Off-grid and grid-connected Hybrid Renewable Energy Systems

L.Bartolucci, S.Cordiner, V.Mulone

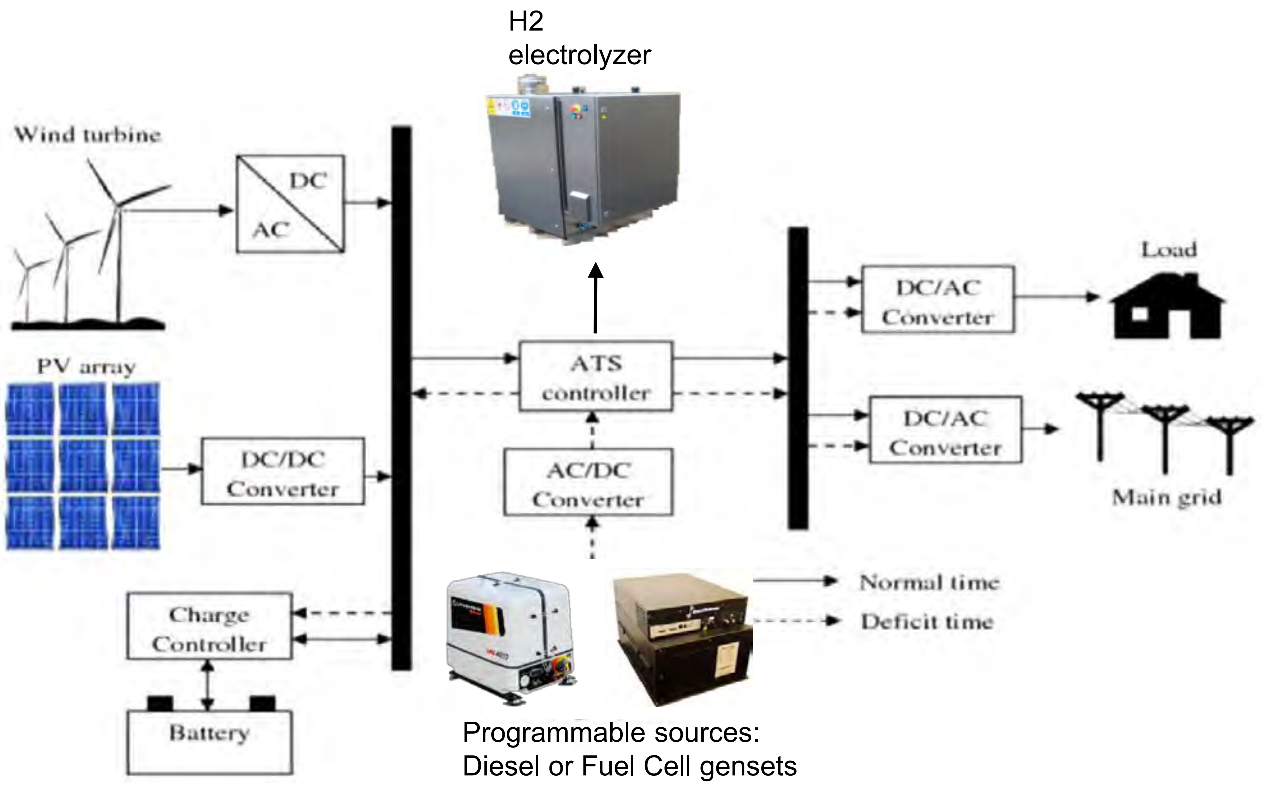
Dipartimento di Ingegneria Industriale
Università di Roma “Tor Vergata”

Outline

- Hybrid Renewable Energy Systems (HRES)
- Control of HRES: The Energy Management System
- Applications:
  - FCPoweredRBS: Telecom Sites Off-grid Power Supply
  - Connected Microgrids with Advanced Control
- Conclusions

The most general layout of HRES

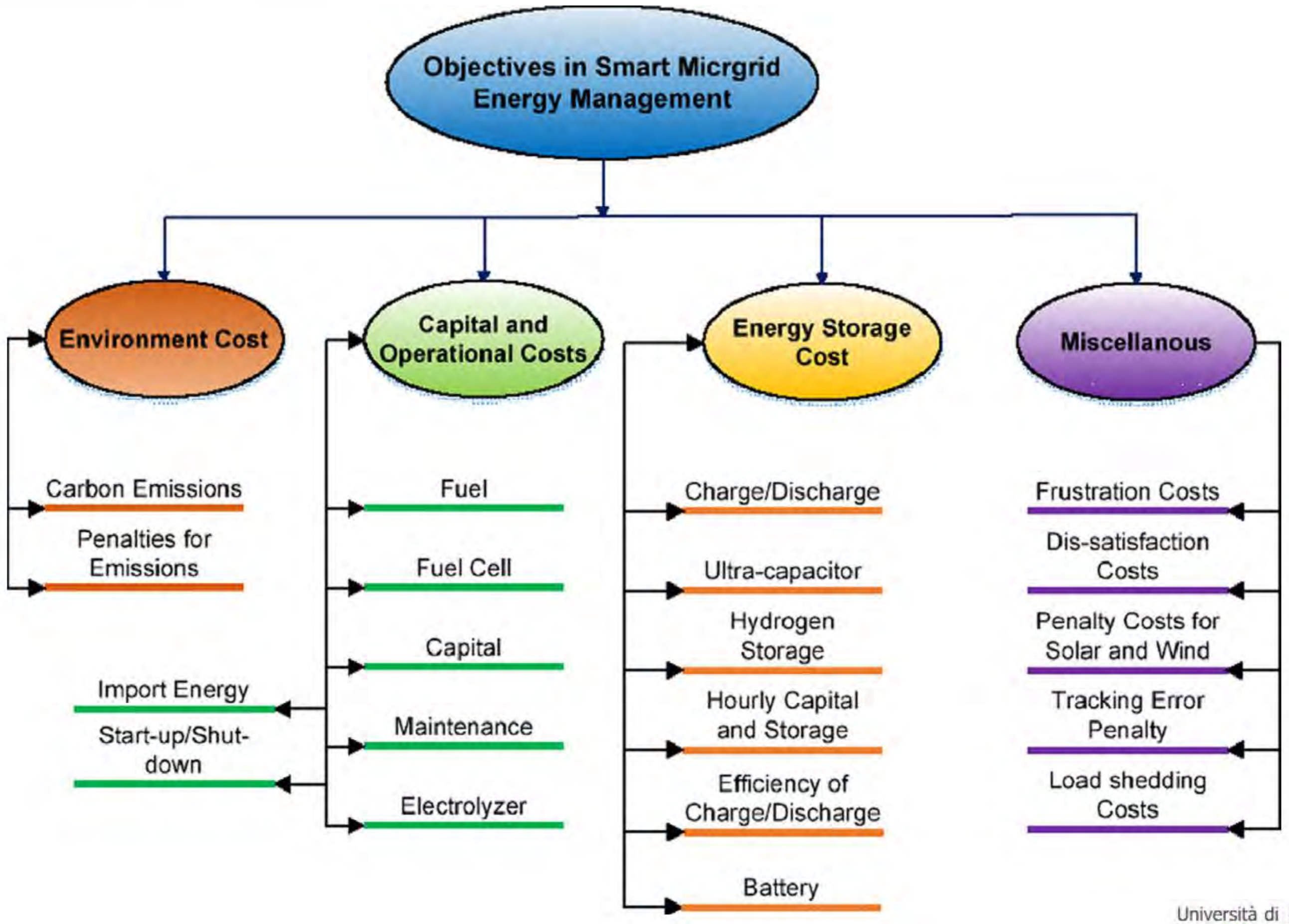
- The most general layout of a HRES is characterized by:
  - Both PV and wind based systems to produce power from renewable sources (RES)
  - Battery to store energy with high turnaround efficiency
  - Use of programmable sources to provide power to the load once the battery is discharged
  - Use of electrolyzer to produce H2 from renewables at the Fuel Cell
  - Connection with the grid



Adapted from Al Busaidi et al., Ren and Sust. Energy Reviews, 53, 2016

The Energy Management System (EMS)

- The EMS is designed and operated depending on objective functions
- The objective functions may be defined depending on costs
  - Environmental costs (penalties due to emissions)
  - Capital and Operating expenses: fuel cells and electrolyzer are key, as well as energy purchase
  - Energy storage costs
  - Miscellaneous, including load shedding, load following, etc



from Ahmada Khan et al., Ren and Sust. Energy Reviews, 58, 2016

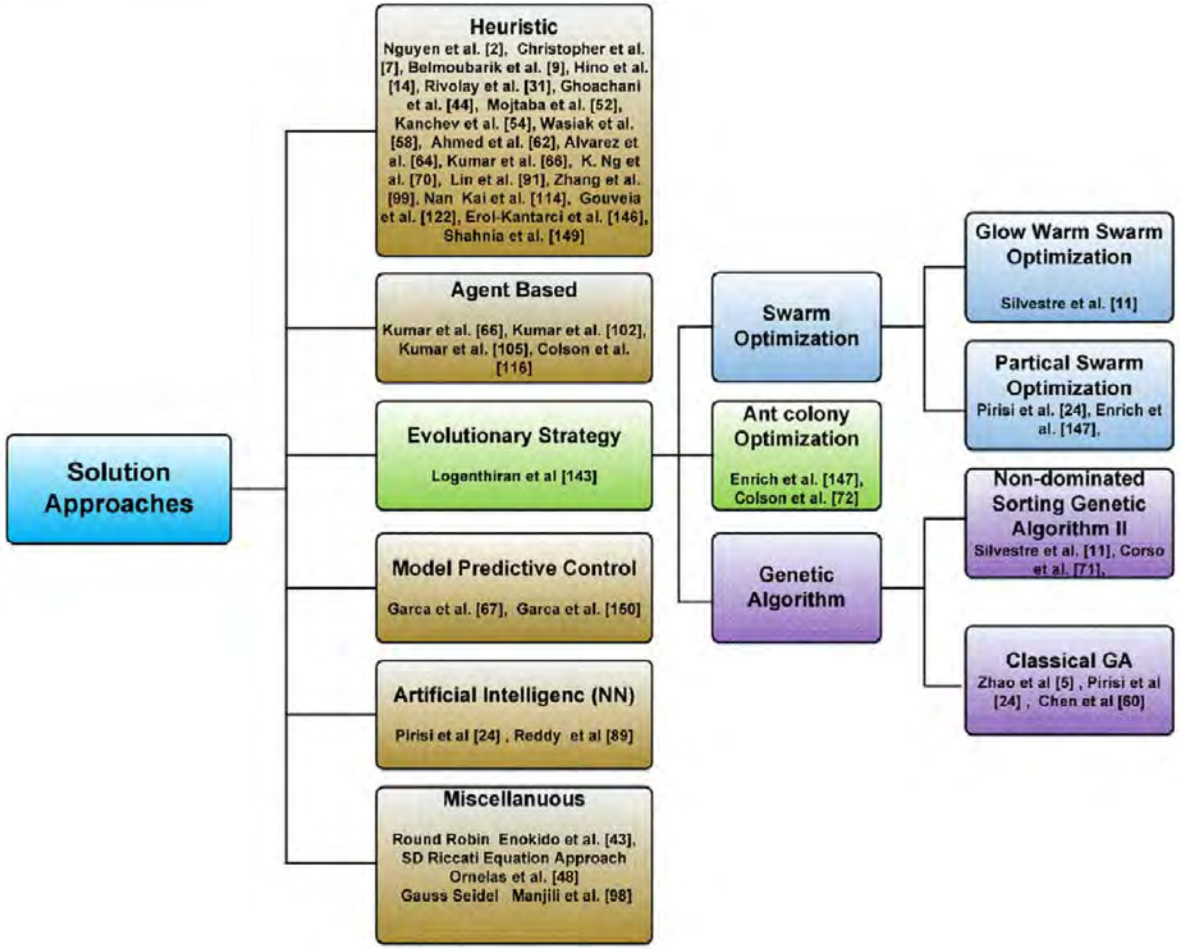
Solution approaches for the EMS

- The solution approach may be very different depending on several factors: accuracy, reliability, computational resources required, etc

- <u>Heuristic</u> approach is used normally, based on simple priority rules (RBC) or fuzzy logic

- <u>Model Predictive Controls</u> (MPC) strategies are used to calculate the current power splitting taking into account the behavior of the system over a given time horizon depending on forecast (weather, load, energy flux from/to the grid)

- The performance would highly depend on the <u>accuracy of input data</u> (e.g. weather forecast)



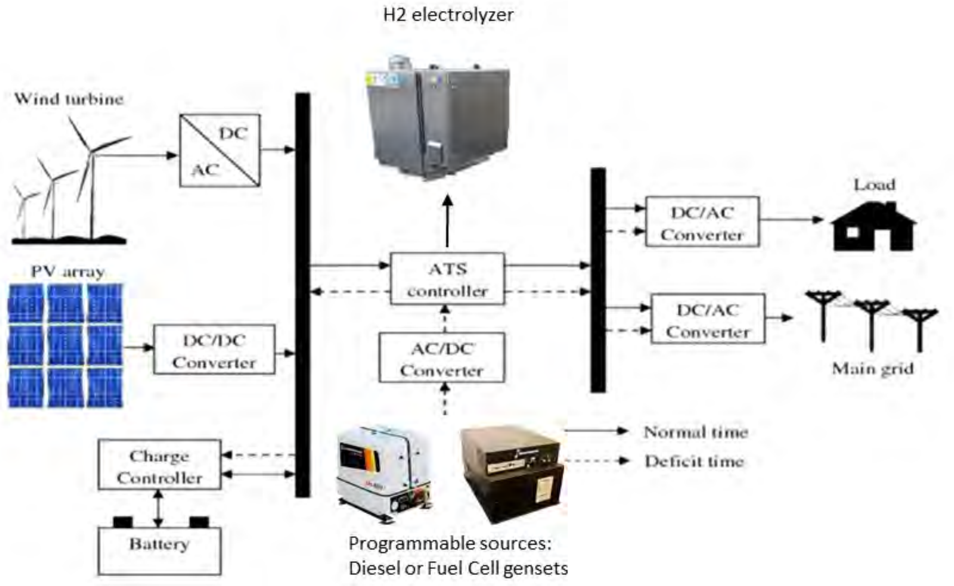
from Ahmada Khan et al., Ren and Sust. Energy Reviews, 58, 2016

Open issues for HRES design, research and development

- HRES system economic and environmental performance parameters depend strongly on
  - SYSTEM SIZING: the relative power size of the different sub-systems if compared to the power requirement at the load
  - ENERGY MANAGEMENT STRATEGY (EMS): power at the load can be provided by one or more power producing sub-systems at once. This is typically decided by an EMS supervisor, that may have rather complicated (e.g. model predictive) or simple (e.g. rule based) strategies implemented
  - SUB-SYSTEM EFFICIENCIES: obviously, the use of better performing sub-systems is reflected in better overall performance parameters of the HR

- The three aspects are related one each other as, for example, the system may be downsized with optimal EMS design

- The sub-systems are characterized by different costs and levels of development: <u>chemistry plays a leading role</u> in the most advanced (expensive) components (batteries, fuel cells, electrolyzers)



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Applications: Telecom Sites Offgrid Power Supply

Project Summary

- **Starting Date**: 01/01/2012
- **Duration**: 48M
- **Budget**: € 10,591,649
- **Funding**: € 4,221,270
- **Partners**: 6 partners
- **Countries**: Belgium, Denmark, Italy, Switzerland
- **Coordinator**: Ericsson
- **2** systems tested in R&D centers for benchmarking
- **11** real RBS station power generation systems in selected sites field trials.

Scope:

› Demonstrate the advantages of a FC stationary application in term of Total Cost of Ownership in telecom off-grid radio sites

› Assess the market readiness of the FC technology vs the telecom reliability demanding targets.

Project Partners

ERICSSON Project Coordinator

Dantherm Power

MES S.A.

European Commission JRC's Institute for Energy and Transport

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HYDROGEN.

Telecom Operators involved

TIM

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On Field Demo Sites Overview

N.	Prov	Site	Location	FC Tech	FC power	# days	Timeframe of operation
1	TIM	Sonnino	Latina	Ballard Methanol	800 W	395	1 Oct2014 ->31 Oct 2015
2	TIM	Fiano Romano	Roma	H2 Dantherm	1400 W	395	1 Oct2014 ->31 Oct 2015
3	TIM	Borgo Grappa	Latina	H2 Dantherm GH Electrolyzer	1300 W	152	1 Apr 2015 ->31 Aug 2015
4	TIM	Colle Turchina	Viterbo	H2 Dantherm	420 W	213	1 May 2015 ->30 Nov 2015
5	TIM	Sasso	Roma	H2 Dantherm	760 W	213	1 Apr 2015 ->30 Oct 2015
6	TIM	Baschi 2	Viterbo	H2 Dantherm	1400 W	152	1 May 2015 ->31Octr 2015
7	TIM	Sant'Oreste	Roma	Ballard Methanol	1730 W	30	1 Oct 2015 ->31Oct 2015
8	TIM	Campoleone	Latina	H2 Dantherm	750 W	185	1 May 2015 ->31Oct 2015
9	3 Italia	Bari Circonvallazione	Bari	H2 Dantherm	1000 W	274	1 Dic 2015 ->31 Aug 2016
10	3 Italia	Bari San Giorgio	Bari	H2 Dantherm	1000 W	181	1 Jan 2016 ->30 June 2016
11	TIM	Bagni VT	Viterbo	H2 Dantherm	1150 W	21	1 Nov 2015 -21 Nov 2015
12	3 Italia	Bari Capurso	Bari	H2 Dantherm		Not installed	Ready, but destroyed

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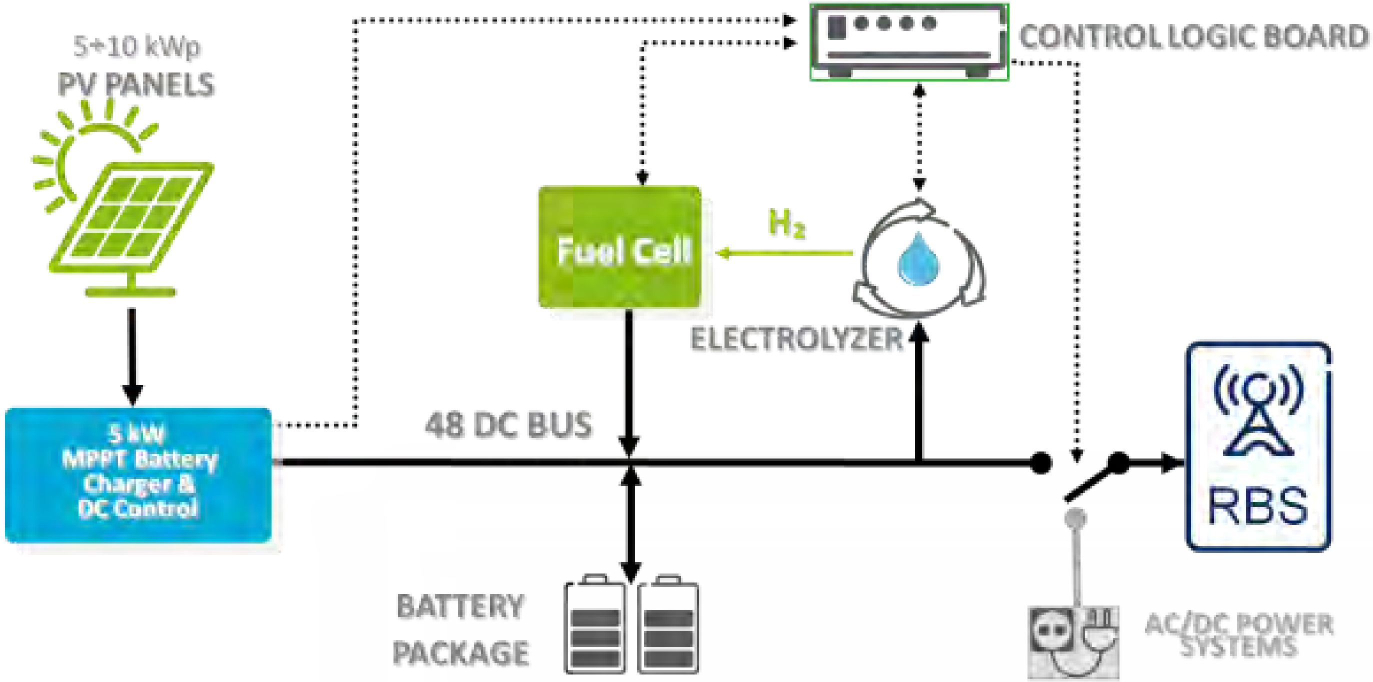
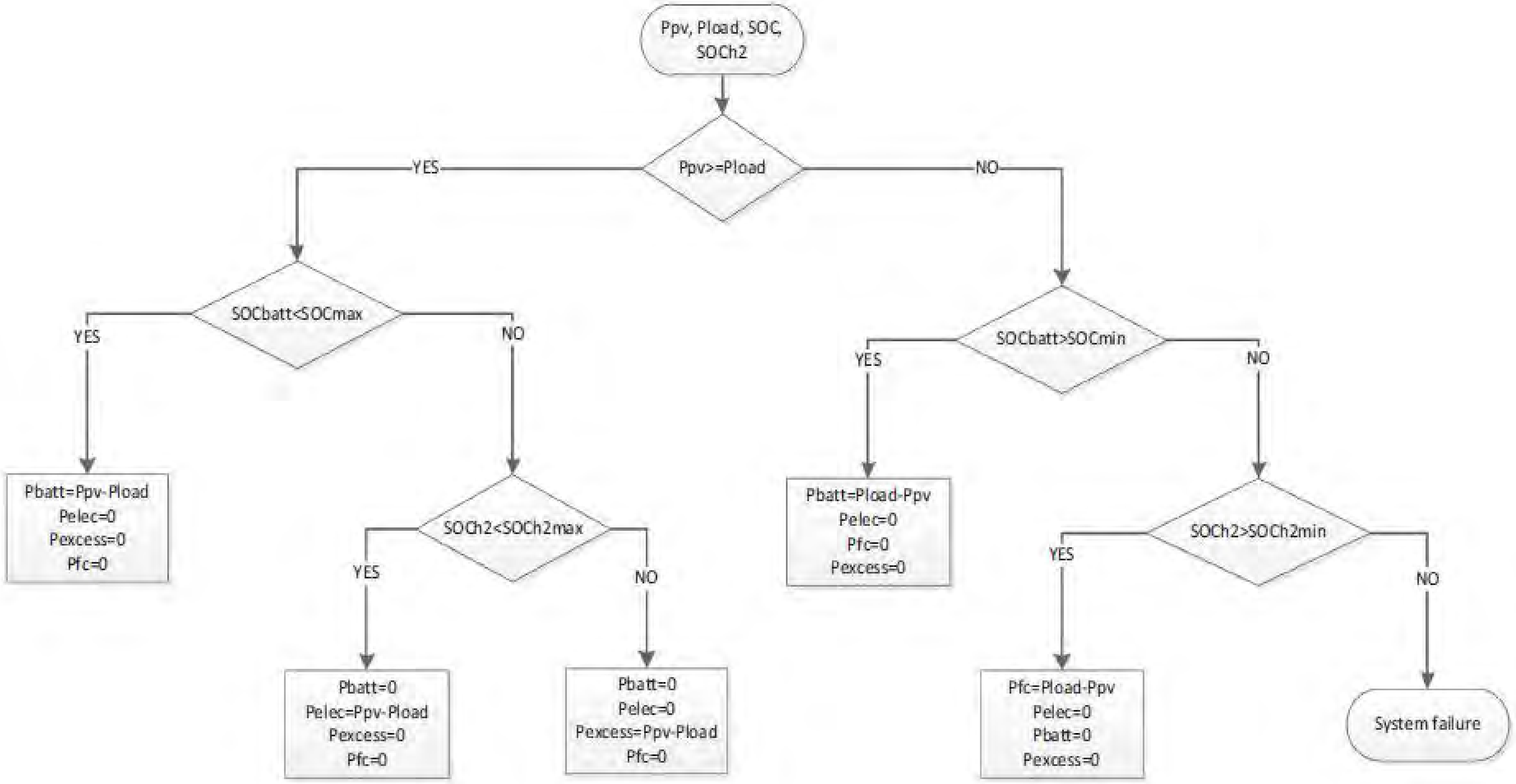
System layout

- Common DC 48V bus
- Continuous 1 kW RBS



Rule Based Control (RBC)
Heuristic Control Strategy



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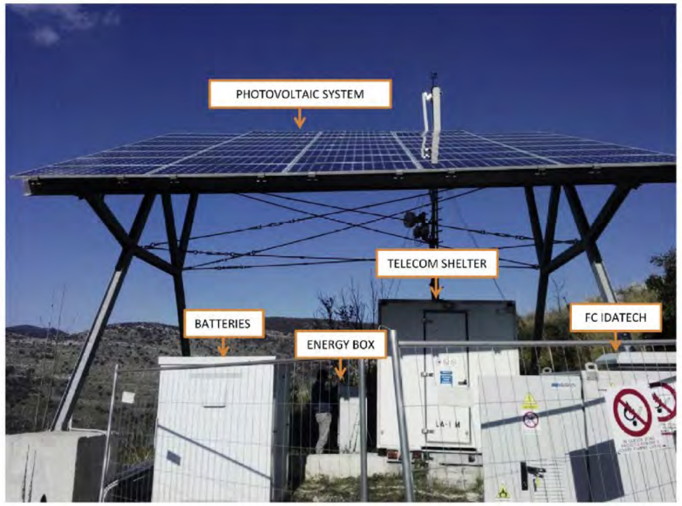
Analysis Over a Full Year Performance (2015)

Design characteristics of the 6 sites installed in Lazio (central Italy).

	Site #1 (Baschi)	Site #2 (Fiano Romano)	Site #3 (Colle Turchina)	Site #4 (Sasso)	Site #5 (Campoleone)	Site #6 (Sonnino)
PV system power	5 kWp	5 kWp	3 kWp	5 kWp	2.5 kWp	5.5 kWp
PV canopy tilt angle	10–25 deg	10 deg	10 deg	10–25 deg	10–25 deg	30 deg
Fuel cell technology	1.7 kW Dantherm H_2 fed	1.7 kW Dantherm H_2 fed	1.7 kW Dantherm H_2 fed	1.7 kW Dantherm H_2 fed	1.7 kW Dantherm H_2 fed	2.5 kW Ballard Methanol fed
Lead-acid battery System	640 Ah at 48 V	640 Ah at 48 V	380 Ah at 48 V	640 Ah at 48 V	320 Ah at 48 V	640 Ah at 48 V
Average power at the RBS load	1.31 kW	1.28 kW	0.35 kW	0.72 kW	0.87 kW	0.65 kW

Installation of the HRESs in Fiano Romano (site #2)



Installation of the HRESs in Sonnino (site #6)

From Cordiner, Mulone et al., Applied Energy, 192, 2017

Analysis Over a Full Year Performance (2015)

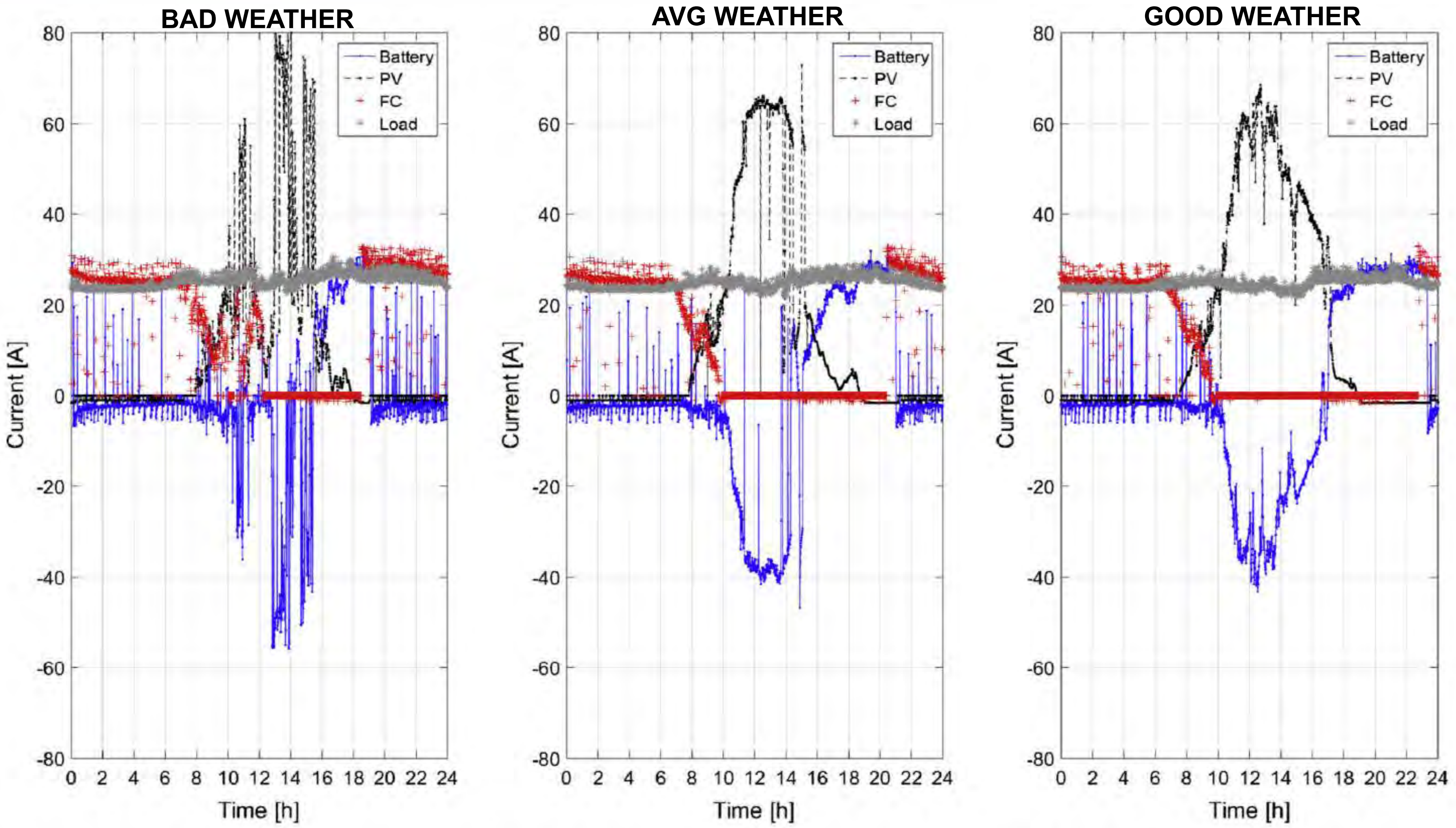


Fig. 9. Current output of PV system, battery, Fuel Cell and load during three representative days in the month of September 2015, Fiano Romano site (#2).

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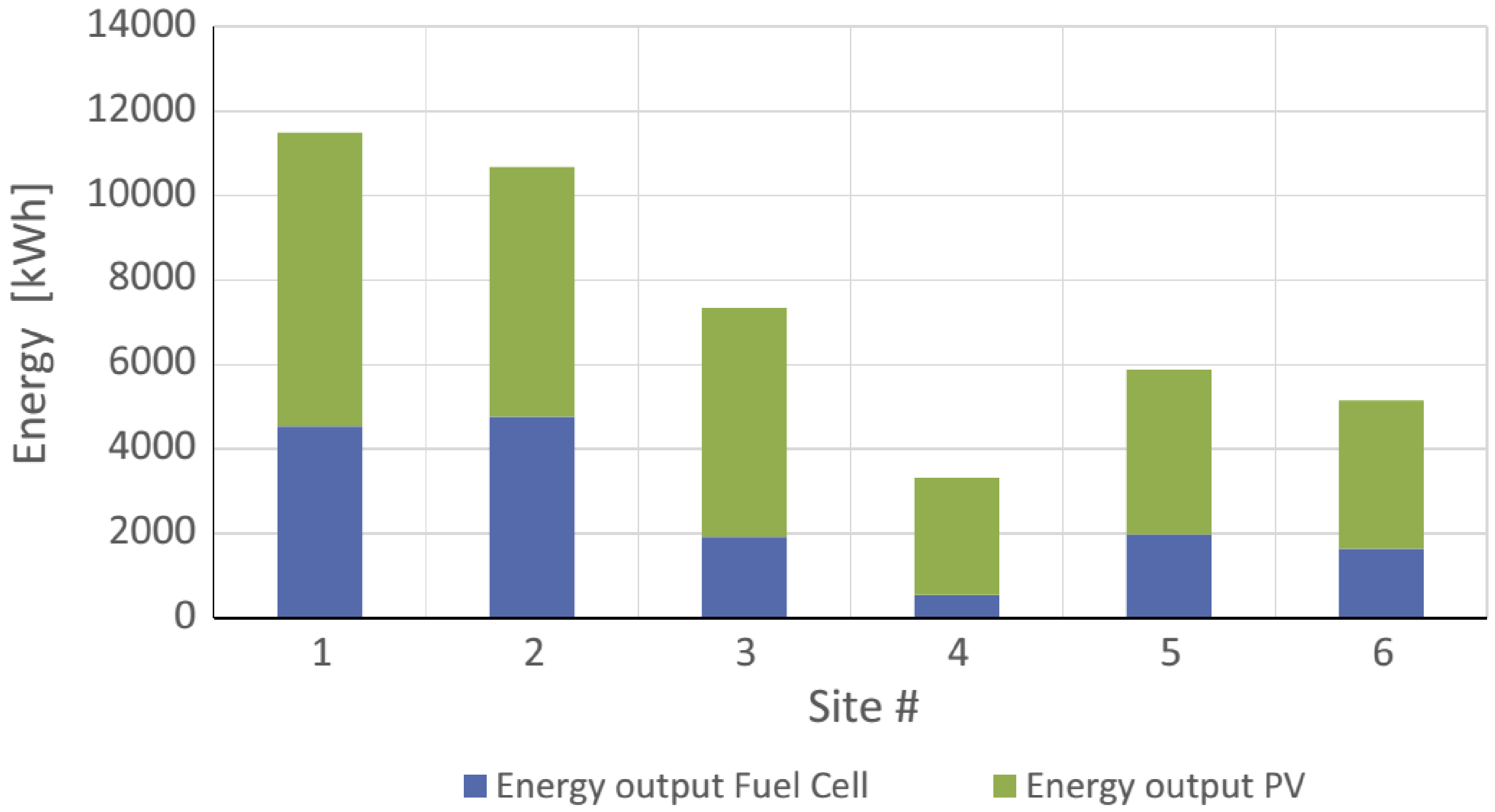
Analysis Over a Full Year Performance (2015)



- Energy at the load is provided from renewables (PV) and through Fuel Cells (H2 or methanol)

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System Performance Parameters

- System performance may be evaluated via efficiency, whose value depends heavily on subsystem power sizings
- The greater the PV power, the closer ηsys would be to η_PV
- The lesser the PV power, the closer ηsys would be to η_FuelCell
- System performance then can be also measured through the ratio E_fes/E_res measuring the effectiveness of the system toward indepedence on fossil (external) sources, and thus in terms of CO2 emission savings

$$I_{size} = \frac{E*_{load}}{E*_{RES}}$$

Class size index

$$\eta_{sys} = \frac{E_{load}}{E_{RES} + E_{FES}}$$

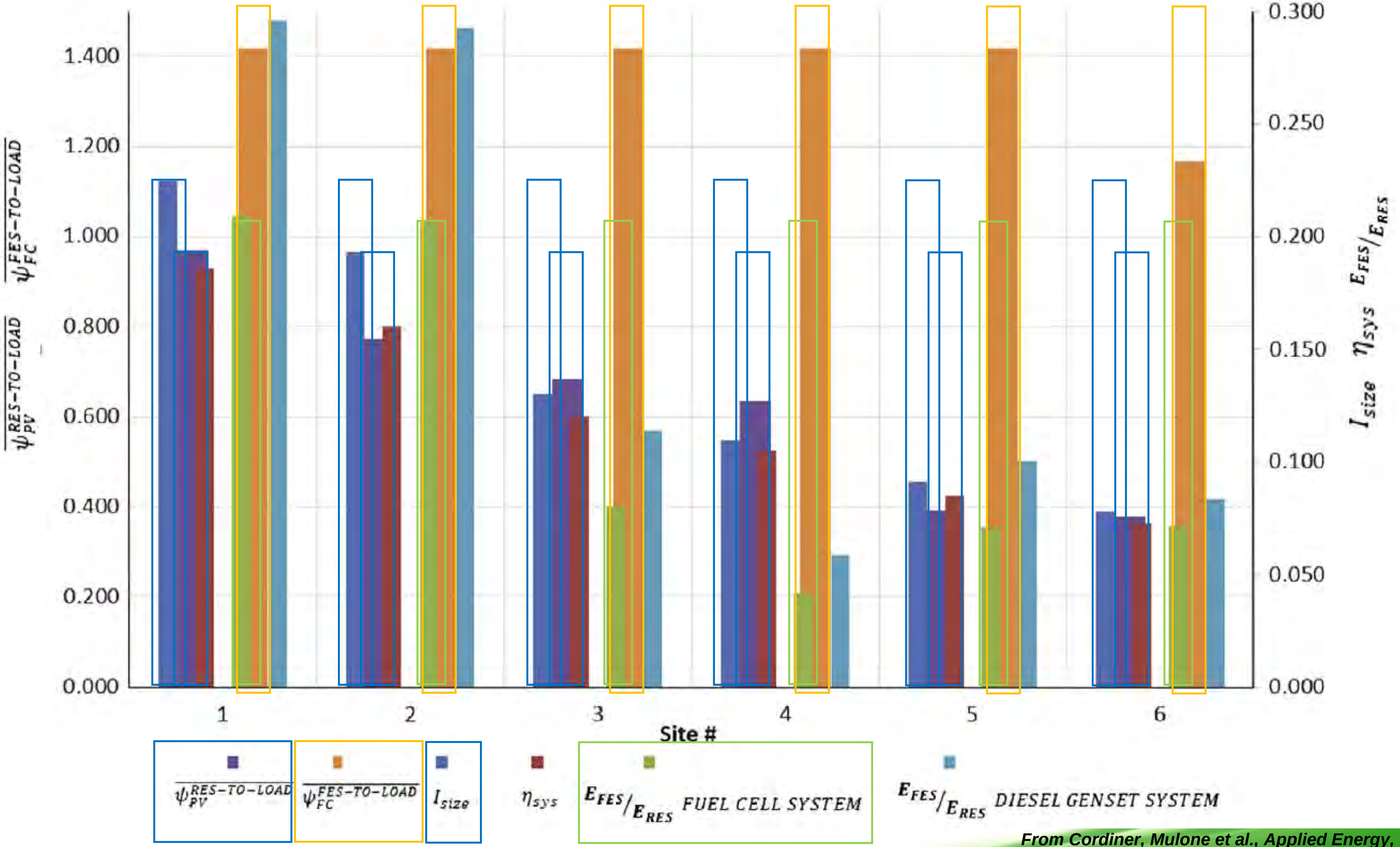
System efficiency

$$\eta_{sys} = \frac{\left(\overline{\psi_{PV}^{RES-TO-Load}}\,\eta_{PV}^{DIRECT*}\right)E_{RES} + \overline{\psi_{FC}^{FES-TO-Load}}\,\eta_{GENSET}^{*}E_{FES}}{E_{RES}+E_{FES}}$$

$$\overline{\psi_{RES-TO-LOAD}} = \frac{\overline{\eta}_{FC}\eta*_{REF}}{\eta_{DIESEL}*}$$

$$\overline{\psi_{FES-TO-LOAD}} = \frac{\overline{\eta}_{PV}}{\eta_{PV}^{DIRECT*}}$$

Analysis of System Performance Parameters



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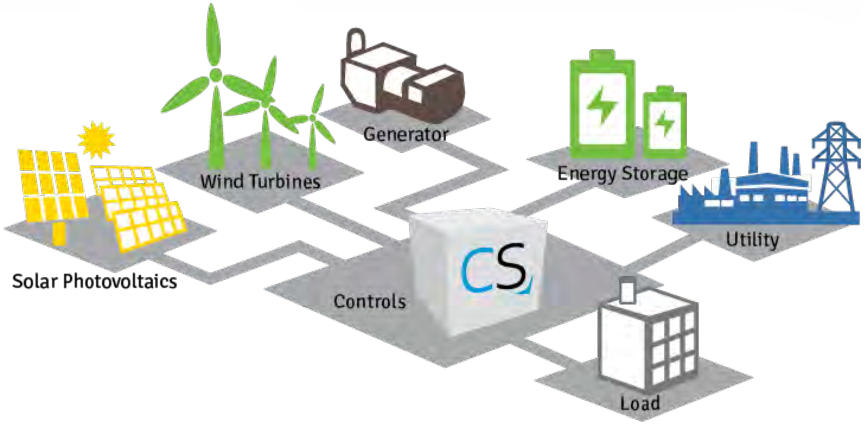
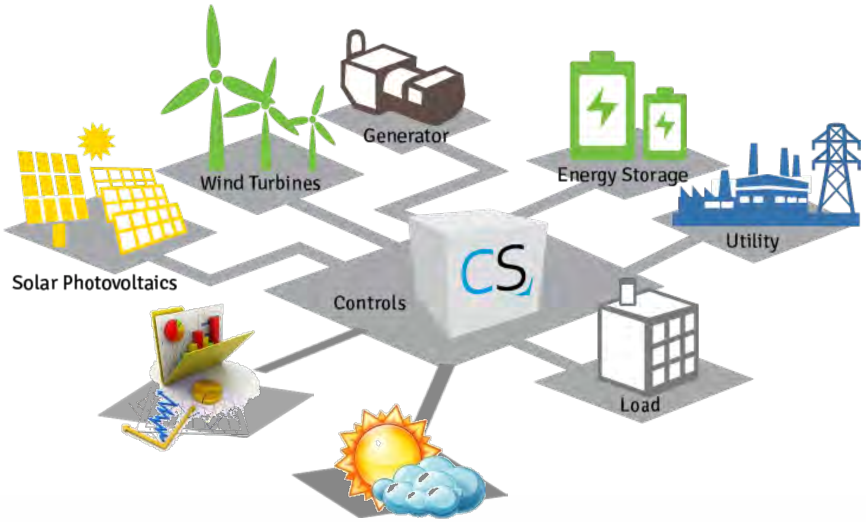
Applications: Connected Microgrids

Standard prosumer (STD)

HRES controlled by RBC strategy

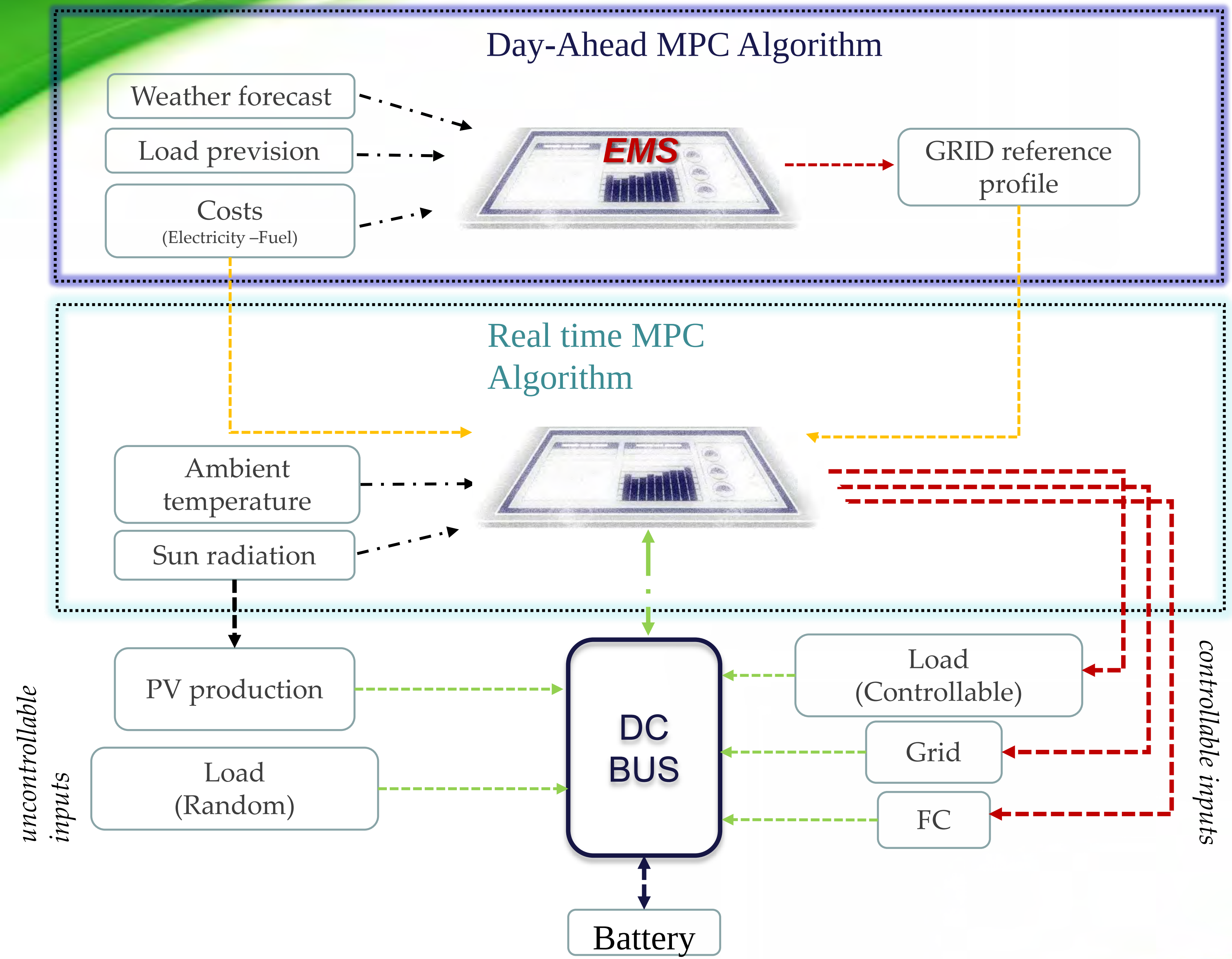


HRES controlled by MPC strategy

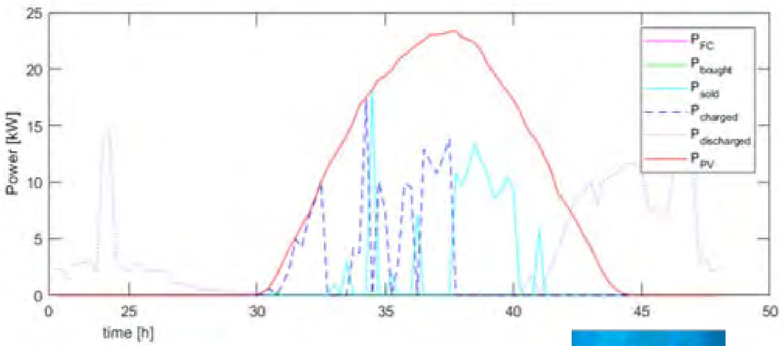


- Same energy consumption over the simulated period;
- Same technical limitations of the sub-system components (Vmin-max battery pack, Pmax exchanged with the grid);
- Same weather conditions.

MPC Control

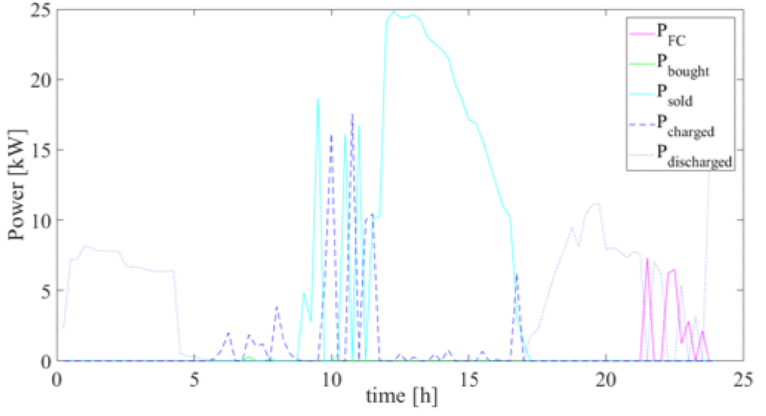


Day-Ahead MPC Algorithm
Weather forecast
Load prevision
Costs
(Electricity –Fuel)
EMS
GRID reference profile
Real time MPC Algorithm
Ambient temperature
Sun radiation
PV production
Load (Random)
uncontrollable inputs
DC BUS
Load (Controllable)
Grid
FC
controllable inputs
Battery



Power [kW]
time [h]
P_FC
P_bought
P_sold
P_charged
P_discharged
P_PV

THURS
29



Power [kW]
time [h]
P_FC
P_bought
P_sold
P_charged
P_discharged

Case study

Residential HPS:

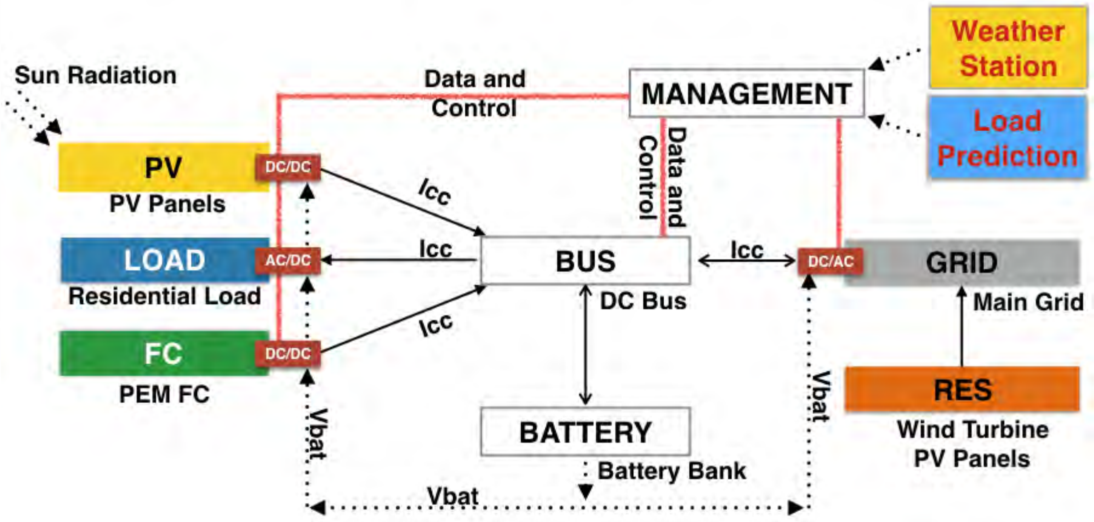
- 8 apartments;
- 2 deferrable loads (per each apartment);
- PV power plant (4.5 kWp);
- Battery Energy Storage System (BESS) 280Ah @ 48V;
- Fuel Cell with rated power 1.2 kW

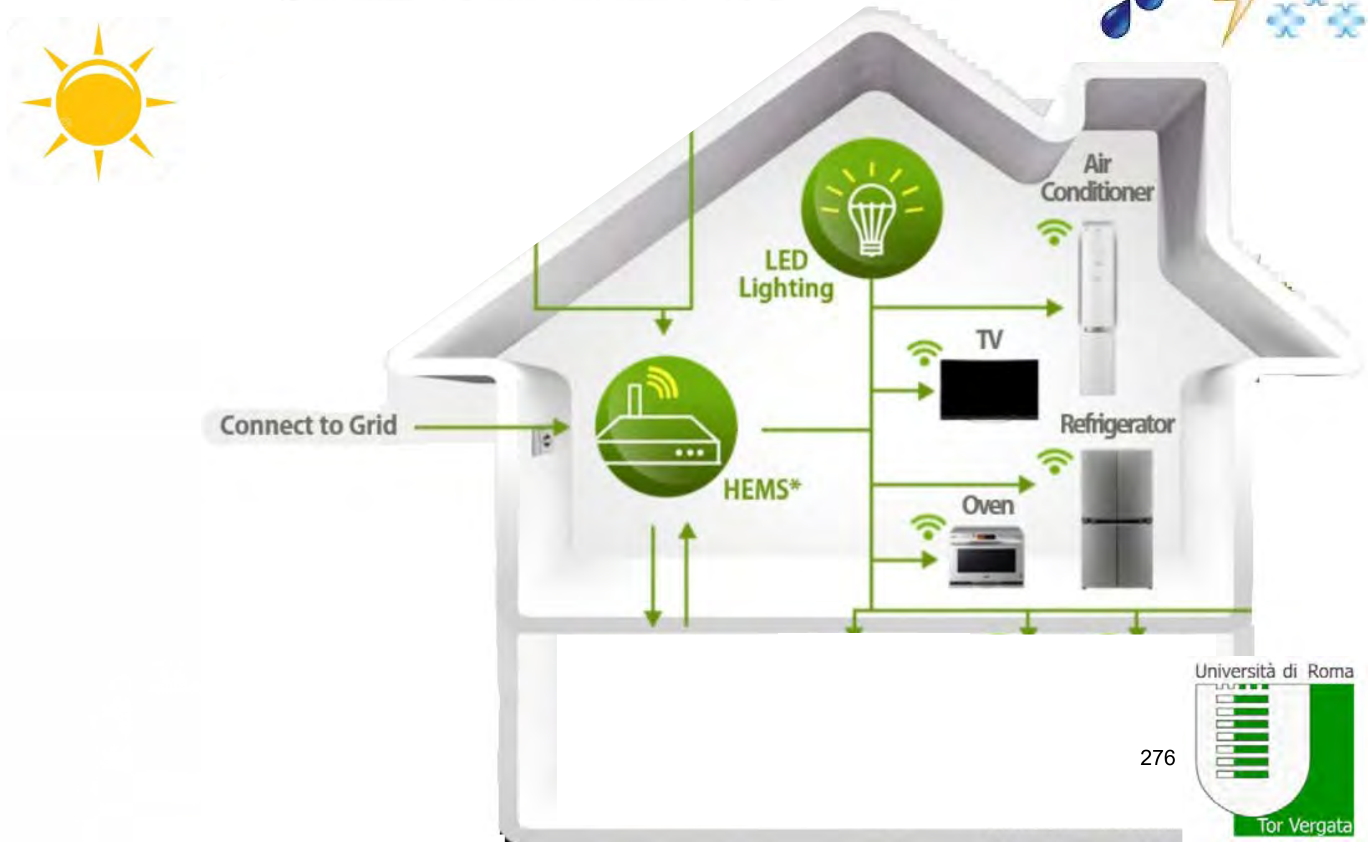
Two characteristic weeks tested (winter and summer)

Effect of load forecasting accuracy on EMS performance.

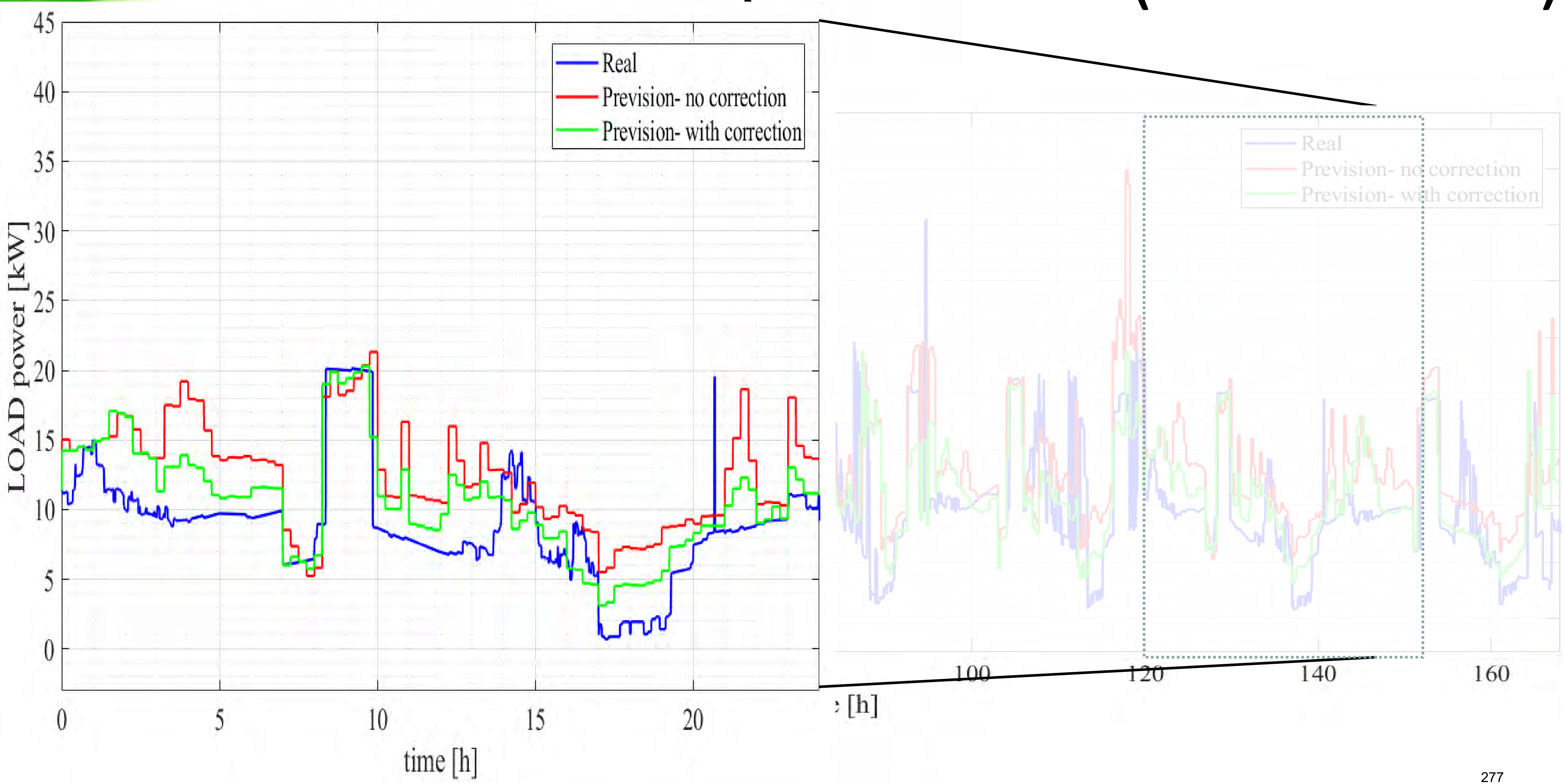
Performance parameters:

- Unbalance energy exchanged with the main grid
- Total operational costs

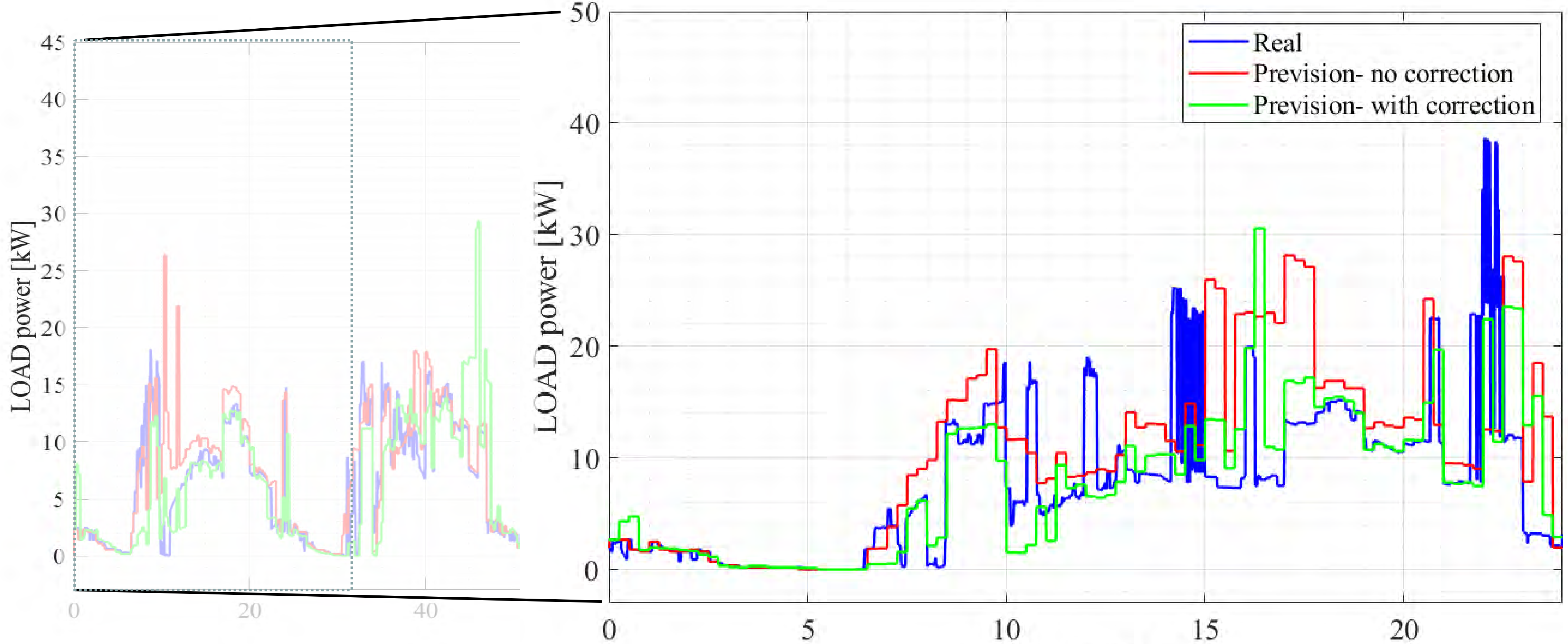




Load forecast improvement (winter case)

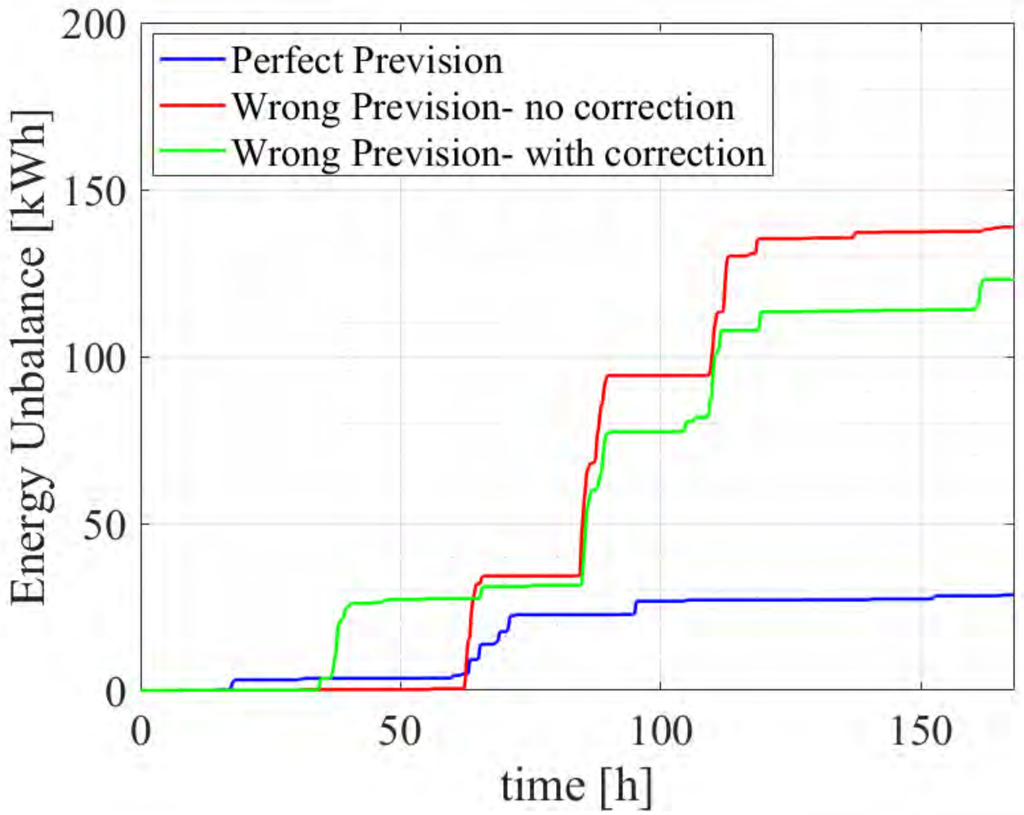


Load forecast improvement (summer case)

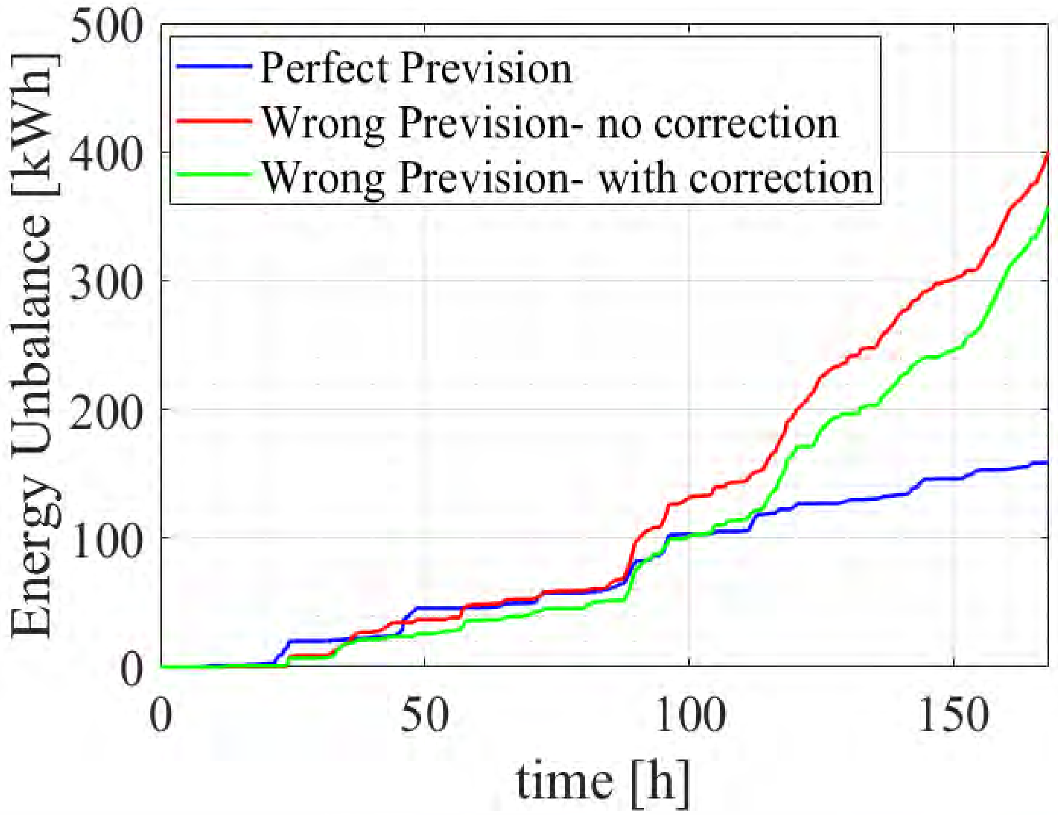


Unbalance energy

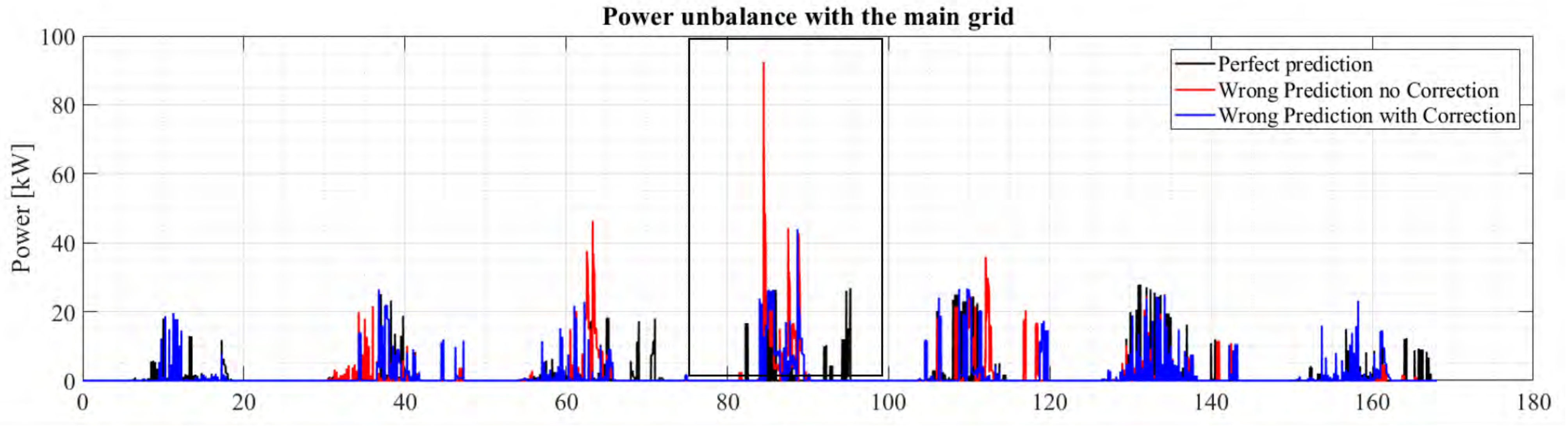
Summer case

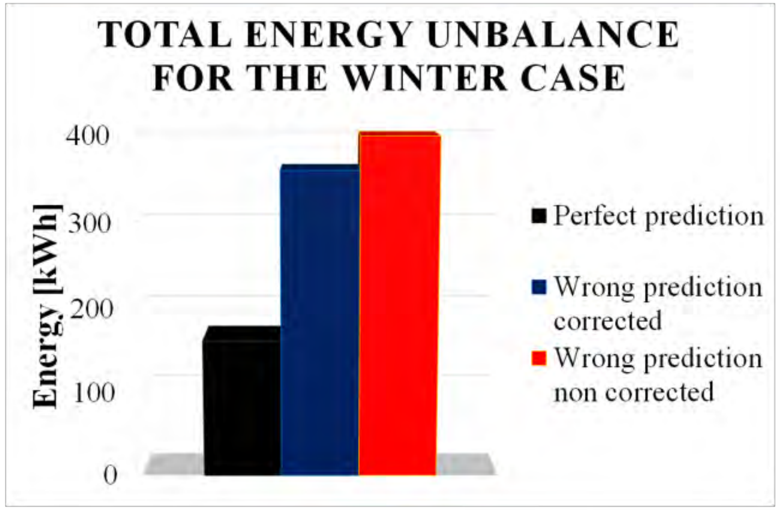


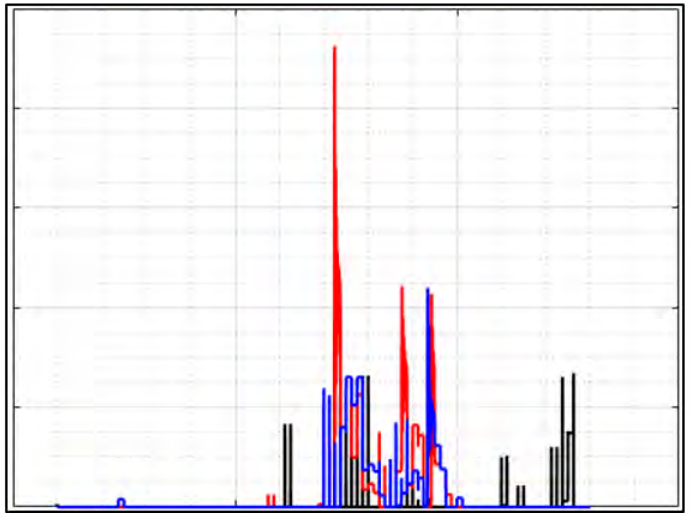
Winter case



Unbalance profiles - winter







Operating costs

Wrong prediction with correction

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Conclusions

- Distributed generation systems may be implemented differently depending on the application

- Control is primarily important to have maximum efficiency, resilience and allow for renewable penetration

- Offgrid renewable microgrids are challenging toward costs and fuel independence

- Grid connected microgrids aim at minimizing unbalance

- MPC based control is valid to implement demand esponse strategy and take decisions based on weather forecast