ELECTROLYSER LOAD MANAGEMENT for MAXIMIZING WIND POWER IN ISLAND POWER SYSTEMS

Seminario AEE: Soluciones para altas penetraciones eólicas - sistemas insulares
Universidad Las Palmas / ITM Power
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BACKGROUND - CONCEPTS

- **WIND PENETRATION, WP** = Ratio of wind installed capacity to maximum system demand (%)

- **(DAILY) CAPACITY FACTOR, CF** = Ratio of available wind generation to output obtainable at maximum rated capacity across 24h (%)

- **THERMAL POWER LOAD** = Aggregate load placed on thermal plant (MW)

- **(DAILY) LOAD FACTOR, LF** = Ratio of average to peak load across 24h (%)
BACKGROUND

CHALLENGES IMPOSED BY WIND INTERMITTENCY & VARIABILITY IN ISLAND POWER SYSTEMS

1) **WIND CURTAILMENT**
   - Penetration limit – wind generation exceeds capacity of power system
   - Loss of available wind power

   **Consequences:**
   - Economic penalties – ↓ revenues / MW installed (↑ pay-back)
   - ↓ CO$_2$ abatement benefits

2) **INCREASED CYLING DUTIES OF THERMAL PLANT**
   - ↓ efficiency (part load)
   - ↑ number of start-ups
   - More back-up plant required

   **Consequences:**
   - ↑ Wear and tear ≡ ↑ O & M costs
   - ↑ Fuel cons / kWh$_e$ ≡ ↑ Generation costs + ↑ Carbon footprint (tC /MWhe)
Island power systems without significant interconnections or energy storage

Curtailment increases drastically with wind penetration
### ANNUAL INCOME LOSS WITH NO ELYS ($ / MW)

<table>
<thead>
<tr>
<th>WIND PENETRATION (%)</th>
<th>20% WIND</th>
<th>50% WIND</th>
<th>100% WIND</th>
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<tbody>
<tr>
<td></td>
<td>N/A</td>
<td>26580-50000</td>
<td>67240-89130</td>
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### ANNUAL INCOME LOSS OVER NET REVENUES per MW INSTALLED (%)

<table>
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<tr>
<th></th>
<th>N/A</th>
<th>20 - 47</th>
<th>&gt; 75</th>
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### ASSUMPTIONS
- Island power system
- Penetration Limit 20-30% of inst. demand
- CF = 21%
- Electricity price = $0.1/kWh
- Average WPP cap cost = $1.6m / MW
- O&M cost = $0.025/kWh
- Discount rate = 5%
APPROACH – ELECTROLYSER LOAD MANAGEMENT

SUPPLY SIDE
- WIND POWER PLANT
- ELECTROLYSER
- Z-C THERMAL POWER PLANT (Nuclear, CO2-seq)

DELIVERING INFRASTRUCTURE
- T & D SYSTEM
- H2 TRUCKING/PIPING
- THERMAL POWER PLANT

DEMAND SIDE
- ELECTRICITY CONSUMERS
- SOLAR / WIND DISTRIBUTED
- ELECTROLYSER
- H2 CONSUMERS
  - INDUSTRIAL GAS
  - TRANSPORT
  - STAND ALONE POWER ...

H2 CONSUMERS
1) **Optimization of the power system:**
   - Larger wind penetration into the power system
   - Load management - more efficient operation of power system

2) **Source of “green” hydrogen (and by-product oxygen):**
   - Current industrial gas markets
   - Low carbon transport fuel
   - Stand alone power/energy storage
   - NG + H2 fuel mix (gas turbines, heating)

**DEPLOYMENT OF ELECTROLYSERS IN THE POWER SYSTEM**

**BENEFITS**

**Increased ENERGY INDEPENDENCE**
APPROACH – ELECTROLYSER LOAD MANAGEMENT

HOW TO OPERATE A SYSTEM WITH LARGE CAPACITIES OF WIND, THERMAL POWER PLANT + ELECTROLYSERS?

Filling valleys + creating a plateau on thermal power load profile by operating electrolysers as controllable loads (on/off as required)
IMPLEMENTATION MODEL

INPUTS

System demand forecast

Wind generation forecast

- Fuel mix
- Plant availability
- Tech limits
- CO\(_2\) / kWh

OUTPUTS

Power & Energy flows
- Load Factor
- Electrolyser capacity
- Utilization Factors
- Carbon Intensity
- CO\(_2\) emissions

Operating strategy
(Thermal and wind power plant and electrolyzers)

CONTROL STRATEGY
IMPLEMENTATION MODEL – Control Strategies

STRATEGY A – CASE 1

A proportion, $\alpha$, of the ZPP output $PZPC(t)$ is directed to the grid and the remainder $PZPSE$ is directed to the SSE stock.

$PZPSE(t) = PZPP(t) - PZPG(t)$ (1)

Based on this information and taking into account the LFTH desired, the FPP load profile $PFPP$ is obtained by filling the early morning and night-time valleys to create a late morning-afternoon plateau at the level of the maximum load appointed to FPP, but of much greater duration than applies for the conventional FPP profile. Subject to the low load limit,

$PW(t) \leq 0.3 PC(t)$ (2)

The wind power output is directed to the grid and the SSE stock

$PW(t) = PC(t) - [PFPP(t) + PZPG(t)]$ (3)

$PWSE(t) = PW(t) - PW(t)$ (4)

Because zero-carbon hydrogen is required ($CIH = 0$), $PFPSE(t) = 0$ (5)

The operational strategy for the SSE stock, $PSSE(t)$, can be defined:

$PSSE(t) = PZPSE(t) + PWSE(t) + PFPSE(t)$ (6)

The net electrical energy exchanges are obtained across a specific time period. For example, in the case of the load placed on thermal power plant:

$EFPP = \sum_{i=1}^{n} PfPpi(t) \times \Delta t$ (7)

Where $PfPpi(t)$ = average power output at $i$

Once the energy flows have been obtained, the main output variables (such as $UFPF$, $UFEL$, $CIe$, $CIH$) can be computed.

A proportion, $\alpha$, of the ZPP output $PZPC3$ is directed to the grid and the remainder $PZPSE$ is directed to the DSE stock.

$PZPDE(t) = PZPP(t) - PZPC(t)$ (8)

Based on this information and taking into account the LFTH desired, the FPP load profile $PFPP$ is obtained as in Strategy A1. Subject to the low-load limit,

$PW(t) + PWDE(t) \leq 0.3 [PC(t) + PDSE(t)]$ (9)

The wind power output is directed to the grid and the DSE stock:

$PW(t) = PC(t) - PFPP(t) - PZPC(t)$ (10)

$PWDE(t) = PW(t) - PW(t)$ (11)

Because zero-carbon hydrogen is required ($CIH = 0$), $PFPDE(t) = 0$ (12)

The operational strategy for the DSE stock, $PDSE(t)$, is then defined subject to the restriction:

$PC(t) + PDSE(t) \leq SMD$ (13)

$PDSE(t) = PZPDE(t) + PWDE(t) + PFPDE(t)$ (14)

The net electrical energy exchanges are obtained across a specific time period. Once the energy flows have been obtained, the main output variables can be computed.

Based on this information and subject to ZPP availability, the FPP load profile $PFPP$ is obtained by filling the early morning and night-time valleys to create a plateau at the level of the maximum load appointed to FPP, taking into account the LFTH desired.

The ZPP output is primarily directed to the grid, $PZPG$, to supply the remainder consumer demand:

$PZPG(t) = PC(t) - PW(t) - PFPP(t)$ (15)

The wind power output is directed to the grid, and the DSE stock

$PW(t) = PC(t) - PFPP(t) - PZPG(t)$ (16)

$PWSE(t) = PW(t) - PW(t)$ (17)

Because zero-carbon hydrogen is required ($CIH = 0$), $PFPSE(t) = 0$ (18)

The operational strategy for the DSE stock, $PDSE(t)$, is then defined subject to the restriction:

$PC(t) + PDSE(t) \leq SMD$ (19)

$PDSE(t) = PZPDE(t) + PWDE(t) + PFPDE(t)$ (20)
RESULTS – THERMAL LOAD MANAGEMENT

1) Increased LF - Virtually flat thermal profile on high wind days (wind penetrations above 40%)

(1) + (2) = CARBON AND ECONOMIC BENEFITS!!

2) Elimination of wind curtailment
➢ AND THE ECONOMICS?  
ACCEPTABLE RATES OF RETURN?

➢ WHAT TO DO WITH THIS “GREEN” HYDROGEN?
USING WIND CURTAINALMENT FOR INDUSTRIAL (MERCHANT) HYDROGEN PRODUCTION

WIND POWER PLANT + ELECTROLYSIS PLANT

2 REVENUE STREAMS: ELECTRICITY + MERCHANT HYDROGEN SALES

CURRENT MERCHANT MARKETS
Demand AAGR > 5%; market price $10-100 / kg H2
- Refinery & petrochemicals (AAGR > 10%)
- Glass manufacturing
- Metal manufacturing
- Power plant cooling
- Semiconductor manufacturing
- Analytical labs

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RESULTS - WIND CURTAILMENT FOR INDUSTRIAL HYDROGEN PRODUCTION

ECONOMICS INVESTIGATED AS A FUNCTION OF:
- Wind penetration and curtailment level (WCT)
- Wind and electrolysis plant cost
- Electrolysis efficiency
- Hydrogen market price

ASSUMPTIONS – MODEL PARAMETERS
- Island power system (wind penetration limit = 25%)
- Electrolyser cost $300-740/kW
- Hydrogen storage cost = $820 / kg
- Compressor cost= $2000 / kW
- Electricity price = $0.1/ kWh
- Hydrogen market price $20 - $30/kg (incl distribution costs)
- Plant installation cost = 10% of capital cost
- O&M cost = 5% of cap cost

ANALYSIS BASED ON DISCOUNTED PAY-BACK PERIOD – OUTPUTS:
1) Electrolysis capacity requirement next to WPP
2) Capital investment and annualized costs for WPP deploying electrolysis plant
3) Annual hydrogen and electricity production
4) Annual revenues from electricity and merchant hydrogen sales
5) Discounted pay-back periods (average across WPP portfolio)
 RESULTS - WIND CURTAINMENT FOR INDUSTRIAL HYDROGEN PRODUCTION – PAYBACK PERIODS

WIND PENETRATION 50%, WCT = 50%
HYDROGEN market price $30/Kg

At 50% wind penetration capturing 100% of curtailed energy only if electrolysis plant costs are low (< $600/kW)

How can we minimize pay-back at low wind penetrations (e.g. 30%)?

Low curtailment capture at low wind penetrations

Minimizes financial risk for wind-electrolysis plant!
CONCLUSIONS

- Wind curtailment \( \uparrow \) drastically at high wind penetrations for island power systems
  \((+ 30\% \text{ of available energy curtailed across the year for 50\% wind penetration!})\)

- Economic penalties for wind operators:
  Annual income loss between 20-50\% of net revenues per MW installed for 50\% wind penetration!

- Deployment of electrolysers in the power system can (i) mitigate curtailment and (ii) \( \uparrow \) \( LF_{TH} \) up to 100\% for WP \( >50\% \) \( \equiv \) minimize carbon & economic penalties

- For early developers minimize financial risk by capturing 50-60\% of curtailed wind

- Discounted pay-back periods of between 6 – 9 years can be obtained at current hydrogen market prices and electrolysis plant costs (electrolysis plant average efficiency \( \geq 60\%) \)}