    - The devices consumes P_i^{STB} with $\delta_i^{STB}(k) = 1$
    - Standby power keeps the devices stacks warm
  - **At OFF state**
    - No hydrogen production and consumption
    - The devices goes to their off state $\delta_i^{OFF}(k)$ when power value is zero
  - Mixed linear dynamic (MLD) formulation
  - $\sigma_{\alpha_i}^{\beta}$ are state transitions with $\alpha, \beta \in \{ON, OFF, STB\}$ $\alpha \neq \beta$

HAEOLUS Lower Level Mathematical Model



Operational modes automaton for the electrolyser and the fuel cell

Lower Level Modeling

- **The five logic states *OFF*, *CLD*, *STB*, *WRM*, *ON* characterizes the electrolyser and fuel cell model**

- The states have been modeled with mutually exclusive logical variables

$$\delta_i^{\mathrm{ON}}(k) + \delta_i^{\mathrm{OFF}}(k) + \delta_i^{\mathrm{STB}}(k) + \delta_i^{\mathrm{CLD}}(k) + \delta_i^{\mathrm{WRM}}(k) = 1.$$

- The cold and warm states defines the exact amount of waiting time needed for their cold and warm start T^{CLD} and T^{WRM}, respectively

Constraint Formulation of the Devices Discrete States

- Each of the five boolean states $\delta_i^{\mathrm{ON}}(k), \delta_i^{\mathrm{OFF}}(k), \delta_i^{\mathrm{STB}}(k), \delta_i^{\mathrm{CLD}}(k)$ and $\delta_i^{\mathrm{WRM}}(k)$ of both devices allows at any time a specific operating power $P_i(k)$

Allowed range of operating power with respect to the operational states

$$\begin{cases} P_i^{\min} \leq P_i(k) \leq P_i^{\max} & \Longleftrightarrow \quad \delta_i^{\mathrm{ON}} \quad = 1, \\ P_i(k) = P_i^{\mathrm{CLD}} & \Longleftrightarrow \quad \delta_i^{\mathrm{CLD}} \quad = 1, \\ P_i(k) = P_i^{\mathrm{STB}} & \Longleftrightarrow \quad \delta_i^{\mathrm{STB}} \quad = 1, \\ P_i(k) = P_i^{\mathrm{WRM}} & \Longleftrightarrow \quad \delta_i^{\mathrm{WRM}} = 1, \\ P_i(k) = 0 & \Longleftrightarrow \quad \delta_i^{\mathrm{OFF}} \quad = 1. \end{cases}$$

Logical Formulation of the Devices Discrete States Transitions

Devices discrete operational states transitions

- The following logical expressions define the allowed operational state transitions

$$\sigma_{\mathrm{ON}_i}^{\mathrm{OFF}}(k) = \delta_i^{\mathrm{ON}}(k-1) \wedge \delta_i^{\mathrm{OFF}}(k),$$
$$\sigma_{\mathrm{STB}_i}^{\mathrm{OFF}}(k) = \delta_i^{\mathrm{STB}}(k-1) \wedge \delta_i^{\mathrm{OFF}}(k),$$
$$\sigma_{\mathrm{ON}_i}^{\mathrm{STB}}(k) = \delta_i^{\mathrm{ON}}(k-1) \wedge \delta_i^{\mathrm{STB}}(k),$$
$$\sigma_{\mathrm{OFF}_i}^{\mathrm{CLD}}(k) = \delta_i^{\mathrm{OFF}}(k-1) \wedge \delta_i^{\mathrm{CLD}}(k),$$
$$\sigma_{\mathrm{CLD}_i}^{\mathrm{STB}}(k) = \delta_i^{\mathrm{CLD}}(k-1) \wedge \delta_i^{\mathrm{STB}}(k),$$
$$\sigma_{\mathrm{STB}_i}^{\mathrm{WRM}}(k) = \delta_i^{\mathrm{STB}}(k-1) \wedge \delta_i^{\mathrm{WRM}}(k),$$
$$\sigma_{\mathrm{WRM}_i}^{\mathrm{ON}}(k) = \delta_i^{\mathrm{WRM}}(k-1) \wedge \delta_i^{\mathrm{ON}}(k).$$

Electrolyser and Fuel cell Cost Function

$$
\begin{aligned}
\mathrm{J_e}(k) = &\left(\frac{S_{\mathrm{rep,e}}}{\mathrm{NH}_e} + \mathrm{Cost}_{\mathrm{e}}^{\mathrm{OM}}\right)\delta_{\mathrm{e}}^{\mathrm{ON}}(k)\\
&+ \mathrm{Cost}_{\mathrm{ON_e}}^{\mathrm{OFF}}\sigma_{\mathrm{ON_e}}^{\mathrm{OFF}}(k)\\
&+ \mathrm{Cost}_{\mathrm{CLD_e}}^{\mathrm{STB}}\sigma_{\mathrm{CLD_e}}^{\mathrm{STB}}(k)\\
&+ \mathrm{Cost}_{\mathrm{STB_e}}^{\mathrm{OFF}}\sigma_{\mathrm{STB_e}}^{\mathrm{OFF}}(k)\\
&+ c(k)P_{\mathrm{e}}^{\mathrm{STB}}\delta_{\mathrm{e}}^{\mathrm{STB}}(k)\\
&+ c(k)P_{\mathrm{e}}^{\mathrm{CLD}}\delta_{\mathrm{e}}^{\mathrm{CLD}}(k)\\
&+ c(k)P_{\mathrm{e}}^{\mathrm{WRM}}\delta_{\mathrm{e}}^{\mathrm{WRM}}(k),
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{J_f}(k) = &\left(\frac{S_{\mathrm{rep,f}}}{\mathrm{NH}_f} + \mathrm{Cost}_{\mathrm{f}}^{\mathrm{OM}}\right)\delta_{\mathrm{f}}^{\mathrm{ON}}(k)\\
&+ \mathrm{Cost}_{\mathrm{ON_f}}^{\mathrm{OFF}}\sigma_{\mathrm{ON_f}}^{\mathrm{OFF}}(k)\\
&+ \mathrm{Cost}_{\mathrm{CLD_f}}^{\mathrm{STB}}\sigma_{\mathrm{CLD_f}}^{\mathrm{STB}}(k)\\
&+ \mathrm{Cost}_{\mathrm{STB_f}}^{\mathrm{OFF}}\sigma_{\mathrm{STB_f}}^{\mathrm{OFF}}(k)\\
&+ c(k)P_{\mathrm{f}}^{\mathrm{STB}}\delta_{\mathrm{f}}^{\mathrm{STB}}(k)\\
&+ c(k)P_{\mathrm{f}}^{\mathrm{CLD}}\delta_{\mathrm{f}}^{\mathrm{CLD}}(k)\\
&+ c(k)P_{\mathrm{f}}^{\mathrm{WRM}}\delta_{\mathrm{f}}^{\mathrm{WRM}}(k),
\end{aligned}
$$

Terms accounting for the devices working Hours

- $S_{\mathrm{ref,i}}$ = devices stack replacement cost , $\mathrm{Cost}_{\mathrm{i}}^{\mathrm{OM}}$ = operational and management cost of the devices

Terms accounting for the devices working cycles

- $\mathrm{Cost}_{\mathrm{ON}_i}^{\mathrm{OFF}}$ is the switching cost from on-off state (half working cycle), $\mathrm{Cost}_{\mathrm{CLD}_i}^{\mathrm{STB}}$ is the switching cost from cold-standby state (quarter working cycle) and $\mathrm{Cost}_{\mathrm{STB}_i}^{\mathrm{OFF}}$ defines the devices Standby-off switching cost

Terms accounting for the power consumptions

$P_{\mathrm{i}}^{\mathrm{STB}}$, $P_{\mathrm{i}}^{\mathrm{CLD}}$ and $P_{\mathrm{f}}^{\mathrm{WRM}}$ are the powers at standby, warm and cold state, while $c(k)$ is the power spot price

State Space Model

System state dynamics

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

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

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

- $H(k)$ $\zeta_e(k)$ $\zeta_f(k)$ are the hydrogen level production and consumption rates, respectively
- d is the degradation rate, (HY) is the number of life hours of devices and T_s is the sampling time

Operating Constraints I

System Constraints

- The power balancing equation

$$P_w(k) - P_e(k)\delta_e^{\mathrm{ON}}(k) + P_f(k)\delta_f^{\mathrm{ON}}(k) - P_{\mathrm{avl}}(k) - P_{\mathrm{dump}}(k) = 0.$$

- Mixed integer linear (MIL) constraints formulation of the devices states

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

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

$$\Rightarrow$$

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

$$\begin{aligned} (1 - \delta_i^{\mathrm{ON}}(k)) + z_i^{\geq P_i^{\min}}(k) &\geq 1, \\ (1 - \delta_i^{\mathrm{ON}}(k)) + z_i^{\leq P_i^{\max}}(k) &\geq 1. \end{aligned}$$

Operating Constraints II

System Constraints

- Mixed integer linear (MIL) constraints formulation of the devices state transitions

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

- Feasibility and operating constraints

$$
H^{\min} \leq H(k) \leq H^{\max},
$$

$$
0 \leq P_{\mathrm{dump}}(k) \leq P_w(k).
$$

Operating Constraints III

System Constraints

- Exact amount of waiting time constraints for warm and the cold start of the devices

$$\delta_i^{\mathrm{CLD}}(k) - \delta_i^{\mathrm{CLD}}(k-1) \leq \delta_i^{\mathrm{CLD}}(\tau^{\mathrm{CLD}}), \text{where } \tau^{\mathrm{CLD}} = k+1, \cdots, T^{\mathrm{CLD}} - 1$$
$$\delta_i^{\mathrm{CLD}}(k) + \delta_i^{\mathrm{CLD}}(k+1) + \cdots + \delta_i^{\mathrm{CLD}}(k + T^{\mathrm{CLD}}) \leq T^{\mathrm{CLD}}$$

- Rump up/down constraints

$$|(P_{\mathrm{e}}(k+1) - P_{\mathrm{e}}(k))\delta_{\mathrm{e}}^{\mathrm{ON}}| \leq R_{\mathrm{e}},$$
$$|(P_{\mathrm{f}}(k+1) - P_{\mathrm{f}}(k))\delta_{\mathrm{f}}^{\mathrm{ON}}| \leq R_{\mathrm{f}}.$$

Lower Level Controller

Lower Level Controller

- **Lower level control objectives are**
  - To track the references coming from the HLC at minimum operating cost
  - Providing smooth power to the grid

Issues

- How to achieve both control objectives simultaneously?

Solution

- Design an optimal controller which solves a multi-objective optimization problem recasting it in sequential optimizations

Optimal Controller Design

Multi Objective Optimization

$$\min_{\substack{\underline{P}_{i,k}^{T-1},\\ \underline{P}_{\mathrm{dump,k}}^{T-1},\\ \underline{\delta}_{i,k}^{\alpha\,T-1},\\ \underline{\sigma}_{\alpha_{i,k}}^{\beta\,T-1},\\ \underline{z}_{i,k}^{\gamma\,T-1},\\ \underline{y}_{k}^{T-1,\tau}}} \{\xi \quad J\}$$

Subject to

Storage dynamics,

Discrete logical states,

Mode transitions,

Physical constraints,

Operating constraints,

Ramp Up constraints,

$$\delta_i^{\alpha} \in [0,1], \qquad \alpha \in \{\mathrm{ON}, \mathrm{CLD}, \mathrm{STB}, \mathrm{WRM}, \mathrm{OFF}\}$$

$$\delta_{\alpha_i}^{\beta} \in [0,1], \qquad \alpha, \beta \in \{\mathrm{ON}, \mathrm{CLD}, \mathrm{STB}, \mathrm{WRM}, \mathrm{OFF}\}, \alpha \neq \beta$$

$$z_i^{\gamma} \in \{0,1\}, \qquad \gamma \in \{\geq 0, \leq 0, \ldots, \leq P_i^{\max}\},$$

$$i \in \{\mathrm{e}, \mathrm{f}\}.$$

The multi objective optimization problem is then recast in to two sequential optimization problems with optimization priority to the smoothing 1st, followed by the load tracking optimization.

Receding Horizon decisions vectors for MPC:

$$\underline{P}_{i,k}^{T-1} = [P_i(k) + P_i(k+1), \cdots, P_i(k+T-1)]^{\top}$$

Similarly, all the decision variable vector horizon's have been computed

Optimal Controller Design

Power trajectory smoothing cost function [Priority 1]

Power reference tracking cost function [Priority 2]

Multi Objective Optimization

$$\min_{\substack{\underline{P}_{i,k}^{T-1},\\ \underline{P}_{\mathrm{dump},k}^{T-1},\\ \underline{\delta}_{i,k}^{\alpha T-1},\\ \underline{\sigma}_{\alpha_{i,k}}^{\beta T-1},\\ \underline{z}_{i,k}^{\gamma T-1},\\ \underline{y}_{k}^{T-1,\tau}}} \{\xi \quad J\}$$

Subject to

Storage dynamics,

Discrete logical states,

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Ramp Up constraints,

$$\delta_i^\alpha \in [0,1], \qquad \alpha \in \{\mathrm{ON}, \mathrm{CLD}, \mathrm{STB}, \mathrm{WRM}, \mathrm{OFF}\}$$

$$\delta_{\alpha_i}^\beta \in [0,1], \qquad \alpha, \beta \in \{\mathrm{ON}, \mathrm{CLD}, \mathrm{STB}, \mathrm{WRM}, \mathrm{OFF}\}, \alpha \neq \beta$$

$$z_i^\gamma \in \{0,1\}, \qquad \gamma \in \{\geq 0, \leq 0, \ldots, \leq P_i^{\max}\},$$

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The multi objective optimization problem is then recast in to two sequential optimization problems with optimization priority to the smoothing 1st, followed by the load tracking optimization.

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$$\underline{P}_{i,k}^{T-1} = [P_i(k) + P_i(k+1), \cdots, P_i(k+T-1)]^\top$$

Similarly, all the decision variable vector horizon’s have been computed

Power Smoothing

Smoothing Optimization Problem

$$\xi^* = \min_{\substack{j=0,\cdots,T-1,\\ \tau=1,\cdots,\tau_B,\\ \underline{P}_{i,k}^{T-1},\\ \underline{P}_{\text{dump,k}}^{T-1},\\ \underline{\delta}_{i,k}^{\alpha T-1},\\ \underline{\sigma}_{\alpha_{i,k}}^{\beta T-1},\\ \underline{z}_{i,k}^{\gamma T-1},\\ \underline{y}_k^{T-1,\tau}}} \sum_{j=0}^{T-1} \sum_{\tau=1}^{\tau_B} \omega^{k,\tau} y^{(k+j,\tau)}$$

s.t.

$$|P_{\text{avl}}(k+j) - P_{\text{avl}}(k+j-\tau)| \leq \bar{y}^{\tau} + y^{(k+j,\tau)},$$

$$y^{(k+j,\tau)} \geq 0,$$

Storage dynamics, System physical and operating constraints,

Discrete logical states, Mode transitions, Ramp up constraints,

All Boolean and continous variables,

$$i \in \{\text{e}, \text{f}\}.$$

Power Smoothing

Smoothing Optimization Problem

$$
\xi^* = \min_{\substack{j=0,\cdots,T-1,\\ \tau=1,\cdots,\tau_B,\\ \underline{P}_{i,k}^{T-1},\\ \underline{P}_{\mathrm{dump,k}}^{T-1},\\ \underline{\delta}_{i,k}^{\alpha T-1},\\ \underline{\sigma}_{\alpha_{i,k}}^{\beta T-1},\\ \underline{z}_{i,k}^{\gamma T-1},\\ \underline{y}_{k}^{T-1,\tau}}} \sum_{j=0}^{T-1} \sum_{\tau=1}^{\tau_B} \omega^{k,\tau} y^{(k+j,\tau)}
$$

Power trajectory smoothing decision variables

s.t.

$$
|P_{\mathrm{avl}}(k+j) - P_{\mathrm{avl}}(k+j-\tau)| \leq \bar{y}^{\tau} + y^{(k+j,\tau)},
$$

$$
y^{(k+j,\tau)} \geq 0,
$$

Storage dynamics, System physical and operating constraints,

Discrete logical states, Mode transitions, Ramp up constraints,

All Boolean and continous variables,

$$
i \in \{\mathrm{e}, \mathrm{f}\}.
$$

Load Tracking

Load Tracking Optimization Problem

$$
\mathrm{J} = \min_{\substack{j=0,\cdots,T-1,\\ \tau=1,\cdots,\tau_B,\\ \underline{P}_{i,k}^{T-1},\\ \underline{P}_{\mathrm{dump},\mathrm{k}}^{T-1},\\ \underline{\delta}_{i,k}^{\alpha T-1},\\ \underline{\sigma}_{\alpha_{i,k}}^{\beta T-1},\\ \underline{z}_{i,k}^{\gamma T-1},\\ \underline{y}_{k}^{T-1,\tau}}} \sum_{j=0}^{T-1} \rho_l \mathrm{J}_l(k+j) + \rho_e \mathrm{J}_e(k+j) + \rho_f \mathrm{J}_f(k+j)
$$

s.t.

$$
y^{(k+j,\tau)} \geq 0,
$$

$$
|P_{\mathrm{avl}}(k+j) - P_{\mathrm{avl}}(k+j-\tau)| \leq \bar{y}^{\tau} + y^{(k+j,\tau)}, \tau = 1,\cdots,\tau_B,
$$

$$
\sum_{j=0}^{T-1} \sum_{\tau=1}^{\tau_B} \omega^{k,\tau} y^{(k+j,\tau)} \leq \xi^{*},
$$

Storage dynamics, System physical and operational constraints,

Discrete states and transitions,Mode transitions, Rump up constraints,

All Boolean and continous variables,

$i \in \{\mathrm{e}, \mathrm{f}\}$.

Load Tracking

Load Tracking Optimization Problem

$$\mathrm{J} = \min_{\substack{j=0,\cdots,T-1,\\ \tau=1,\cdots,\tau_B,\\ \underline{P}_{i,k}^{T-1},\\ \underline{P}_{\mathrm{dump,k}}^{T-1},\\ \underline{\delta}_{i,k}^{\alpha T-1},\\ \underline{\sigma}_{\alpha i,k}^{\beta T-1},\\ \underline{z}_{i,k}^{\gamma T-1},\\ \underline{y}_{k}^{T-1,\tau}}} \sum_{j=0}^{T-1} \rho_l \mathrm{J}_l(k+j) + \rho_e \mathrm{J}_e(k+j) + \rho_f \mathrm{J}_f(k+j)$$

Fuel cell operating cost

Electrolyser operating cost

Tracking error cost

s.t.

$$y^{(k+j,\tau)} \geq 0,$$

$$|P_{\mathrm{avl}}(k+j) - P_{\mathrm{avl}}(k+j-\tau)| \leq \bar{y}^{\tau} + y^{(k+j,\tau)}, \tau = 1, \cdots, \tau_B,$$

$$\sum_{j=0}^{T-1} \sum_{\tau=1}^{\tau_B} \omega^{k,\tau} y^{(k+j,\tau)} \leq \xi^*,$$

Storage dynamics, System physical and operational constraints,

Discrete states and transitions,Mode transitions, Rump up constraints,

All Boolean and continous variables,

$i \in \{\mathrm{e}, \mathrm{f}\}.$

Load Tracking

Load Tracking Optimization Problem

$$
\mathrm{J} = \min_{\substack{j=0,\cdots,T-1,\\ \tau=1,\cdots,\tau_B,\\ \underline{P}_{i,k}^{T-1},\\ \underline{P}_{\mathrm{dump,k}}^{T-1},\\ \underline{\delta}_{i,k}^{\alpha\, T-1},\\ \underline{\sigma}_{\alpha\, i,k}^{\beta\, T-1},\\ \underline{z}_{i,k}^{\gamma\, T-1},\\ \underline{y}_{k}^{T-1,\tau}}} \sum_{j=0}^{T-1} \rho_l \mathrm{J}_l(k+j) + \rho_e \mathrm{J}_e(k+j) + \rho_f \mathrm{J}_f(k+j)
$$

The optimal value of the smoothing cost function is passed as a constrain to the tracking problem, in order to have a smoothed tracking of load demand.

s.t.

$$
y^{(k+j,\tau)} \geq 0,
$$

$$
|P_{\mathrm{avl}}(k+j) - P_{\mathrm{avl}}(k+j-\tau)| \leq \bar{y}^{\tau} + y^{(k+j,\tau)}, \tau = 1, \cdots, \tau_B,
$$

$$
\sum_{j=0}^{T-1} \sum_{\tau=1}^{\tau_B} \omega^{k,\tau} y^{(k+j,\tau)} \leq \xi^*,
$$

Storage dynamics, System physical and operational constraints,

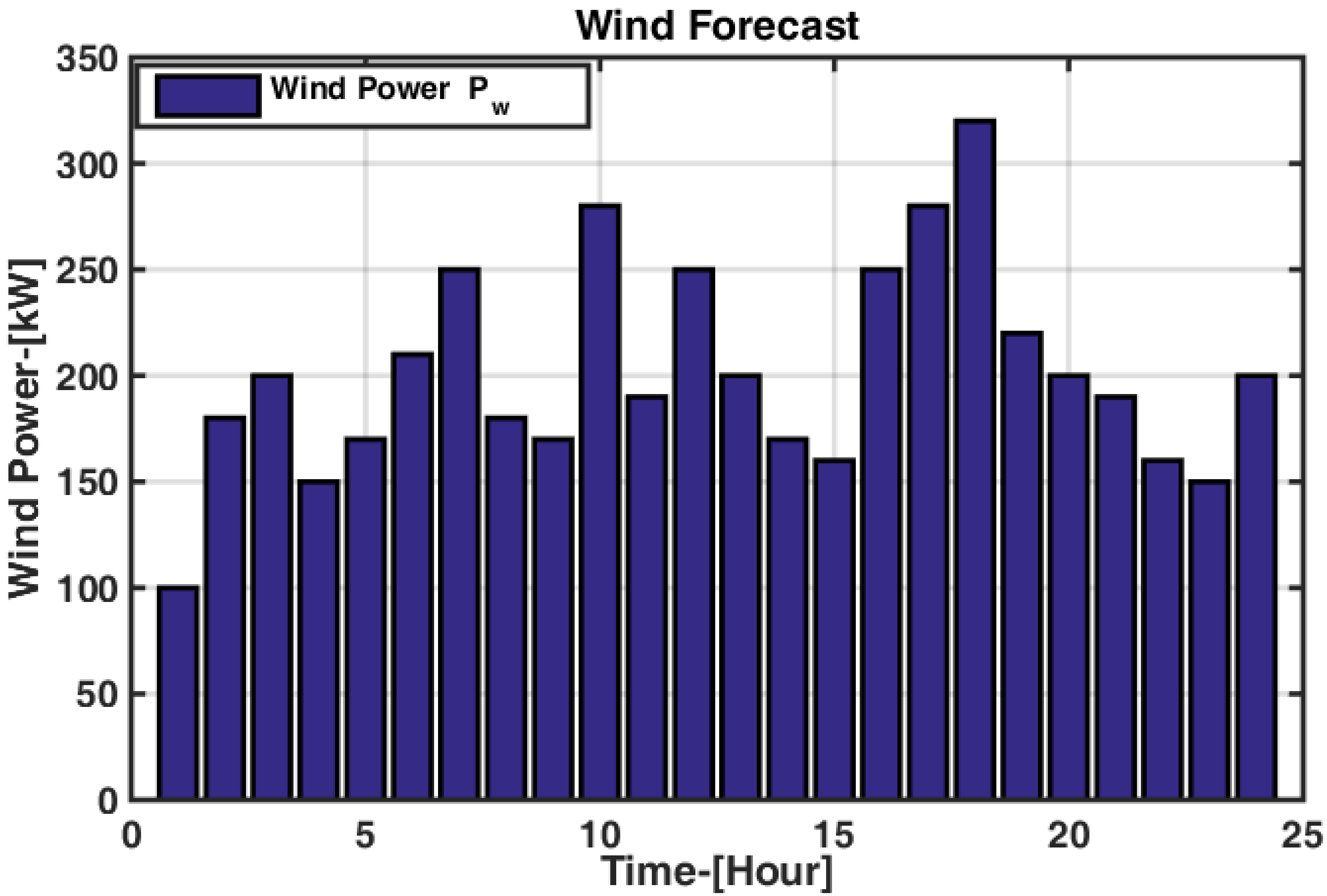
Discrete states and transitions,Mode transitions, Rump up constraints,

All Boolean and continous variables,

$i \in \{\mathrm{e}, \mathrm{f}\}$.

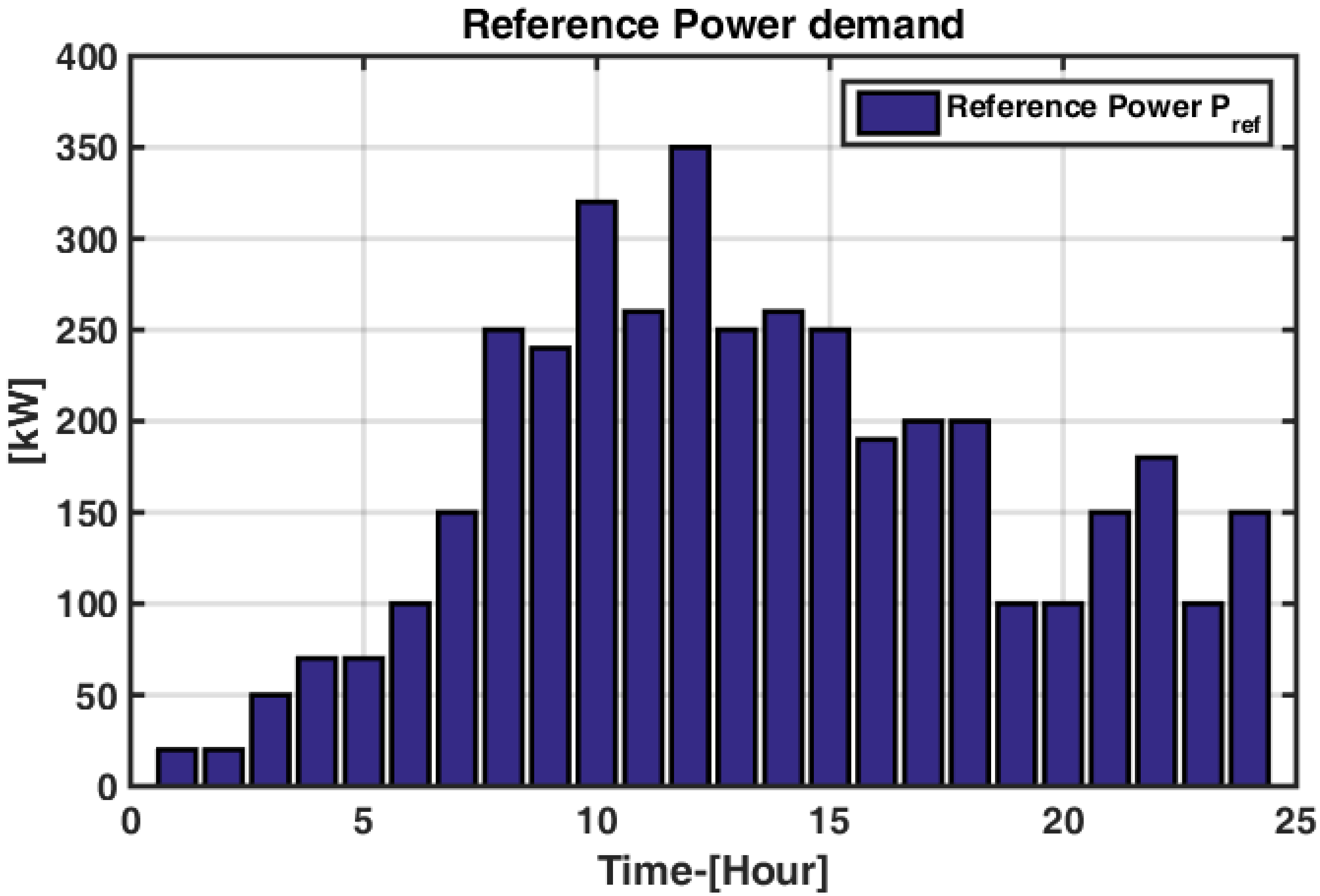
Numerical Results

Wind Power



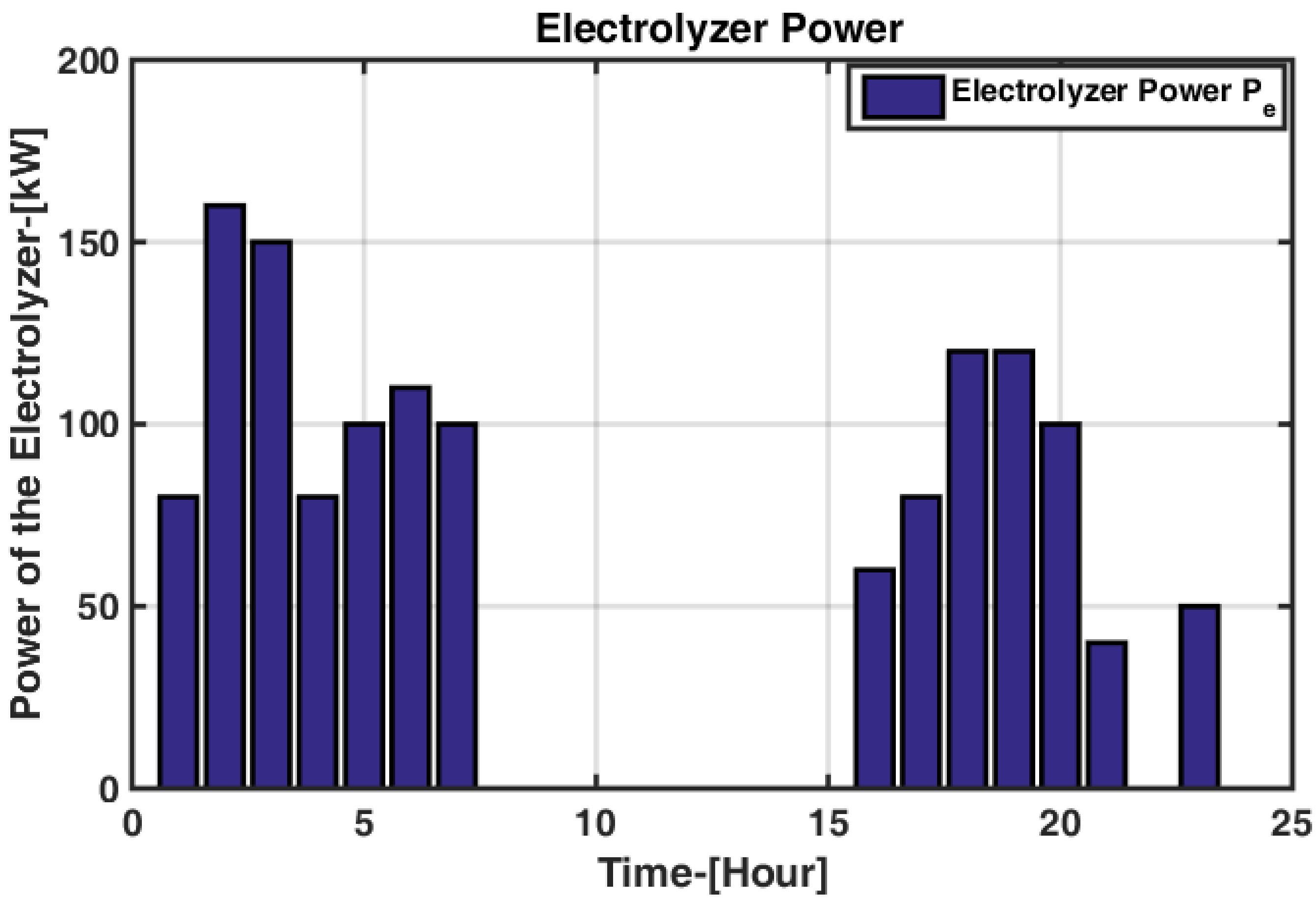
Numerical Results

Reference Power



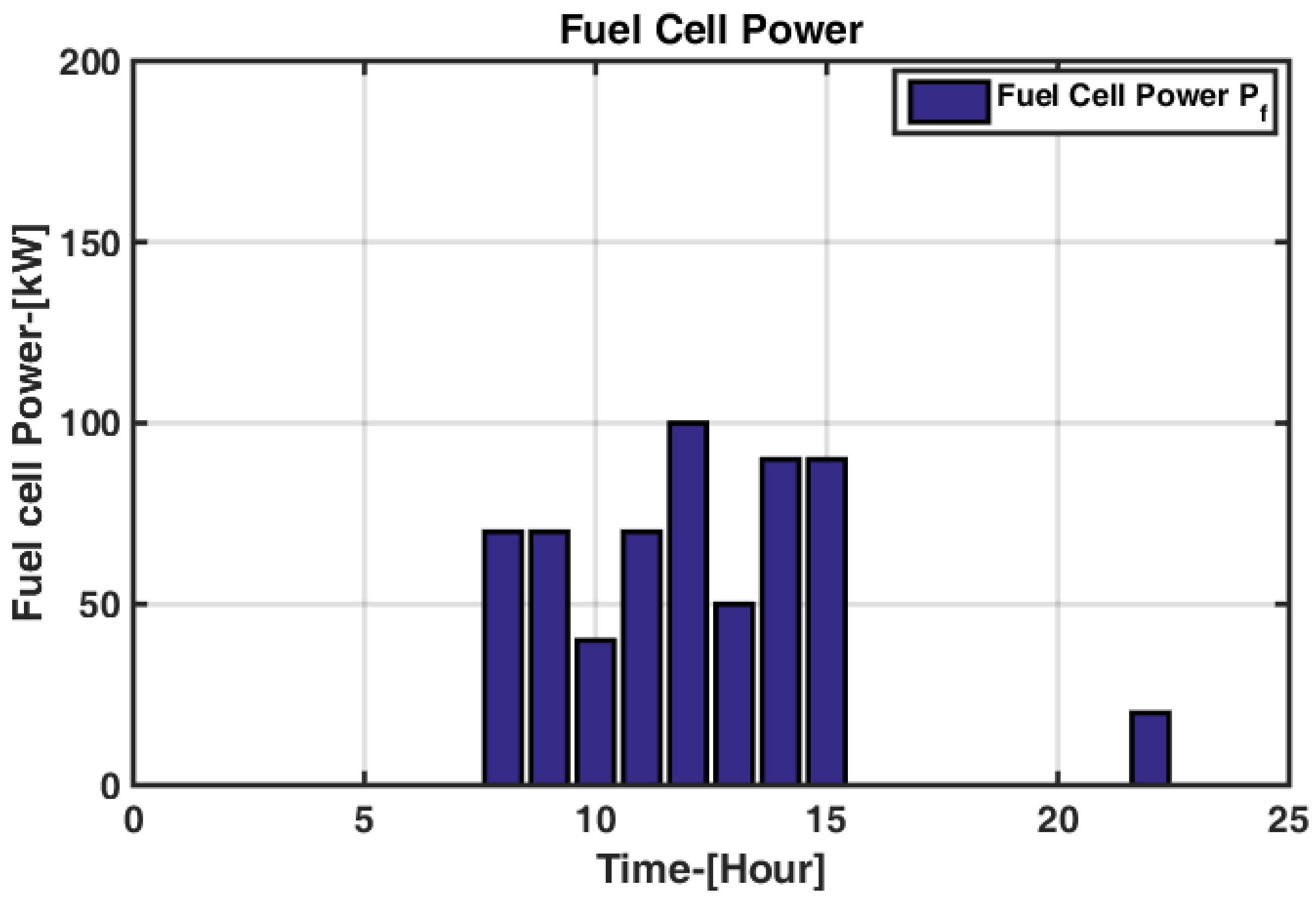
Numerical Results

Electrolyzer Power



Numerical Results

Fuel Cell Power



Conclusions

HAEOLUS

- **The HAEOLUS project aims at:**
  - Design, build and integrate a 2.5 MW hydrogen storage system within a wind farm fence
  - Test several control strategies (energy storage, minigrid, fuel production)
  - Guarantee highly autonomous system operations and remote monitoring

Modeling and control

- **Charaterized by the following features**
  - Multi-layer/multi-timescale modeling criteria: three and five logical operating modes of the electrolyser and the fuel cell
  - Physical and operational constraints
  - Hydrogen tank dynamics
  - Efficiency degradation dynamics of the elctrolyser and the fuel cell
  - Multi objective optimization technique (smoothing and optimal power tracking)

Hydrogen-**A**eolic **E**nergy with **O**ptimised e**L**ectrolysers **U**pstream of **S**ubstation

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www.haeolus.eu

Questions & Answers

Appendix

System Constraints

- The power balancing equation

$$P_w(k) - P_e(k)\delta_e^{\mathrm{ON}}(k) + P_f(k)\delta_f^{\mathrm{ON}}(k) - P_{\mathrm{avl}}(k) - P_{\mathrm{dump}}(k) = 0.$$

- Feasibility and operating constraints

$$P_i^{\min} \leq P_i(k) \leq P_i^{\max},$$
$$H^{\min} \leq H(k) \leq H^{\max},$$
$$0 \leq P_{\mathrm{dump}}(k) \leq P_w(k).$$

- Rump up/down constraints

$$|(P_{\mathrm{ez}}(k+1) - P_{\mathrm{ez}}(k))\delta_{\mathrm{ez}}^{\mathrm{ON}}| \leq R_{\mathrm{ez}},$$
$$|(P_{\mathrm{fc}}(k+1) - P_{\mathrm{fc}}(k))\delta_{\mathrm{fc}}^{\mathrm{ON}}| \leq R_{\mathrm{fc}},$$

System Constraints

- Mixed linear dynamics (MLD) constraints formulation of the devices states

$$z_i^{\geq 0}(k) = \begin{cases} 1 & P_i(k) \geq 0, \\ 0 & P_i(k) < 0, \end{cases}$$

$$z_i^{\leq 0}(k) = \begin{cases} 0 & P_i(k) > 0, \\ 1 & P_i(k) \leq 0, \end{cases}$$

$$z_i^{\geq P_i^{\mathrm{CLD}}}(k) = \begin{cases} 1 & P_i(k) \geq P_i^{\mathrm{CLD}}, \\ 0 & P_i(k) < P_i^{\mathrm{CLD}}, \end{cases}$$

$$z_i^{\leq P_i^{\mathrm{CLD}}}(k) = \begin{cases} 0 & P_i(k) > P_i^{\mathrm{CLD}}, \\ 1 & P_i(k) \leq P_i^{\mathrm{CLD}}, \end{cases}$$

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

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

$$z_i^{\geq P_i^{\mathrm{WRM}}}(k) = \begin{cases} 1 & P_i(k) \geq P_i^{\mathrm{WRM}}, \\ 0 & P_i(k) < P_i^{\mathrm{WRM}}, \end{cases}$$

$$z_i^{\leq P_i^{\mathrm{WRM}}}(k) = \begin{cases} 0 & P_i(k) > P_i^{\mathrm{WRM}}, \\ 1 & P_i(k) \leq P_i^{\mathrm{WRM}}, \end{cases}$$

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

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

$$\begin{aligned}
(1-\delta_i^{\mathrm{ON}}(k)) + z_i^{\geq P_i^{\min}}(k) &\geq 1, \\
(1-\delta_i^{\mathrm{ON}}(k)) + z_i^{\leq P_i^{\max}}(k) &\geq 1; \\
(1-\delta_i^{\mathrm{CLD}}(k)) + z_i^{\geq P_i^{\mathrm{CLD}}}(k) &\geq 1, \\
(1-\delta_i^{\mathrm{CLD}}(k)) + z_i^{\leq P_i^{\mathrm{CLD}}}(k) &\geq 1; \\
(1-\delta_i^{\mathrm{STB}}(k)) + z_i^{\geq P_i^{\mathrm{STB}}}(k) &\geq 1, \\
(1-\delta_i^{\mathrm{STB}}(k)) + z_i^{\leq P_i^{\mathrm{STB}}}(k) &\geq 1; \\
(1-\delta_i^{\mathrm{WRM}}(k)) + z_i^{\geq P_i^{\mathrm{WRM}}}(k) &\geq 1, \\
(1-\delta_i^{\mathrm{WRM}}(k)) + z_i^{\leq P_i^{\mathrm{WRM}}}(k) &\geq 1; \\
(1-\delta_i^{\mathrm{OFF}}(k)) + z_i^{\geq 0}(k) &\geq 1, \\
(1-\delta_i^{\mathrm{OFF}}(k)) + z_i^{\leq 0}(k) &\geq 1; \\
\delta_i^{\mathrm{ON}}(k) + \delta_i^{\mathrm{OFF}}(k) + \delta_i^{\mathrm{STB}}(k) + \delta_i^{\mathrm{CLD}}(k) + \delta_i^{\mathrm{WRM}}(k) &= 1.
\end{aligned}$$

System Constraints

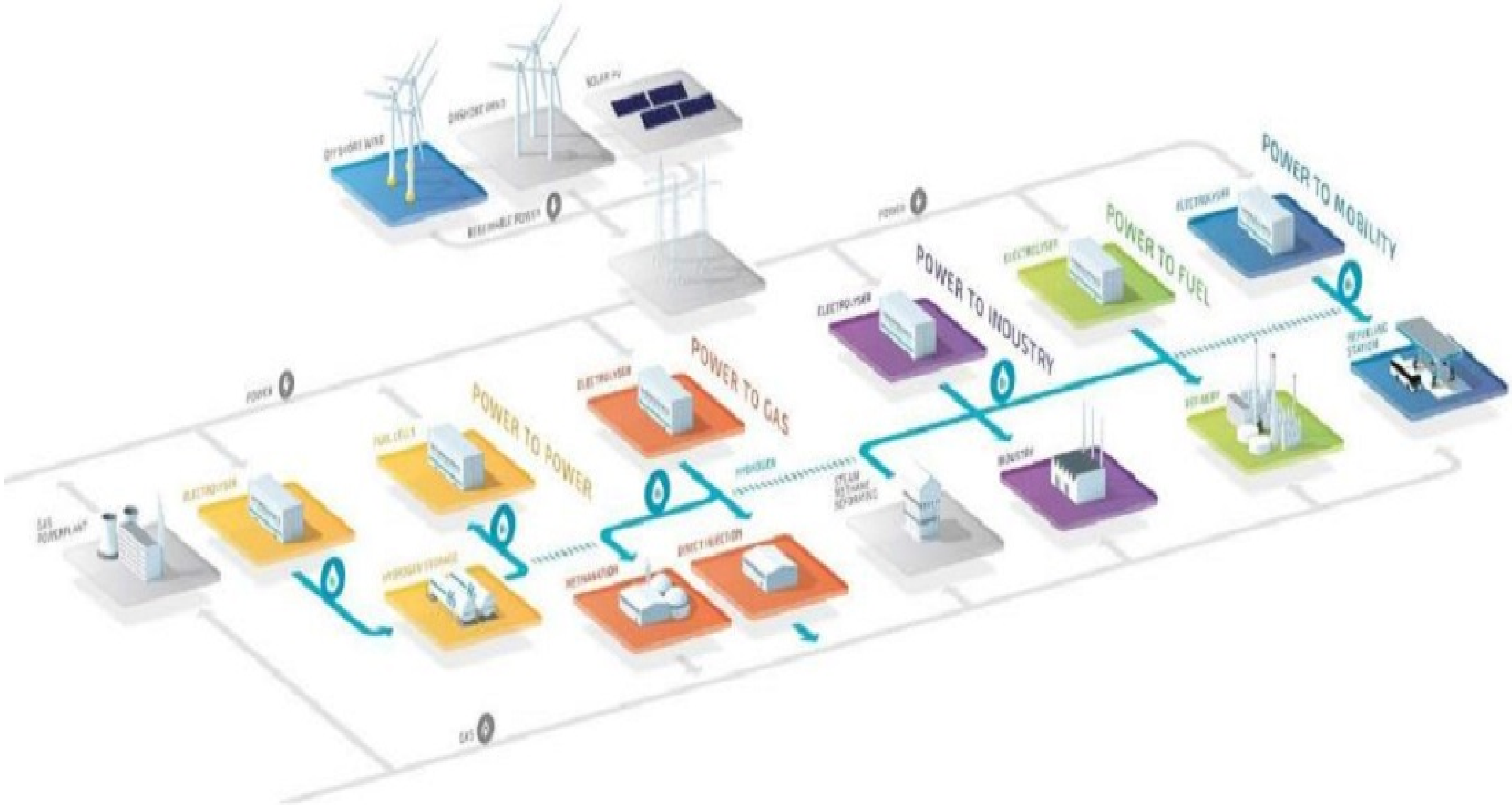
- Mixed linear dynamics (MLD) constraints formulation of the devices states transitions

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

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

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

Renewable Hydrogen



Numerical Results

Power Smoothing