System Engineering Technologies in Autonomous Power Systems Using Renewable Energy Sources and Hydrogen

Laboratory of Process Systems Design and Implementation
Chemical Process Engineering Research Institute (CPERI)
Centre for Research and Technology – Hellas (CERTH)
and
Department of Mechanical Engineering
Aristotle University of Thessaloniki (AUTH)
Contributors

• Dr. Panos Seferlis (AUTH, LPSDI/CPERI)
• Dr. Athanassios Papadopoulos (AUTH, LPSDI/CPERI)
• Dr. Spyros Voutetakis (LPSDI/CPERI)
• Dr. Fotis Stergiopoulos (TEITHE, LPSDI/CPERI)
• Dr. Simira Papadopoulou (TEITHE, LPSDI/CPERI)
• Chrysa Ziogou (LPSDI/CPERI)
• Garyfallos Giannakoudis (AUTH, LPSDI/CPERI)
• Dimitris Ipsakis (AUTH, LPSDI/CPERI)
• Costas Elmasides (Systems Sunlight SA)
Outline

• Introduction - Motivation
• System description
• Design methodology
• Power management strategies
• Uncertainty in power systems
• Integrated optimal design framework
• Case study
• Implementation and operation
• Concluding Remarks
Renewable Energy Systems (RES) can be used for power production in various applications:

- Electrification of remote installations that are not connected to the main grid (e.g., islands, rural areas)
- Powering telecommunication stations and other small applications
- Energy used in irrigation systems for the supply of pure water especially for developing countries
Introduction

Energy from RES can be stored in the form of hydrogen via an eco-friendly process such as water electrolysis that can subsequently utilized in fuel cells.

- Advantages from such integrated systems are:
  - Zero production of gas emissions
  - Relatively long lifetime
  - Relatively low maintenance cost
  - Solar and wind energy is abundant, clean and inexhaustible

GREEN POWER
RES based Stand-Alone Power System

PV ARRAY

WIND GENERATORS

ELECTRICAL ENERGY

ELECTROLYZER

PRODUCED HYDROGEN

BATTERY

STORAGE

FUEL CELL

ELECTRICAL LOAD

ELECTRICAL LOAD
RES based Stand-Alone Power System

- PHOEBUS-JÜLICH research Institute in Germany (Barthels et al, 1998).
- HRI (Hydrogen Research Institute) at Quebec of Canada (Kolhe M. et al, 2002).
- PURE project in Unst Island in Shetland- (Gazey R. et al, 2006).
- Cooma-Australia (Shakya B.D. et al, 2005).
- HELPS project (Hydrogen Based Electrical Energy System for Local Power Storage), Athens (Varkaraki E. et al, 2003).
- Helsinki-Finland in University of Technology, (Kauranen et al, 1994).
- ENEA Research Institute in Rome, Italy (Solar-Hydrogen Cycle Project), (Galli S. and Stefanoni M., 1994).
- HARI (Hydrogen and Renewables Integration), West Beacon Farm-Leicestershire, U.K., (Gammon R. et al, 2006).
RES based Stand-Alone Power System

PV GENERATORS $I_{PV}$

WIND GENERATORS $I_{WG}$

DC BUS BAR

LEAD-ACID ACCUMULATOR $I_{BAT}$

BACK-UP UNIT $I_{BU}$

1kW LOAD $I_{LOAD}$

1kW LOAD

PEM ELECTROLYZER

HYDROGEN STORAGE

PEM FUEL CELL $I_{FC}$

AIR

H$_2$O (to electrolyzer)

H$_2$

O$_2$

H$_2$O

$H_2$
Motivation

- Characteristics and challenges in the design of hybrid systems for production of power from renewable energy sources
- A systems engineering approach is necessary
  - for the efficient representation of hybrid systems
  - for design optimization under uncertainty
  - for optimal operation
- System implementation, automation and control
Hybrid power systems

- Hybrid systems involve multiple types of subsystems for power generation and storage (PV panels, wind generators, batteries, electrolyzer, fuel cells)
- This enables reduced interruptions in power flows and increased autonomy from conventional fuels
- Main challenges in the development of such systems
  1) Integration of numerous subsystems with heterogeneous operating characteristics
  2) Consideration of numerous alternatives for power utilization at each time instance
  3) Large variability in the behavior of renewable energy sources
## Integration of heterogeneous subsystems

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
</table>
| - Simple technology to install and use  
- Long lifetime  
- Low maintenance | - Excess energy: power rejected  
- Lack of energy: interruptions in power flow |
| - Fast response when power is required | - Limited storage capacity  
  - Satisfaction of short term power needs  
  - Replacement after a certain amount of cycles |
| • Increased storage capacity  
  - Satisfaction of long term needs | • Slower deployment of power  
  • High maintenance costs |

### Subsystems:
- **PV ARRAY**
- **WIND GENERATORS**
- **BATTERY**
- **ELECTROLYZER**
- **FUEL CELL**
- **STORAGE**

### Hydrogen infrastructure
Integration of heterogeneous subsystems

- Complex decision making involves several structural and operating decisions:
  - What is the optimum type and size of equipment?
  - How many systems of each type are required?
  - How should they be connected for feasible and efficient interoperation?
  - What is the suitable energy flow management?
  - What would be the operating policy for each subsystem?

- Multiple criteria and constraints must be satisfied:
  - Ensure non-intermittent load satisfaction
  - Maintain safe operation
  - Prolong equipment lifetime
Alternatives for power utilization

• At the same time instance power can:
  - Be consumed directly from RES (if available) to serve the needs of the application
  - Be used to charge the batteries (if available and if batteries require charging)
  - Be used to produce hydrogen (if available and if storage tanks can take more)
  - Be consumed from batteries (if available), or produced from fuel cell (if hydrogen is available and there is enough time to start it)
Consideration of variability

- Renewable energy sources are based on natural phenomena that are difficult to predict
  - Example: Average solar radiation and wind speed may vary significantly from year-to-year.

- The efficiency of sub-systems varies based on the frequency of utilization or other random effects.
  - Example: Batteries faint as the number of charge and discharge cycles increase. The efficiency of fuel cell and electrolyzer might drop due to membrane.
Consideration of variability

- Uncertainty: The lack of exact knowledge regarding the state or future outcome of the behavior of a system at a particular instance.
- Uncertainty is an important that affects system performance and should be considered during design.
- Systems designed based on approximations regarding the state of sub-systems are only optimum within the context of the performed assumptions.
Conventional design approach

- Power demands of a targeted application
- Conceptual design
- Analytical calculations
- "Optimization"
- Empirical evaluation of required equipment and possible connections
- Empirical testing of subsystem options (size, type etc.) and potential connections
- System flowsheet?
- Simulation of integrated system
- Parametric evaluation of the system operation
- Treatment of uncertainty?
Conventional design approach

- The design procedure requires systematic comparison of numerous flowsheet options (structural, operating etc.).
- At the simulator a large number of decisions has already been determined empirically.
- A systemic approach is required that considers the representation of decision options and then addresses integration and optimization.
  - Approach with mathematical and computational tools with parallel use of empirical knowledge.
Systems approach for power systems

Available renewable energy sources and power storage alternatives

Potential energy conversion and storage unit types

Potential connectivity options between subsystems

Potential operating alternatives

Potential uncertainty sources and associated patterns

Power demand (constant or variable)

Representation of structural options

Representation of operating options

Representation of uncertainty options

Representation of application requirements
Systems approach for power systems

- Representation of structural options
- Representation of operating options
- Representation of uncertainty options
- Representation of application requirements

Systematic optimization-based integration

Desired performance measure

Formulation and solution of optimization problem
Structural options

- Assume availability of solar and wind energy
  - Requires PV panels and wind generators
- Assume potential storage technologies of interest: Batteries and Hydrogen
- Hydrogen infrastructure requires electrolyzer, fuel cell and water tank.
- Hydrogen management requires storage under pressure.
- Low pressure hydrogen produced by electrolyzer needs to be pressurized using a compressor.
- Intermediate “buffer” tank is required to build up pressure prior to compressor utilization.
- A diesel generator is also considered to maintain non-intermittent operation.
- Size and number of structural options represent design decisions.
System functionality determines potential feasible connections

- PV panels, wind generators, diesel generator and fuel cell generate power.
- Batteries store and dispatch energy.
- Tanks store and dispatch hydrogen.
- Electrolyzer, compressor and load consume power.
Practical realization of connectivity options

- All power streams are directed to a DC bus bar.
- It includes power electronics that regulate the current flows.
- The systems utilized for power production and consumption at each time instance represent design decisions.
- The design is not about finding which systems are connected together...
- ...it is about finding the contribution or participation of each subsystem to power generation or consumption.
Operating alternatives

The combination of connectivity options and technical features of sub-systems gives rise to operating alternatives.

A “Power Management Strategy” (PMS) captures all such operating alternatives.

The key system indicators are:
1) Power availability from RES (lack or excess) (P)
2) Accumulator state of charge (SOC)
3) Hydrogen inventory

Operating parameters that define the (PMS)
1) SOC limits
2) Hysteresis band range for electrolyzer and fuel cell
3) Operating level for electrolyzer and fuel cell
Operating decisions based on SOC

- PEM FUEL CELL
  USAGE IN CASE OF
  POWER SHORTAGE

- LEAD-ACID
  ACCUMULATOR
  OPERATION

- PEM
  ELECTROLYZER
  USAGE IN CASE OF
  POWER SURPLUS

LOWER SOC LIMIT
(SOC$_{\text{min}}$)

UPPER SOC LIMIT
(SOC$_{\text{min}}$)
Operating decisions with hysteresis band

- Hysteresis Band of PEM Fuel Cell
- Junction of the PEM Fuel Cell Operation
- Termination of the PEM Fuel Cell Operation
- Fuel Cell Operation
- Charge or Discharge with Respect to the RES
- Lead-Acid Accumulator Usage for Energy Fluctuations
- Junction of the PEM Electrolyzer Operation
- Termination of the PEM Electrolyzer Operation
- Electrolyzer Operation
- Charge or Discharge with Respect to the RES
- Accumulator Operation
- Charge or Discharge with Respect to the SOC
- Further Allowed Energy

SOC\(_{min}\) \quad SOC_{fc} \quad SOC_{elec} \quad SOC_{max} \quad SOC_{max\_charge}
• Eliminates frequent start-ups and shut-downs in electrolyzer and fuel cell operation.
• Prolongs or avoids the operation of fuel cell and electrolyzer based on their previous operating state.
Representation of uncertainty

- **System-inherent uncertainty**: System operating parameters that vary (e.g., efficiency of subsystems).
- **External uncertainty**: Variations observed in environmental conditions, power demand, prices etc.
- **Model inherent uncertainty**: Physical, chemical, mechanical, electrical etc. parameters that are used in models (e.g., mass transfer coefficients etc.)
- **Discrete uncertainty such as equipment availability based on desired specifications**
Subsystem models

- PV system

The equivalent circuit for the one-diode PV-generator model (Ulleberg Ø., Phd Thesis, 1998)

The electrical model consists of various non-linear equations that are based on the I-V characteristic.
Subsystem models

- **WT system**

\[ P_m = c_p(\lambda, \beta) \cdot \frac{\rho \cdot A}{2} v_{\text{wind}}^3 \]

- \( P_m \): mechanical output power of the turbine, W
- \( c_p \): operation coefficient of the turbine
- \( \rho \): air density, kg/m³
- \( A \): swept area of turbine, m²
- \( v_{\text{wind}} \): wind speed, m/s
- \( \lambda \): tip speed ratio
- \( \beta \): blade pitch angle, deg

Comparison between the simulation results and the wind generator type Whisper 200
Subsystem models

- Accumulator

Battery electrical schematic, (J.F. Manwell and J.G. McGowan, 1993)
Subsystem models

- **Water electrolysis with PEM**

\[ H_2O(l) + \text{energy} \rightarrow H_2(g) + \frac{1}{2}O_2(g) \]

**ANODE REACTION**
\[ H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2H^+(aq.) + 2e^- \]

**CATHODE REACTION**
\[ 2H^+(aq.) + 2e^- \rightarrow H_2(g) \]

**I-V characteristic for the electrolyzer**

\[
V = V_{rev} + \frac{r_1 + r_2 \cdot T}{A} \cdot I + \left( s_1 + s_2 \cdot T + s_3 \cdot T^2 \right) \cdot \log \left( \frac{t_1 + t_2 / T + t_3 / T^2}{A} \cdot I + 1 \right)
\]

- \( r_i \): parameters for the ohmic resistance of electrolyte, (\( = 1 \ldots 2 \))
- \( s_i \): parameters for overvoltage on electrodes (\( = 1 \ldots 3 \))
- \( A \): area of electrode, \( m^2 \)
- \( T \): temperature of electrolyte, °C
- \( V \): operation cell voltage, V
- \( V_{rev} \): reversible cell voltage, V
- \( I \): current through the cell, A
Subsystem models

- Water electrolysis with PEM

\[
\text{H}_2\text{O}(l) + \text{energy} \rightarrow \text{H}_2(g) + \frac{1}{2}\text{O}_2(g)
\]

**ANODE REACTION**
\[
\text{H}_2\text{O}(l) \rightarrow \frac{1}{2}\text{O}_2(g) + 2\text{H}^+(\text{aq.}) + 2\text{e}^-
\]

**CATHODE REACTION**
\[
2\text{H}^+(\text{aq.}) + 2\text{e}^- \rightarrow \text{H}_2(g)
\]

I-V characteristic for the electrolyzer

\[
V = V_{\text{rev}} + \frac{r_1 + r_2 \cdot T}{A} \cdot I + (s_1 + s_2 \cdot T + s_3 \cdot T^2) \cdot \log \left( \frac{t_1 + t_2 / T + t_3 / T^2}{A} \right) 
\]

- \( r_i \): parameters for the ohmic resistance of electrolyte, (= 1...2)
- \( s_i, \): parameters for overvoltage on electrodes (= 1...3)
- \( A \): area of electrode, \( \text{m}^2 \)
- \( T \): temperature of electrolyte, °C
- \( V \): operation cell voltage, \( V \)
- \( V_{\text{rev}} \): reversible cell voltage, \( V \)
- \( I \): current through the cell, \( A \)
Subsystem models

- **PEM fuel cell**

ANODE REACTION
\[ H_2(g) \rightarrow 2H^+(aq.) + 2e^- \]

CATHODE REACTION
\[ \frac{1}{2}O_2(g) + 2H^+ + 2e^- \rightarrow H_2O(l) \]

I-V characteristic for the fuel cell

\[
V = E + \eta_{\text{act}} + \eta_{\text{ohmic}}
\]

\[
V = f(i, T, p_{H_2}^*, p_{O_2}^*)
\]

\[
n_{H_2} = \frac{n_c \cdot I}{n \cdot F \cdot \eta_F}
\]

- $\eta_{\text{ohmic}}$: ohmic overvoltage, Volt
- $\eta_{\text{act}}$: activation overvoltage, Volt
- $p_i$: partial pressure of the hydrogen or oxygen, bar
- $T$: temperature of operation, °C
- $V$: operation cell voltage, V
- $i$: current through the cell, A
- $n_{H_2}$: hydrogen consumption, mol/sec
- $F$: Faraday’s constant As/mol
- $n$: number of electrons per mol of water, $n=2$
- $n_c$: number of cells
- $\eta_F$: Faraday’s efficiency

Temperature and pressure dependent I-V model, (J.C. Amphlett et al., 1995)
Optimization problem formulation

• Given is
  - A set of meteorological or other data associated to RES in a certain geographical area
  - Technical and economical data for the considered individual subsystems used to harness, process, store and/or transform energy into power
  - Patterns of uncertain behavior for parameters affecting the system performance
  - Power requirements of a targeted application
  - A system performance measure

• Determine:
  - The structural and operating system characteristics that optimize the chosen performance measure

• Subject to constraints:
  - The requirements of the targeted application
  - The feasible system operation
Methodological approach of optimization

System representation
- Models
- Physical, chemical, mechanical, electrical char.

Initial state
Iterate for entire range of time dependent parameters
Apply power management strategy

Objective function + constraints

Optimization algorithm
Generate new solution
Update solution

Simulated Annealing

Design degrees of freedom
- Type, number, size of sub-systems
- Mode of system utilization
- Operating conditions

Simulator

SOC_{min} < SOC < SOC_{fc}
SOC_{max} ≥ SOC ≥ SOC_{fc}
SOC_{elec} ≤ SOC_{elec_{max}}
P > 0
I_{elec}(t-1) ≠ 0
P > P_{max_{elec}}
0 ≤ P < P_{min_{elec}}
P_{min_{elec}} ≤ P ≤ P_{max_{elec}}

Charge accumulators

Power from accumulators

Meet load demand

Diesel generator

Electrolyzer

Store hydrogen

NO

YES
Mathematical representation of uncertainty

• Uncertainty can either be considered in a deterministic or in a stochastic form.

• In the deterministic case:
  - Specific bounds can be imposed in the value range of the considered parameters or a fixed number of parameter values can be utilized.

• In the stochastic case:
  - Probability distributions are used to represent uncertainty.
  - They represent the potential values of a parameter in a particular range, but also the frequency of occurrence of each value in that range.
Methodological treatment of uncertainty

- For each set of design variables values a sample is selected from the distribution that represents the behavior of the uncertain parameters.
Case study

Objective

- **Minimize NPV (10 years)**
- The considered costs involve initial purchase and installation capital and additional expenditures for the operation, maintenance and replacement of the employed equipment
- An income is also assumed due to the energy costs avoided by use of the RES system
## Case study

<table>
<thead>
<tr>
<th>Case</th>
<th>Design variables</th>
<th>Uncertain parameters</th>
</tr>
</thead>
</table>
| **A: 1 kW constant load** | • Number of pv panels ($n_{pv}$)  
                          • Number of wind generators ($n_{wg}$)  
                          • Number of accumulators ($n_{acc}$)  
                          • Capacity of intermediate hydrogen buffer storage ($V_{buff}$)  
                          • Maximum operating power of electrolyzer ($P_{max,elec}$)  
                          • Operating power of fuel cell ($P_{oper,fc}$)  
                          • State of charge minimum limit ($SOC_{min}$)  
                          • State of charge maximum limit ($SOC_{max}$) |
| **B: Variable load**     | • Solar radiation ($\theta_s$)  
                          • Wind speed ($\theta_w$)  
                          • Electrolyzer efficiency ($\theta_e$)  
                          • Fuel cell efficiency ($\theta_{fc}$) |
The solar radiation and wind speed data are based on hourly averaged historical observations. Abrupt changes of varying intensity are always likely for both. The variations are emulated through a normal distribution. This indicates that variations are more frequent close to the mean (i.e. the values of the available hourly data) and less frequent further away (up to ±12% from the averaged data).
For the case of electrolyzer and fuel cell efficiency the probability distribution is one sided normal.

It only represents a decrease in efficiency of up to -8%.
## Design results - Case A

<table>
<thead>
<tr>
<th>Design variables</th>
<th>Case A.1</th>
<th>Case A.2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No uncertainty</td>
<td>Uncertainty in solar radiation and wind speed</td>
</tr>
<tr>
<td>Number of PV-panels</td>
<td>21 (1.5 kW)</td>
<td>27 (1.87 kW)</td>
</tr>
<tr>
<td>Number of wind generators</td>
<td>7 (4.55 kW)</td>
<td>11 (7.2 kW)</td>
</tr>
<tr>
<td>Number of accumulators</td>
<td>15 (11.25 kAh)</td>
<td>6 (4.5 kAh)</td>
</tr>
<tr>
<td>Maximum electrolyzer operation</td>
<td>0.5</td>
<td>0.25</td>
</tr>
<tr>
<td>level [kW]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buffer tank capacity [Nm³]</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Fuel cell operation power level</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>[kW]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOC&lt;sub&gt;min&lt;/sub&gt; limit</td>
<td>0.7</td>
<td>0.72</td>
</tr>
<tr>
<td>SOC&lt;sub&gt;max&lt;/sub&gt; limit</td>
<td>0.93</td>
<td>0.91</td>
</tr>
</tbody>
</table>
## Design results - Case A

<table>
<thead>
<tr>
<th>Design variables</th>
<th>Case A.1</th>
<th>Case A.2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No uncertainty</td>
<td>Uncertainty in solar radiation/wind speed</td>
</tr>
<tr>
<td>Number of PV-panels</td>
<td>21 (1.5 kW)</td>
<td>27 (1.87 kW)</td>
</tr>
<tr>
<td>Number of wind generators</td>
<td>7 (4.55 kW)</td>
<td>11 (7.2 kW)</td>
</tr>
<tr>
<td>Number of accumulators</td>
<td>15 (11.25 kAh)</td>
<td>6 (4.5 kAh)</td>
</tr>
<tr>
<td>Maximum electrolyzer operation level [kW]</td>
<td>0.5</td>
<td>0.25</td>
</tr>
<tr>
<td>Buffer tank capacity [Nm³]</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Fuel cell operation power level [kW]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SOC_min limit</td>
<td>0.7</td>
<td>0.72</td>
</tr>
<tr>
<td>SOC_max limit</td>
<td>0.93</td>
<td>0.91</td>
</tr>
</tbody>
</table>

- In Case A.1 we notice fewer PV panels and wind generators, more batteries, larger electrolyzer and buffer tank
- The power contribution to the system from the wind generators is 3 times higher than the contribution of the PV panels in Case A.1 and 3.8 times higher in case A.2
- Results indicate increased use of renewable energy sources and decreased use of power storage and hydrogen utilization infrastructure to meet the load demand in Case A.2
We simulate the optimum design results for Case A.1 and A.2 only for uncertainty in wind speed.

The NPV is negative due to the fact that the hybrid power generation is expensive.

Also it is assumed that all power excess (not consumed) is transformed to stored hydrogen (no load is dumped).

The stored hydrogen was not considered in the objective function (no upper bound in the long term storage tanks, no consideration of hydrogen as a product).
Economic performance - Case A

- In favorable wind conditions (high positive deviation):
  - The design of Case A.2 absorbs the excess available power in an economically efficient manner due to increased use of RES to cover loads.

- In unfavorable wind conditions (reduced wind):
  - The NPV of Case A.1 deteriorates (steep slope) as soon as the wind speed deviation becomes negative.
  - The NPV of Case A.2 withstands intense wind variations (slow drop).
  - Maximum contribution to requested load over 10 years from diesel generators is 4% for A.1 and 1% for A.2.
# Design results - Case B

## Design variables

<table>
<thead>
<tr>
<th>Design variables</th>
<th>Case B.1</th>
<th>Case B.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No uncertainty</td>
<td></td>
<td>Uncertainty in solar radiation, wind speed, electrolyzer and fuel cell efficiency</td>
</tr>
<tr>
<td>Number of PV-panels</td>
<td>49 (3.4 kW)</td>
<td>45 (3.12 kW)</td>
</tr>
<tr>
<td>Number of wind generators</td>
<td>5 (3.25 kW)</td>
<td>6 (3.9 kW)</td>
</tr>
<tr>
<td>Number of accumulators</td>
<td>7 (5.25 kAh)</td>
<td>6 (4.5 kAh)</td>
</tr>
<tr>
<td>Maximum electrolyzer operation level</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>[kW]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buffer tank capacity [Nm³]</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Fuel cell operation power level [kW]</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>SOC&lt;sub&gt;min&lt;/sub&gt; limit [%]</td>
<td>0.66</td>
<td>0.68</td>
</tr>
<tr>
<td>SOC&lt;sub&gt;max&lt;/sub&gt; limit [%]</td>
<td>0.96</td>
<td>0.93</td>
</tr>
</tbody>
</table>

- In Case B.1 we notice a significantly smaller buffer tank and a fuel cell of increased power.
- This indicates a more intense use of the intermediate hydrogen storage in Case B.2 and higher loads required from the fuel cell to cope with the variability of load demand.
- We simulate the optimum design results for Case B.1 and B.2 only for uncertainty in fuel cell efficiency.
- In Case B.1 the deterioration of the NPV is rapid as the efficiency drops.
- In Case B.2 the NPV value is increased at lower efficiency.
- This is because at lower efficiency more hydrogen is consumed from the fuel cell to maintain operation, hence the hydrogen inventory is reduced and the NPV is increased.
• We simulate the optimum design results for Case B.2 for uncertainty in solar radiation, wind speed and electrolyzer efficiency.
• For unfavorable wind conditions and favorable solar conditions high electrolyzer efficiency performs better (wind is dominating over solar).
The very high costs at high deviations are due to penalties involved in the use of the diesel generator.

In Case B.2, it is initiated at -9% wind deviations and provides at maximum 0.65% of the overall requested load for 10 years.

In Case B.1, it is initiated at 0% and provides at maximum 1.3%
HYRES system development

PV 10kW<sub>p</sub>  WT 3x1kW<sub>p</sub>

Accumulators 4x750Ah  DC bar 48V

in operation since 2008 at Xanthi (GR)
HYRES system

Hydrogen storage @ 15-20 barg

Electrolyzer (4.2 kWp) and fuel cell (4 kW)
HYRES automation and control system

Design goals:
- Interoperability, extensibility & automated operation
- Integrate different device & network protocols into one common control system
- Translate field data & device data into OPC based format due to homogeneity reasons

Control architecture:
- Centralized SCADA: collect, process, distribute real-time data
- Implement automated algorithms for the Power Management Strategies

Remote monitoring & control access system:
- User can control the subsystems and make changes on key variables
  - power supply of the PEM electrolyzer & current drawn from the PEM fuel cell
- Real-time data from the unit are stored in a Database server
  - On demand processing through commonly used tools (MS Excel)
Communication and automation infrastructure

- **A**: Field & Device level communication protocols
- **B**: Translation of data into OPC based format
- **C**: Access of SCADA DB to data using OPC protocol
Interface subsystems layout
Concluding remarks

• A systematic method is presented to address the design of a hybrid power generation system under uncertainty.

• The design decision making involves significant complexities due to the integration of multiple components with heterogeneous characteristics.

• Attention is focused
  - On the systematic representation of the options that affect the design decisions such as structural, operating design variables and uncertain parameters.
  - On the systematic integration of the individual system components through optimization.
Concluding remarks

• The implementation of the proposed developments in case studies reveals that:
  - The use of multiple design parameters during optimization provides significant trade-offs among power generation units and power storage infrastructure, especially in view of the complex hydrogen infrastructure.
  - Designs obtained when uncertainty is accounted for successfully address weather and efficiency variations.