RUBY

Robust and reliable general management tool for performance and durability improvement of fuel cell stationary units

Degradation-aware energy management of fuel cell-based VPPs

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RUBY WORKSHOP, LUCERNE (CH)

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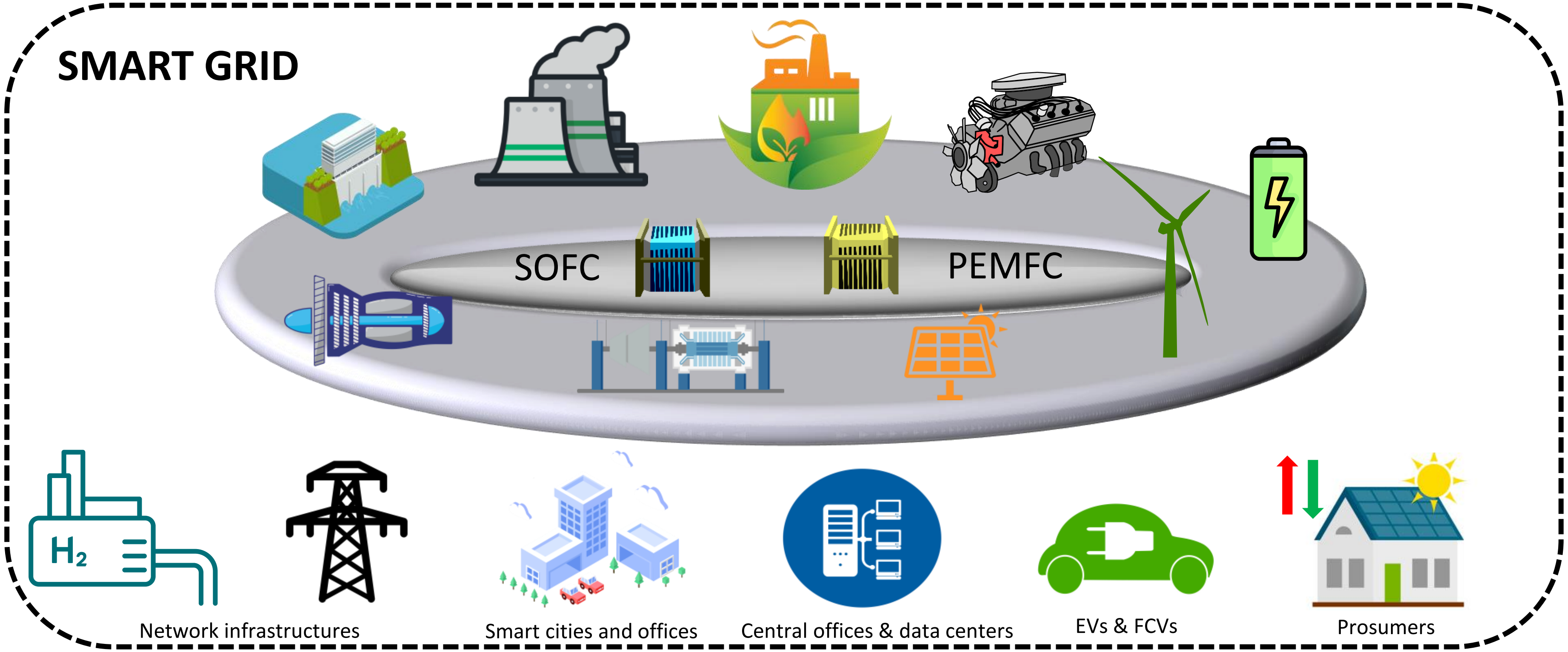
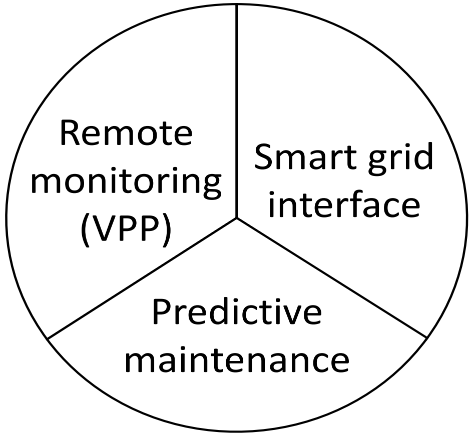
Scenario – Energy Technologies & Uses



Functionalities for:



<u>Objective 4</u>: Management

RUBY aims at improving **FCs** performance and durability (>40000 h) through an **MDPC** algorithm

VPPs are ready-made energy options to be suitably embedded in **Smart Grids**

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What is a Virtual power plant (VPP)?

- A **Virtual Power Plant** is a cloud-based combination of different distributed energy systems (with innovative & traditional technologies).
- The integration of **VPPs** in the energy-market can reduce the **risks of energy shortages**, improve the overall **efficiency of the network** and enhance the **flexibility of the the grid** with respect to load and RES fluctuations.

In such environments, systems like **fuel cells, electrolyzers, reversible cells** and **RES** are perfectly suitable

- FC/Electrolysers/Reversible cells can further support the transition to more distributed energy generation paradigm.

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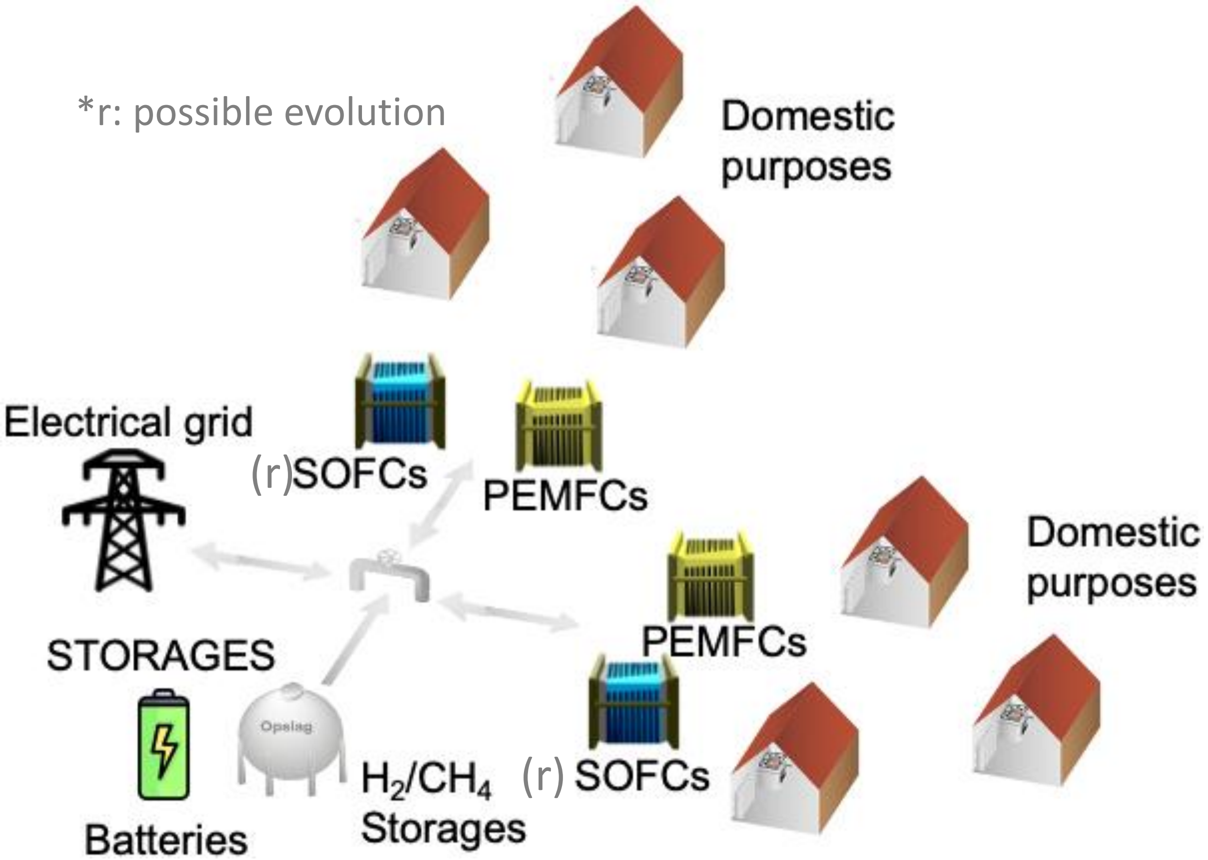
RUBY goals/1

Practical case-study: residential complex*

*r: possible evolution



Configuration:

- Grid-connected virtual power plant
- Both SOFCs and PEMs as energy devices systems
- Electrical storage by means of batteries as well as hydrogen/methane
- Electric and thermal loads coming from the overall residential complex (6 apartments)

In such a case the SOFC and PEM devices can be seen as VPP themselves

* M. Califano et al. – Optimal heat and power management of a reversible solid oxide cell based microgrid for effective technoeconomic hydrogen consumption and storage. Applied Energy 319 (2022) 119268

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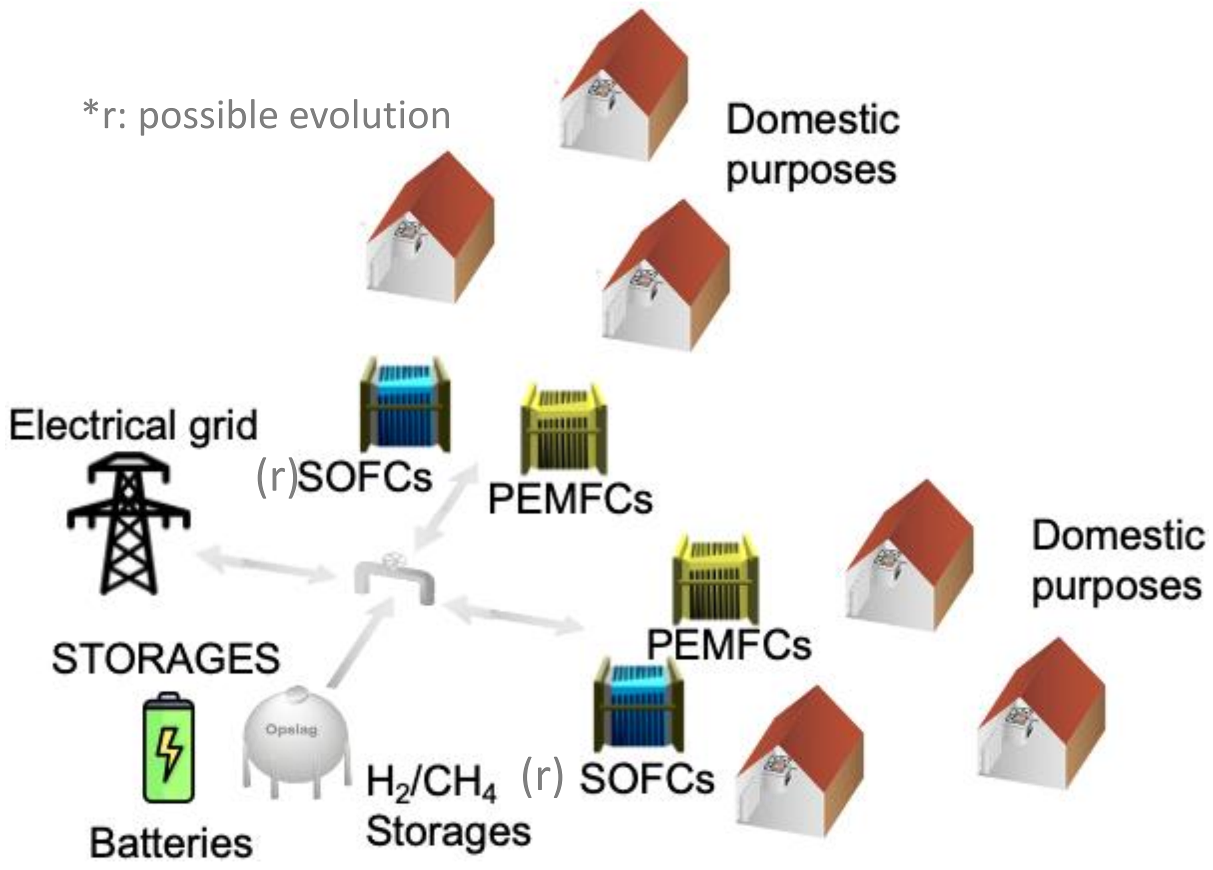
RUBY goals/2



The **MDPC** algorithm serves at:

- FCs monitoring and diagnostics
- FCs management taking advantage of both SOFCs and PEMFCs strengths
- Suitably interfacing with the smart grid requests → Optimal energy management
- FCs scheduled maintenance

Potential combination of two competitive technologies (PEM & SOFC) to:

- different or unexpected power request transients
- reliably meeting peak power demand

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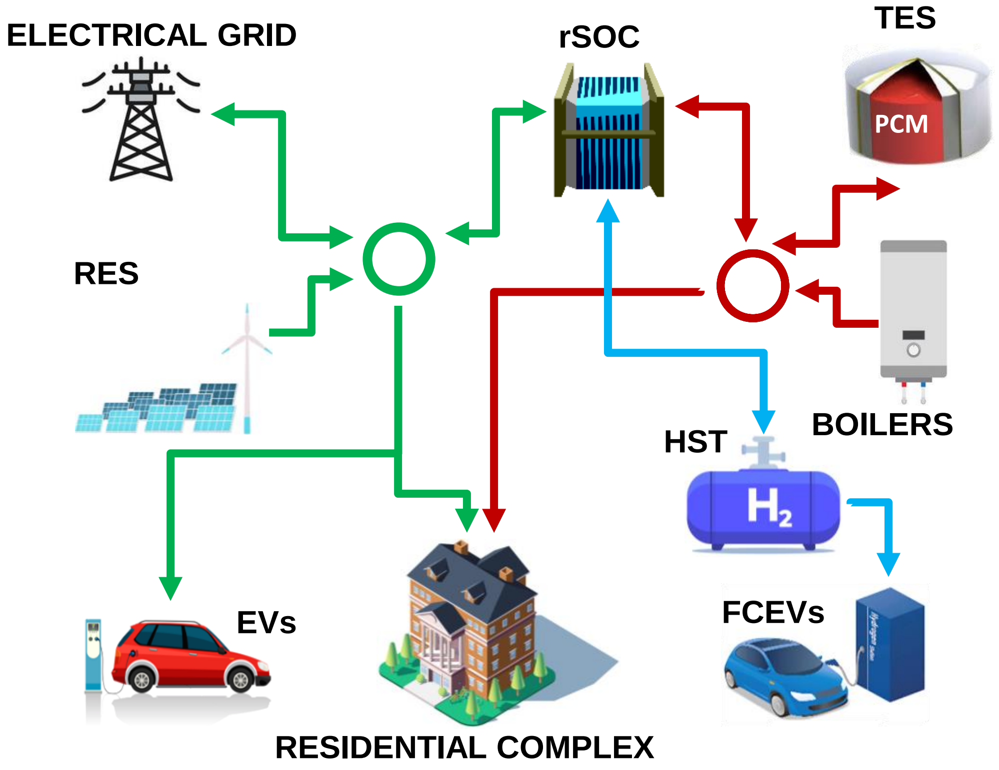
Case study – Example of microgrid



An all-in-one solution

- Renewables → Electricity
- rSOC + Hydrogen storage tank → Hydrogen
- Thermal energy storage → Thermal energy

Test Case Data

- rSOC = 15 kW
- PV = 30 kW
- Wind turbines = 41 kW
- H_2ST capacity = 136 kg
- TES thermal capacity = 51 kWh

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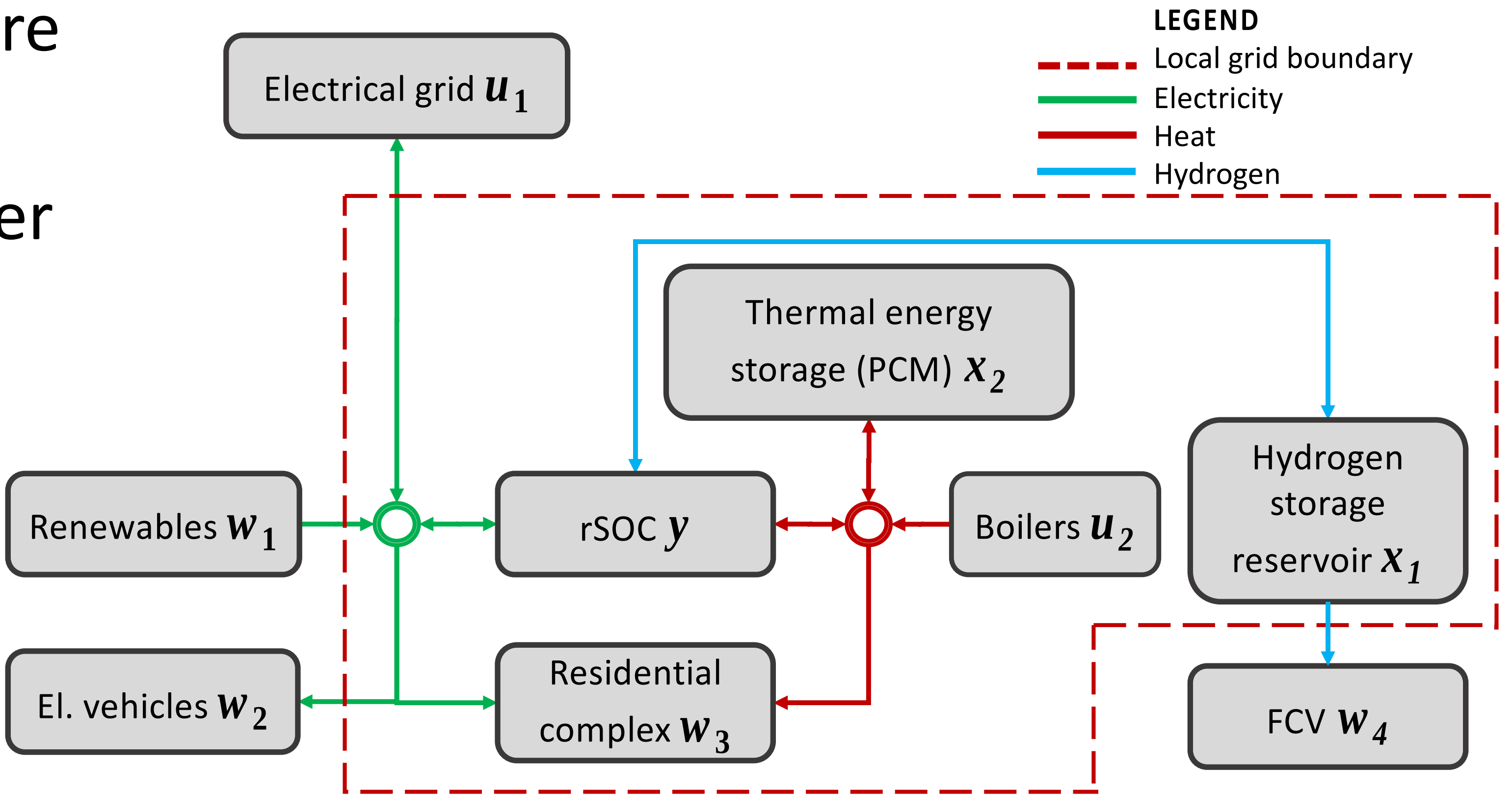
Optimal energy management DP

System variables

- Loads and production (RES) are known a priori (w_i)
- **Control variables** are El. Power from the grid and Thermal energy from boilers (u_i)
- Two **state variables** parallel optimization for both H_2ST and TES state of charge (x_i)
- Output variable (y) is the rSOC electrical power



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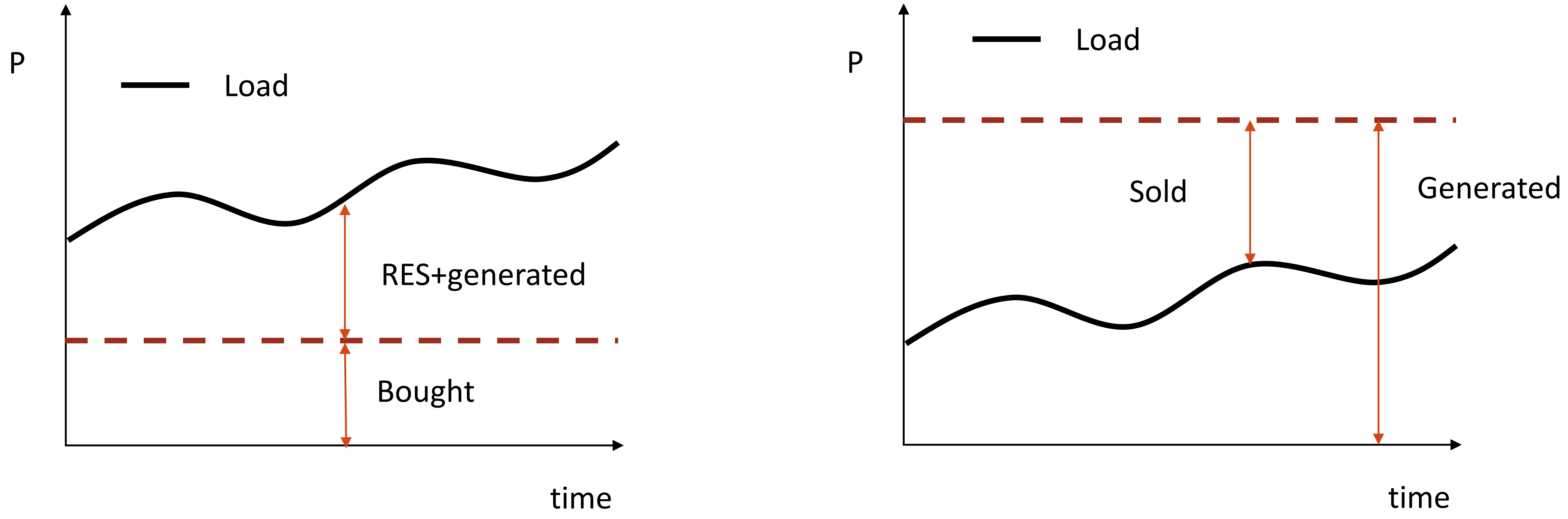
Management concept (prosumer)

Example of Electrical Energy (SOFC mode)



Potentially applicable to thermal energy

RUBY

DP solution scheme

Clean Hydrogen Partnership

Initial plant design and nomial rSOC power →
$HST_{capacity}$, $TES_{capacity}$, PV, W, $P_{rSOC,nominal}$

⇩

Load time profiles are known

Δt = 1 h

DP routine

Input variables:
- **RES production → $P_{PV,j}$, $P_{W,j}$**
- **Electrical loads → $TL_{,j}$, $P_{SOEC,j}$**
- **Thermal loads → $DHW_{,j}$, $P_{th,SOEC,j}$**
- **Hydrogen request → $m_{H_2,car,j}$**

⇩

Electrical strategy → $P_{SOFC,j}$, $P_{grid,j}$
Thermal strategy → $P_{th,TES,j}$, $P_{boilers,j}$, $P_{th,SOFC,j}$

⇩

Cost function minimization → $C_{sold,el,j}$, $P_{bought,el,j}$, $P_{bought,th,j}$

Are the constraints verified?

YES → **{ SOC_{HST} & SOC_{TES} trajectories }**

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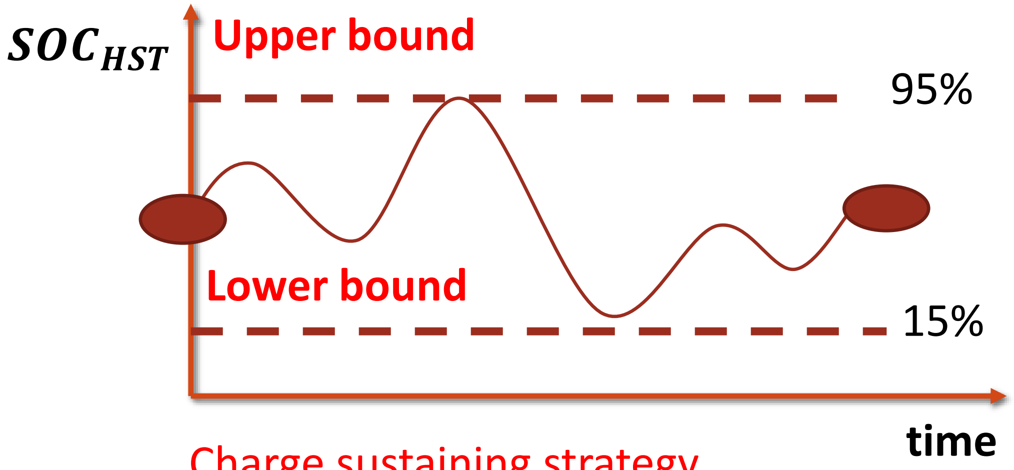
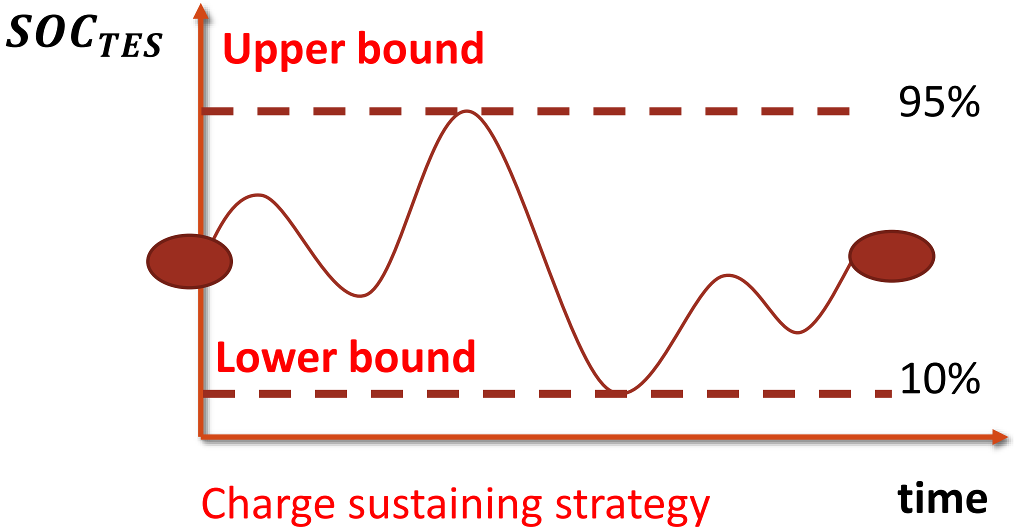
DP routine - State Variables

- The first state variable of the DP optimization is the Hydrogen Storage Tank (HST) state of charge → SOC_{HST}
- The second state variable of the DP optimization is the Thermal Energy Storage (TES) state of charge → SOC_{TES}
- They must be in a region identified by the upper bound and the lower bound
- The **initial and final values** must be the same



Charge sustaining strategy



Charge sustaining strategy

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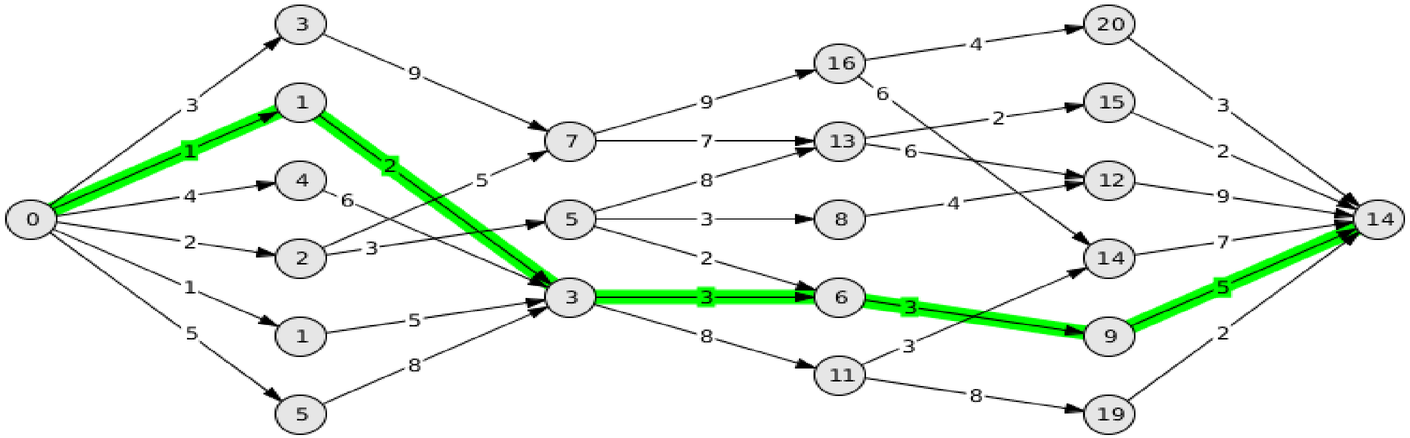
DP routine - Cost function

DP minimizes the performance index that is calculated through the cost function:

$$J = \int_0^t (P_{bought} \cdot C_{bought} - P_{sold} \cdot C_{sold})dt$$

P_{bought} includes both the electric and thermal power (gas), instead P_{sold} includes only the electric power

Different values of the control variables return different state variables paths (green and black) leading to different values of J.



1-D example

DP provides as output the path that has the minimum value of the performance index J

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Source: https://www.cs.rit.edu/~ark/351/dp/notes.shtml

DP Routine - Algorithm Scheme 1/2

Input variables: electric load (complex), H_2 demand from FCHVs, PV and wind power production and nominal P_{rSOC}

$$P_{rSOC} = (\mathbf{P_{el}} - P_{PV} - P_W) - P_{grid}$$

1° control variable

$$\boldsymbol{m_{h2,tank} = (m_{SOEC} - m_{SOFC})}$$

1° state variable

$$\boldsymbol{SOC_{HST,i+1} = SOC_{HST,i} + \frac{m_{h2,tank,i} - m_{h2,car,i}}{tank\ size}}$$

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DP Routine - Algorithm Scheme 2/2

Input variable: thermal load (DHW), thermal power provided by rSOC, thermal power used by rSOC, nominal TES energy

2° control variable

$$P_{th,TES} = P_{\boldsymbol{boilers,th}} + P_{\boldsymbol{th,rSOC}} - \boldsymbol{DHW}$$

TES charging

$$E_{th,in} = P_{th,TES} * \sqrt{\boldsymbol{RTE_{TES}}} * \Delta\boldsymbol{t}$$

TES discharging

$$E_{th,out} = P_{th,TES} * \Delta\boldsymbol{t}/\sqrt{\boldsymbol{RTE_{TES}}}$$

2° state variable

$$\boldsymbol{SOC_{TES,i+1} = SOC_{TES,i} + \frac{E_{th,in,tank,i} - E_{th,out,tank,i}}{tank\ size}}$$

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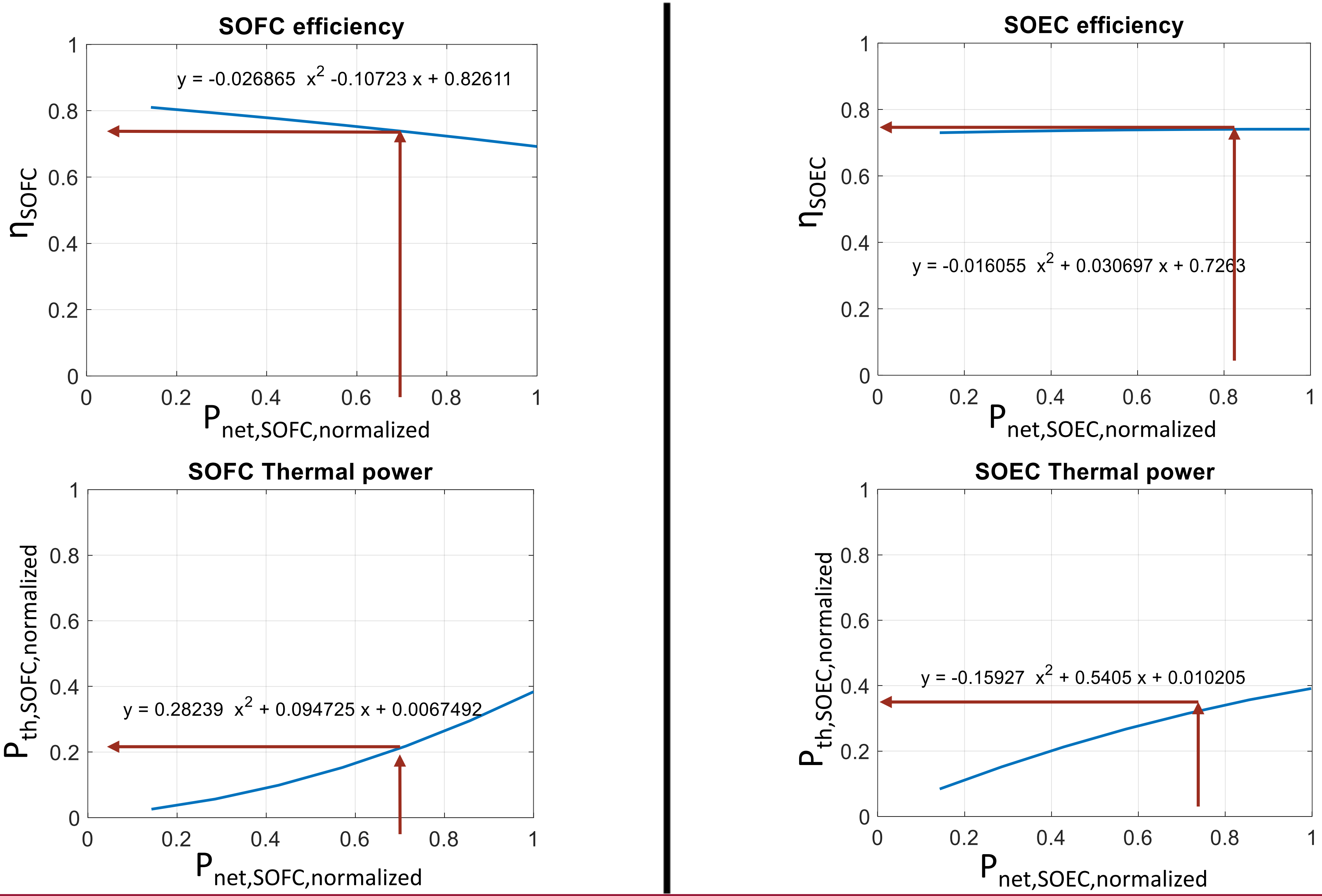
rSOC modelling (maps*)



* M. Scaltritti, Master Thesis Politecnico di Milano (2016)

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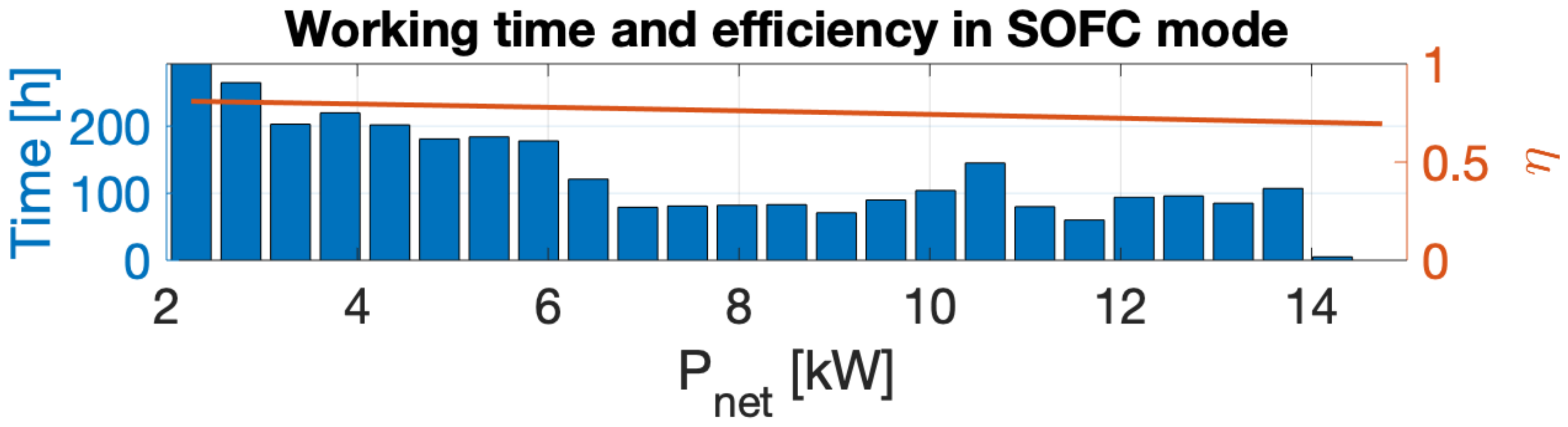
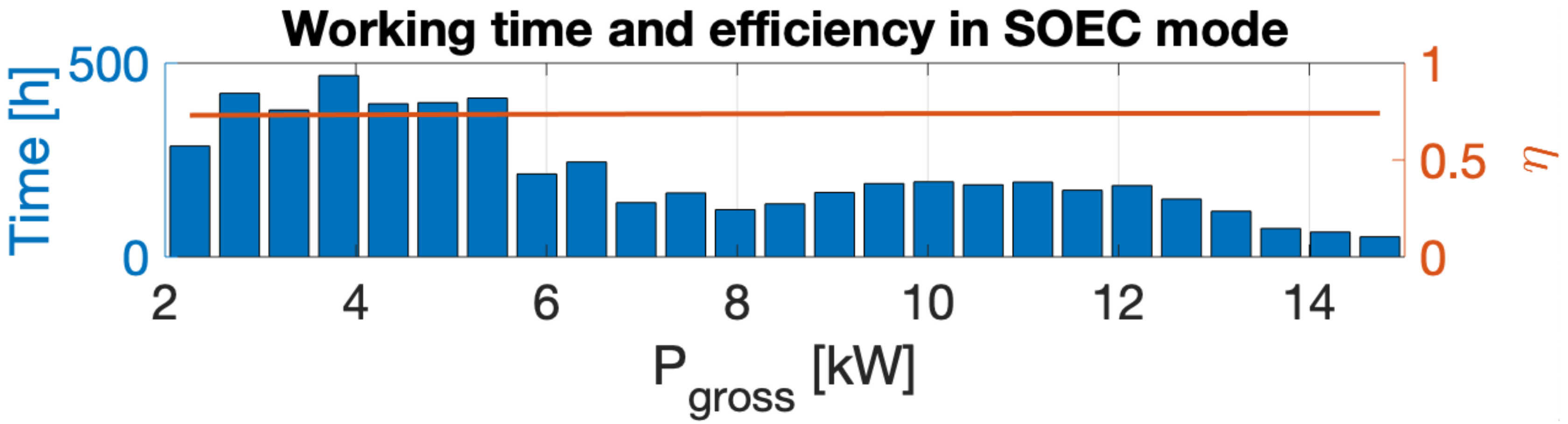
Working time of rSOC in both modes





rSOC 15 kW

DP results*

SOFC=3760 hours

SOEC=5000 hours

The rSOC works 100% of the time

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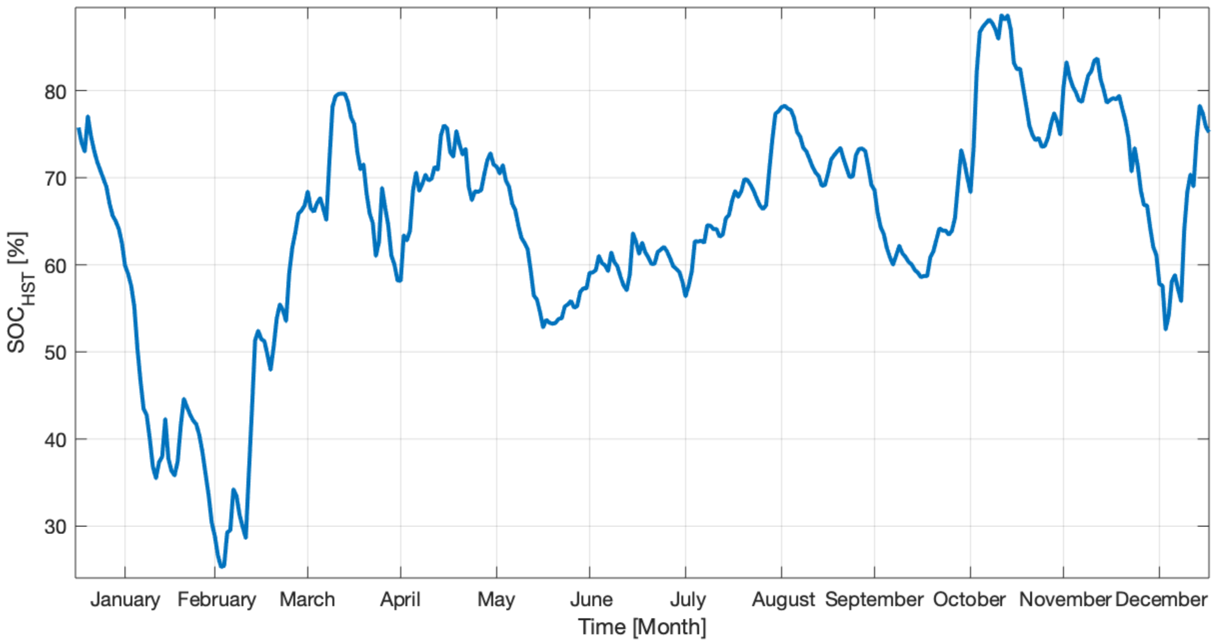
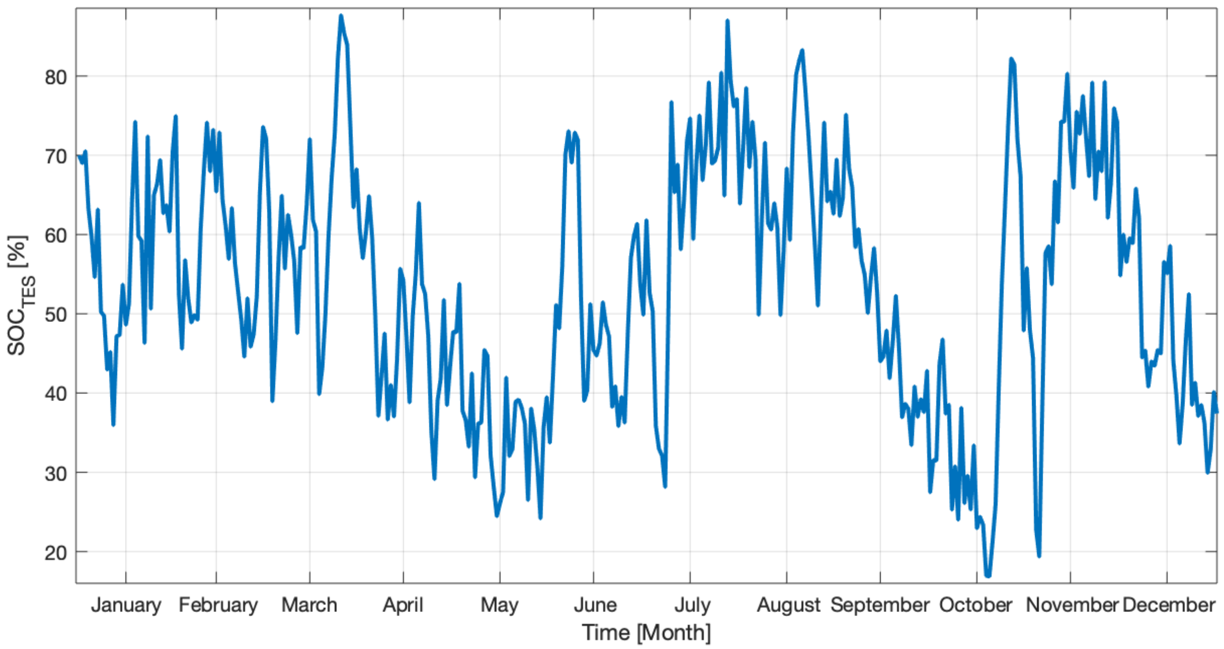
State variables trajectories*

rSOC 15 kW

1° state variable -> $\boldsymbol{SOC_{HST}}$



2° state variable -> $\boldsymbol{SOC_{TES}}$



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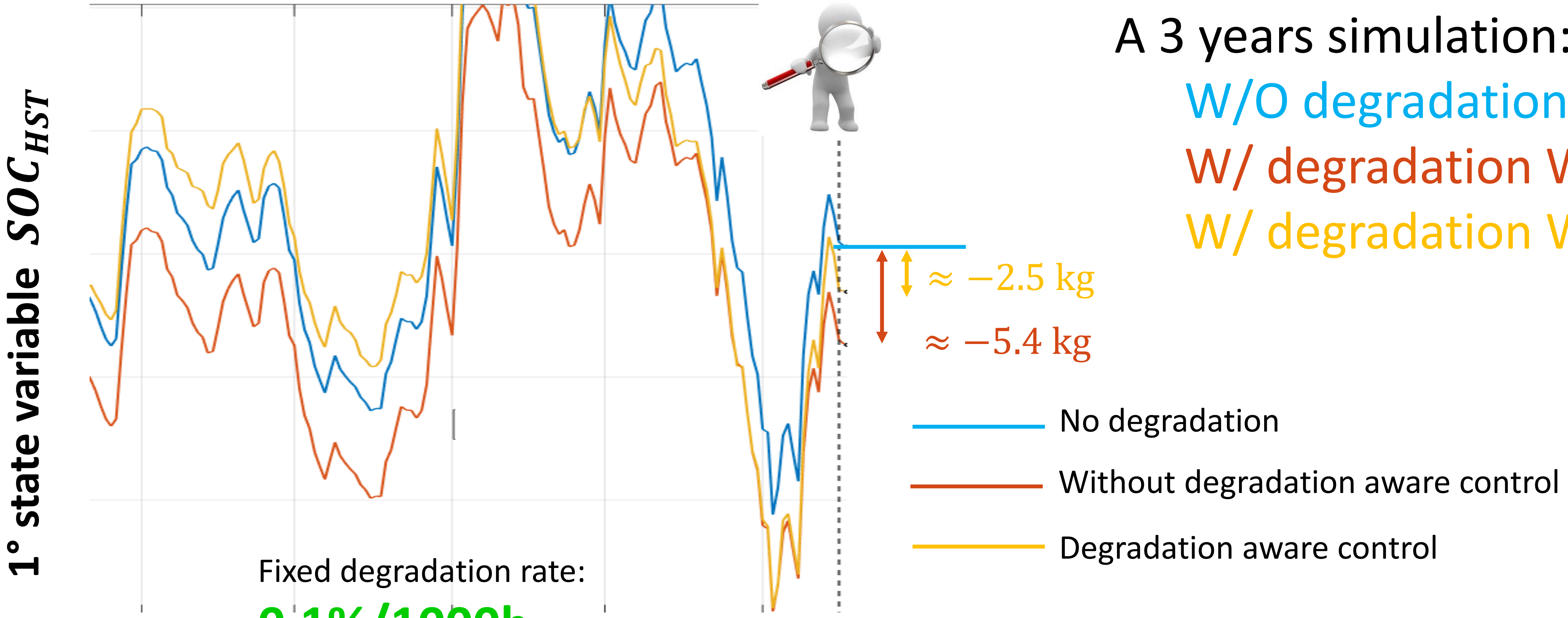
Degradation-Aware Control w/ MDPC

The use of a Prognostic tool (MDPC) for degradation prediction allows to optimize the control leading to a lower H2 consumption (i.e. x_1 = SOC_{HST})



Fixed degradation rate:
0.1%/1000h

End of the 3 years analysis

A 3 years simulation:
- W/O degradation
- W/ degradation W/O DAC
- W/ degradation W/ DAC

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Thanks for your attention

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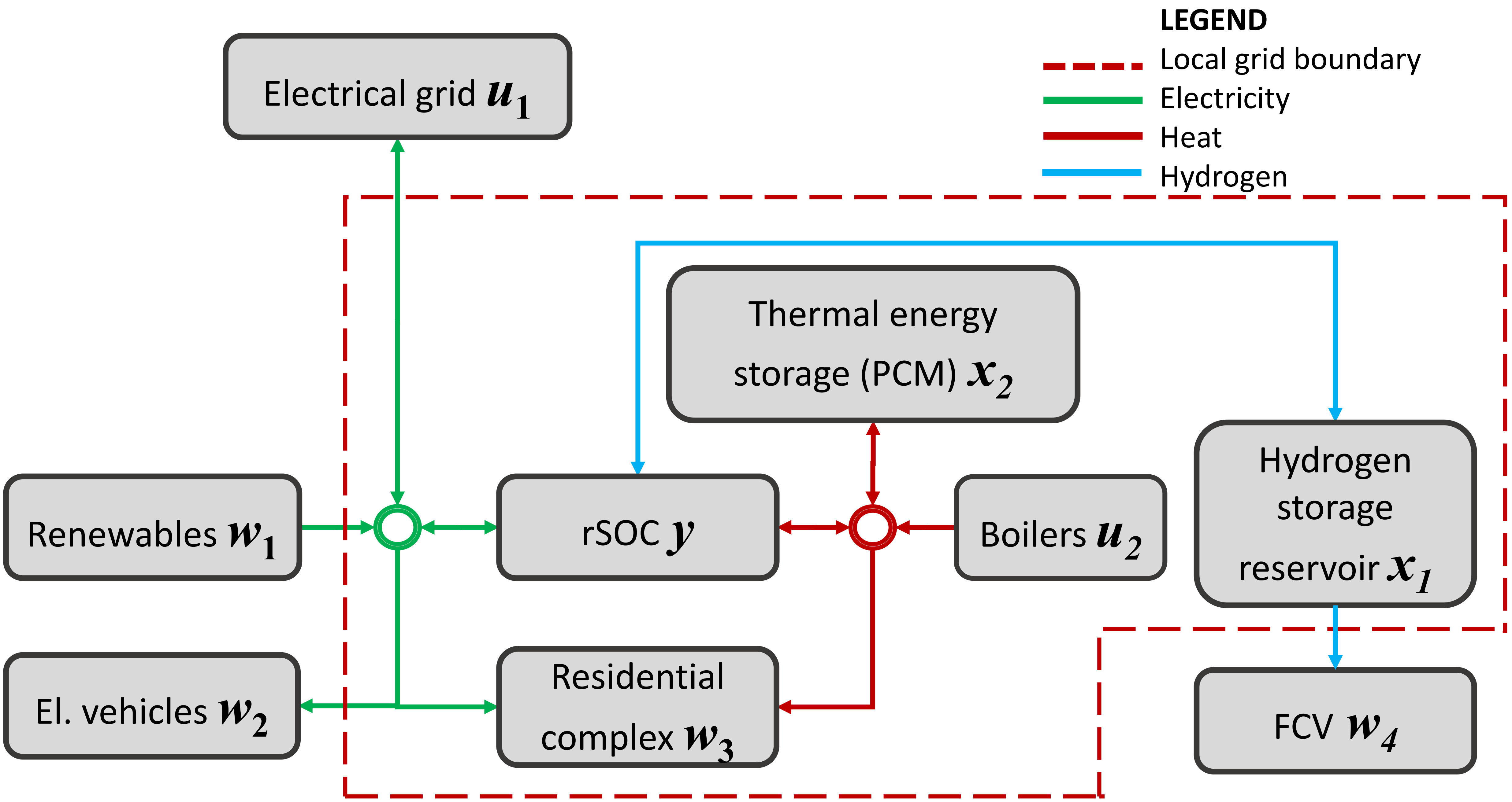
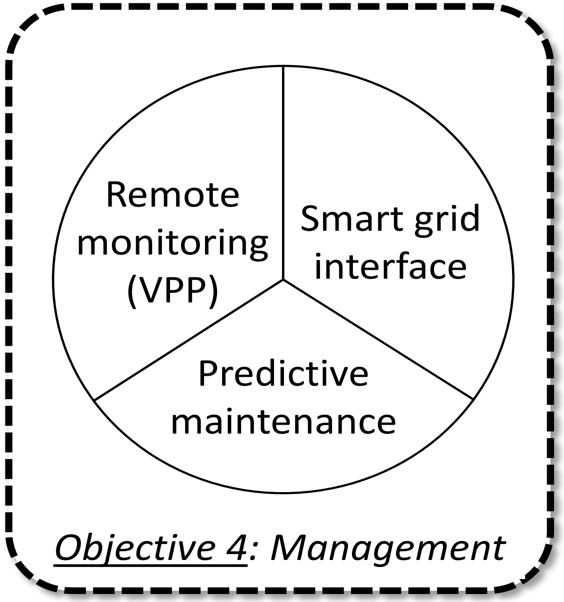

LEGEND
Local grid boundary
Electricity
Heat
Hydrogen
Electrical grid u_1
Thermal energy storage (PCM) x_2
Hydrogen storage reservoir x_1
Renewables w_1
rSOC y
Boilers u_2
El. vehicles w_2
Residential complex w_3
FCV w_4

Benefits of MDPC tool & VPP

Functionalities for:



RUBY outcomes will improve

- Remote monitoring
- Smart grid management &
- Virtual Power Plant-based management
- Maintenance (predictive)

Outline of the presentation

- VPP and application to a