3DMicroGrid
DESIGN, DEVELOPMENT AND DEMONSTRATION OF A SMART MICRO GRID

Workshop: Design of Smart Microgrids
8th November 2017
Escuela Técnica Superior de Ingeniería, Sala Juan Larrañeta

Microgrid Planning and Operation Part 1

Rodrigo Palma Behnke
Guillermo Jiménez Estévez, Patricio Mendoza, Marcia Montedonico, Lorenzo Reyes, Bernardo Severino, Ignacio Polanco, Felipe Valencia.

CE-FCFM / Universidad de Chile

Claudio Cañizares
With content from Mariano Arriaga, Mostafa Farrokhabadi, Jose Lara, Ehsan Nasr, Daniel Olivares, Mehrdad Pirnia, David Romero, and Bharat Solanki.

Department of Electrical and Computer Engineering
University of Waterloo, Canada

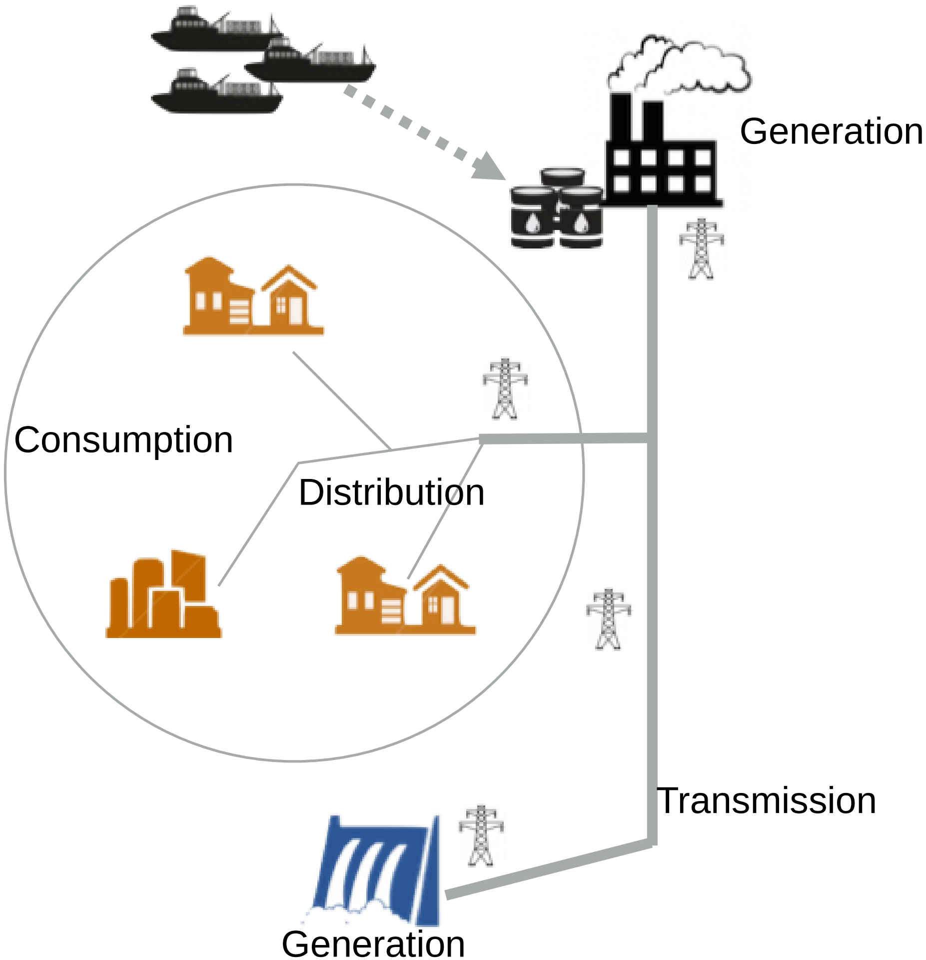
November 8th, 2017

Agenda Part 1

- Introduction
- Co-construction methodology
- Planning tools
- Conclusions and challenges

Introduction

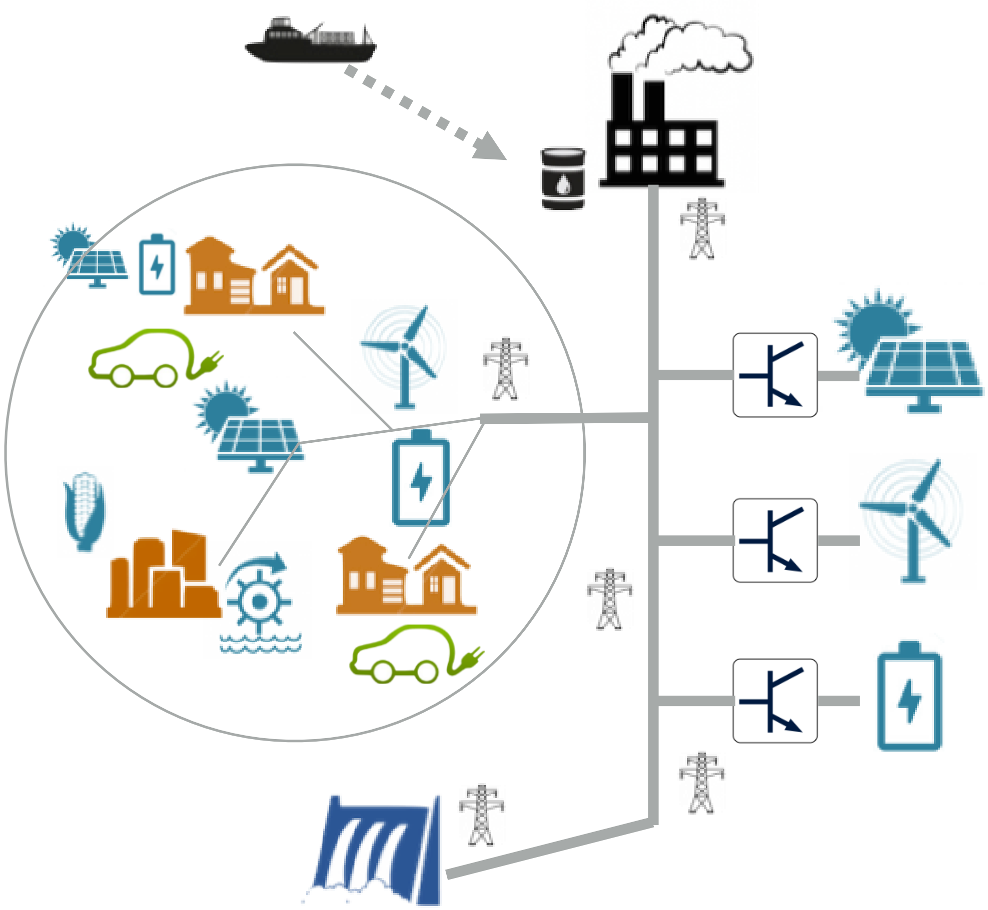
Centralized generation



- Gx —> Tx —> Dx—> Loads
- Climate change
- Energy costs
- Security: high dependency
- Social opposition

Introduction

Distributed Generation
(based on RE)



Advance:

- RE maturity
- Power electronics

Challenge:

- Power system stabiltiy
- System adequacy
- Cost-effectiveness

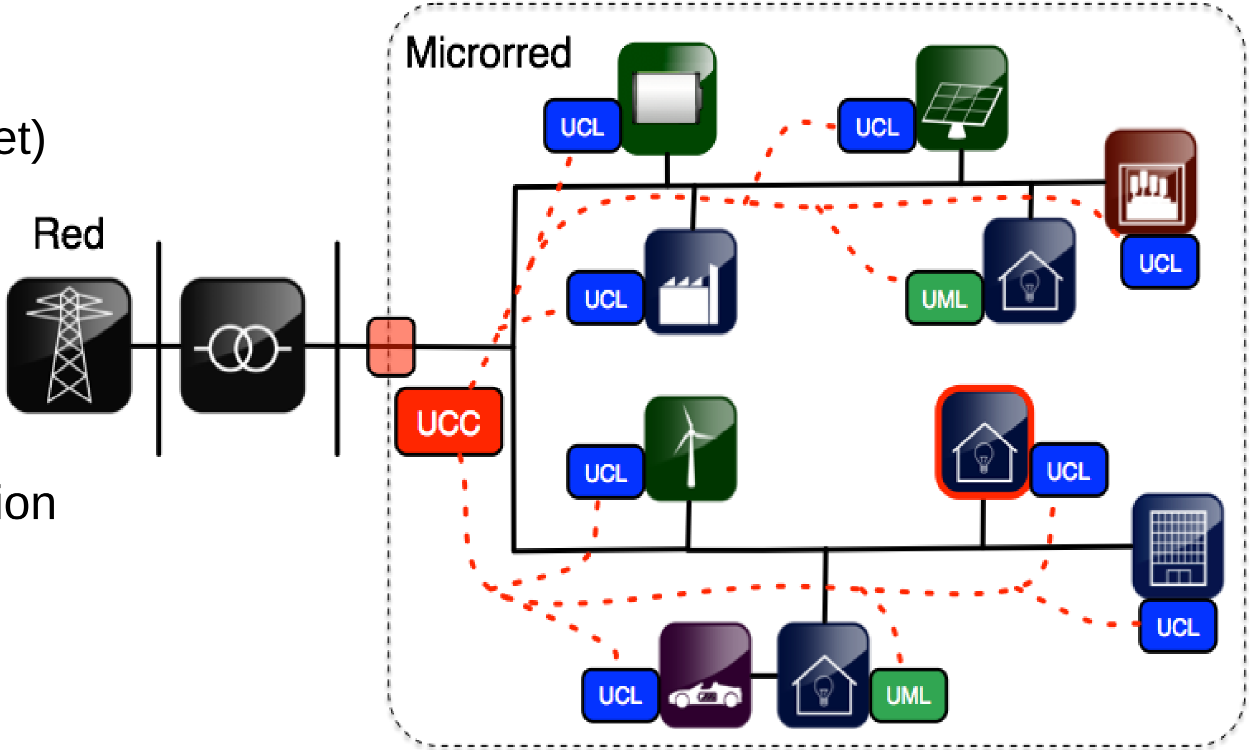
Solution:

Micro-grids

Introduction

Micro-grid concept:

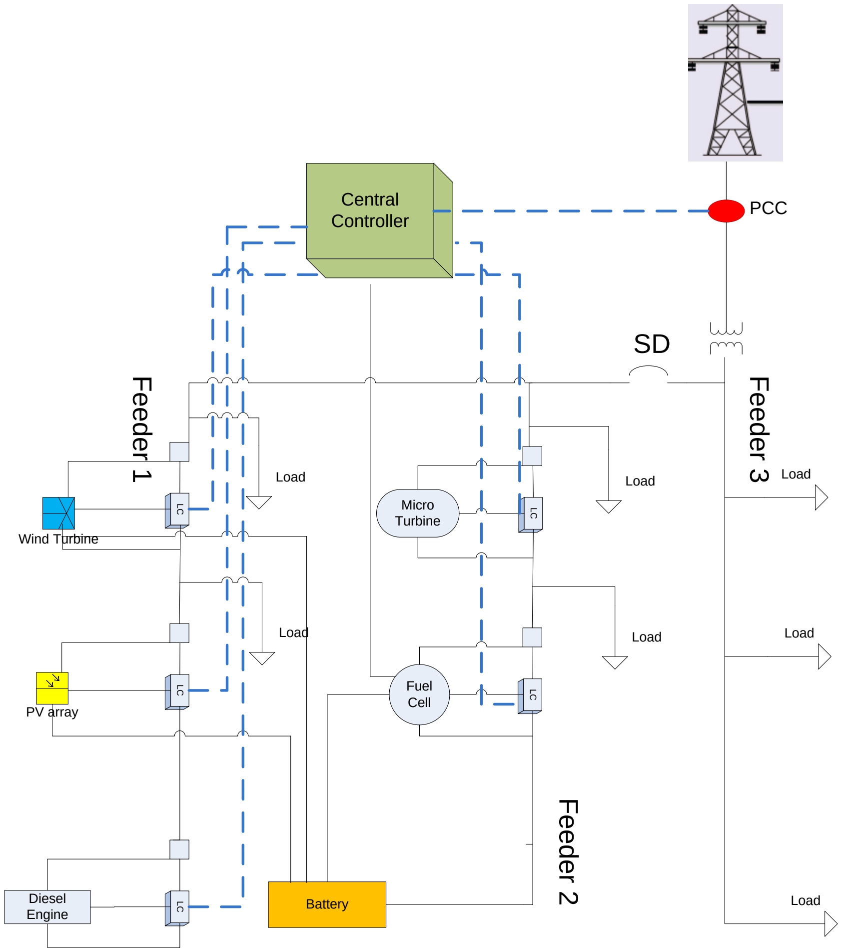
- Distribution network (subset)
- Loads
- DER
  - GD
  - Energy storage systems
  - Controlable loads
- PCC
- Control system: Coordination



Objectives:

- Incorporate local DERs
- Provide controlled power supply profiles
- Power quality and reliability
- Cost-effectiveness

Microgrid



- A “small” grid from some kW to a few MW.
- A “local” grid serving a well-identified, “contained” region.
- Operates at distribution system voltage levels, i.e., medium voltage (a few kV).
- Contains “various” DG units and possibly some energy storage.
- Has enough capacity to supply all or at least most of the loads of the local grid.
- Grid connected: has one well-identifiable point of connection to the transmission system or “rest” of the distribution grid (Point of Common Coupling or PCC).
- Isolated (islanded): operates independently of the “large” grid.

Introduction

Holbox Island,
Design
Yucatan, MX

Puertecitos,
Operative
Baja California, MX

Puerto Alcatraz, San Juanico
Operative
Baja California, MX

Esmeraldas
Operative
Esmeraldas, EC

Ayllu grids
Design
Arica, CH

Huatacondo
Operative
Tarapacá, CH

Ollagüe
Operative
Antofagasta, CH

Easter Island
Feasability
Easter Island, CH

Juan Fernández
Design stage
J. Fernández, CH

J. Painecura Hueñalihuen
Feasibility
Araucanía, Chile

Micro-red UPB
Implementation
Medellín, CO

Lencóis island
Operative
Maranhao, BR

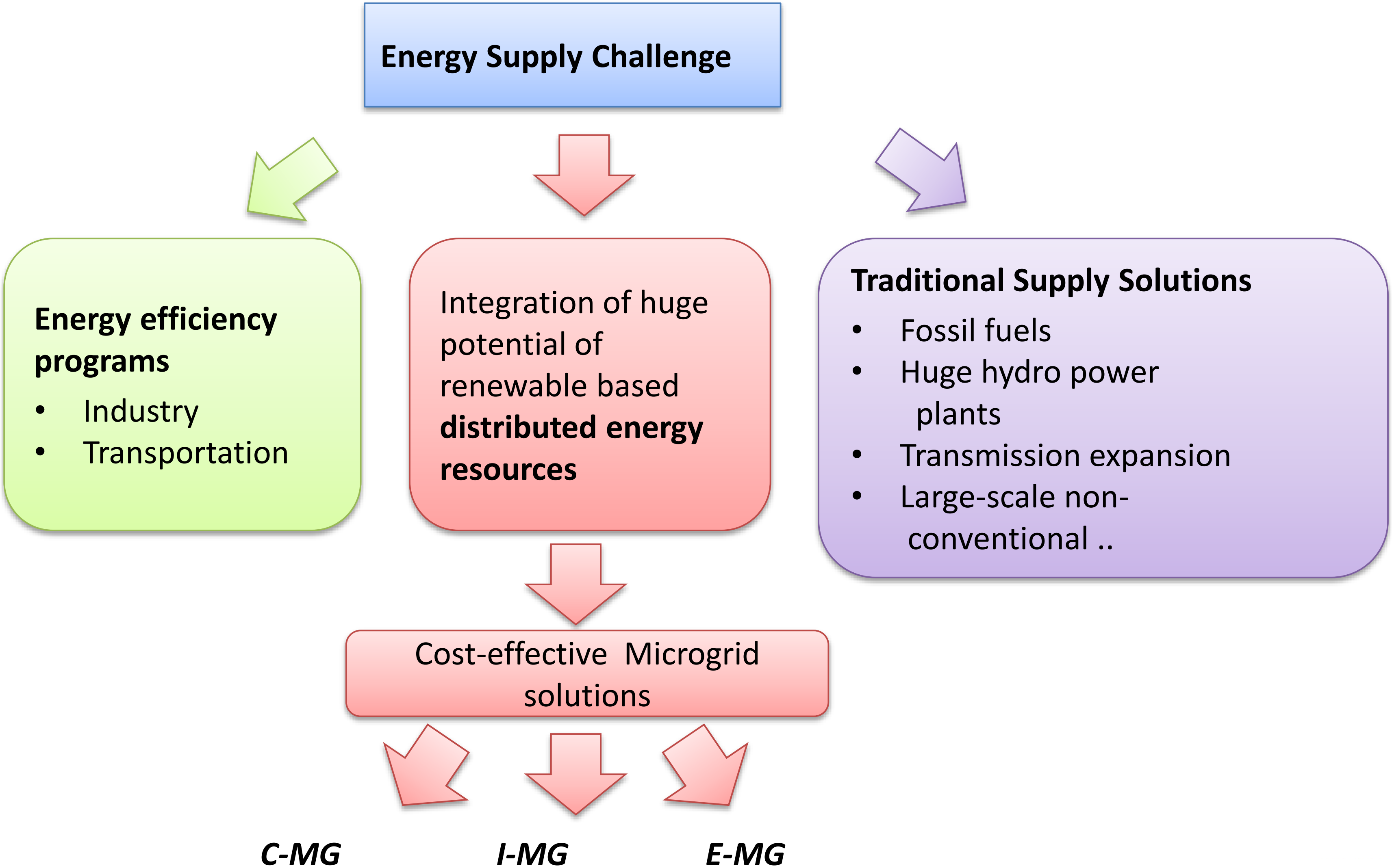
Cemig Grid
Pilot application
Belo Horizonte, BR

Trinidad Island
Feasibility
Rio State, BR

Islas Desertores
Under execution
Chiloé, CH

El Toqui
Operative
Aysén, CH

Introduction

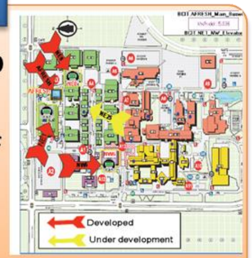


Introduction

C-SPMG (Coordinated integration of distributed renewable resources to the interconnected power grid)

Incorporating distributed generation power injections to grid

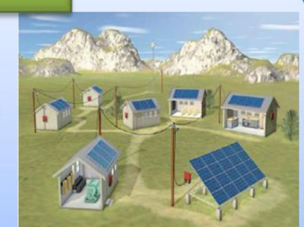
- Coordination platform for a strong control and monitoring of SPMGs
- Virtual Power Plant



I-SPMG (Electrification of remote villages with abundant local renewable energy resource)

SPMG operating in islanding way

- Must be able to integrate and coordinate several energy sources with appropriate load-frequency strategies
- Active participation of the local community

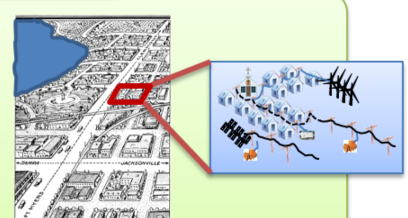


Source: Denda, Shimizu Corpotation

E-SPMG (Development of critical infrastructure power systems)

Emergency systems

- Locations prone to face natural disasters such as earthquakes, tsunamis, storms, floods.
- It is applicable both for islanding and interconnected application where the energy supply for a sector of the system must be continuous for a wide range of contingencies



Microgrids opportunities

Remote locations are a main microgrid development opportunity

Remote (off-grid) microgrids are best hope for developing world, according to the United Nations

- Part of the solution for climate change and ending energy poverty

Physical islands most attractive remote opportunity today

- High fuel costs and supply vulnerability
- Single negotiating party entity for larger scale systems

Source: Navigant

Microgrids opportunities

Remote locations are the main microgrid development opportunity

Technology Drivers

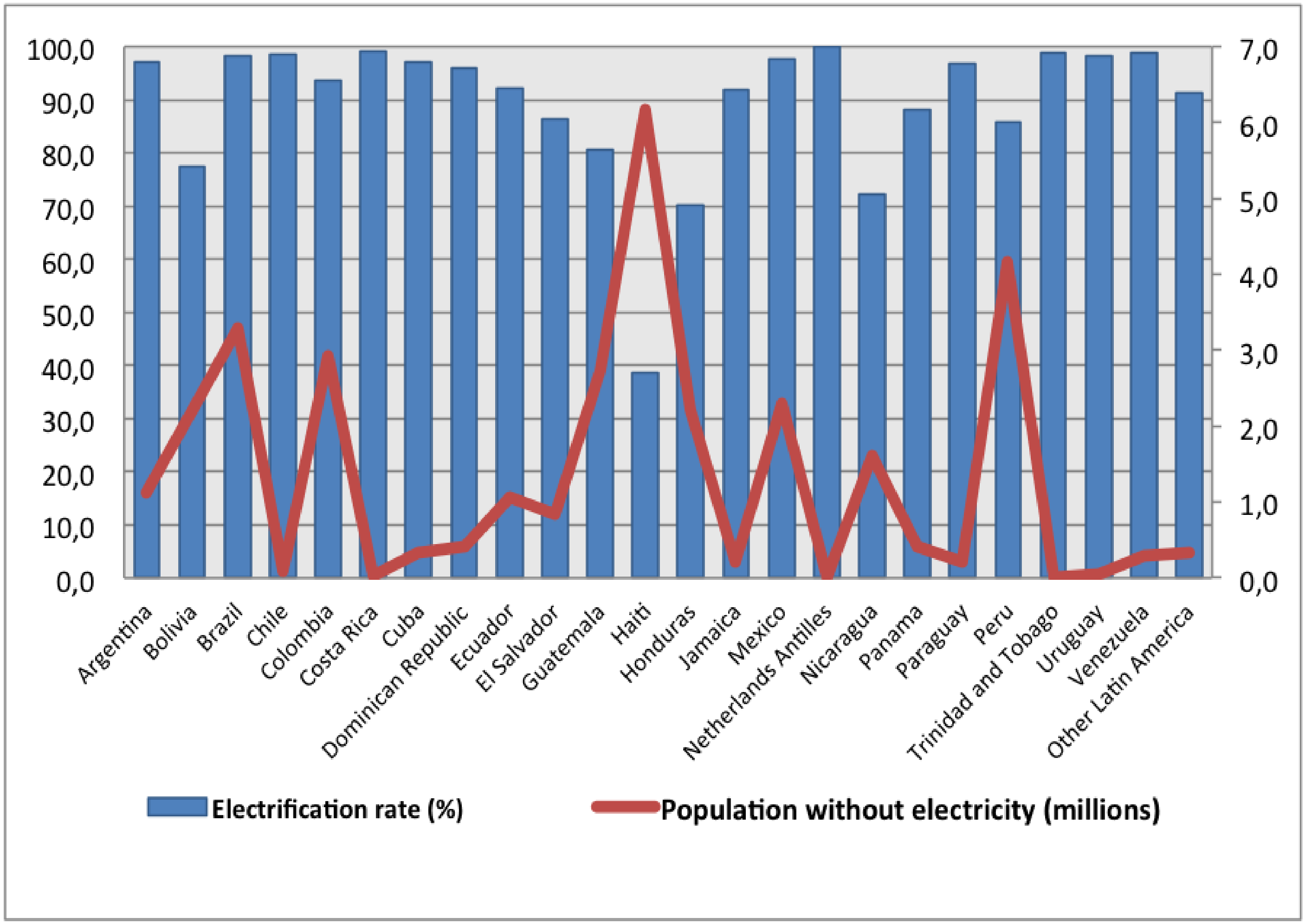
- Declining cost of solar PV
- High cost of diesel ?!
- Three primary segments
  - Commodity extraction systems, *El Toqui mining facili*ty
  - Physical islands, *Easter island*
  - Village electrification, *Huatacondo*

Source: Navigant

Introduction

Electricity Coverage in Latin America

Electricity coverage



Agenda

- Introduction
- Co-construction methodology
- Planning tools
- Conclusions and challenges

Methodology

CHALLENGE

How to develop **energy projects** that foster the use of **renewable energies** and achieve **improvements in the livelihoods of a community** in a lasting manner?

OBJECTIVE

To develop energy solutions where **communities appropriate themselves of the technologies** and manage to establish **resilient socio-technical systems**, in the context of successful energy transitions.

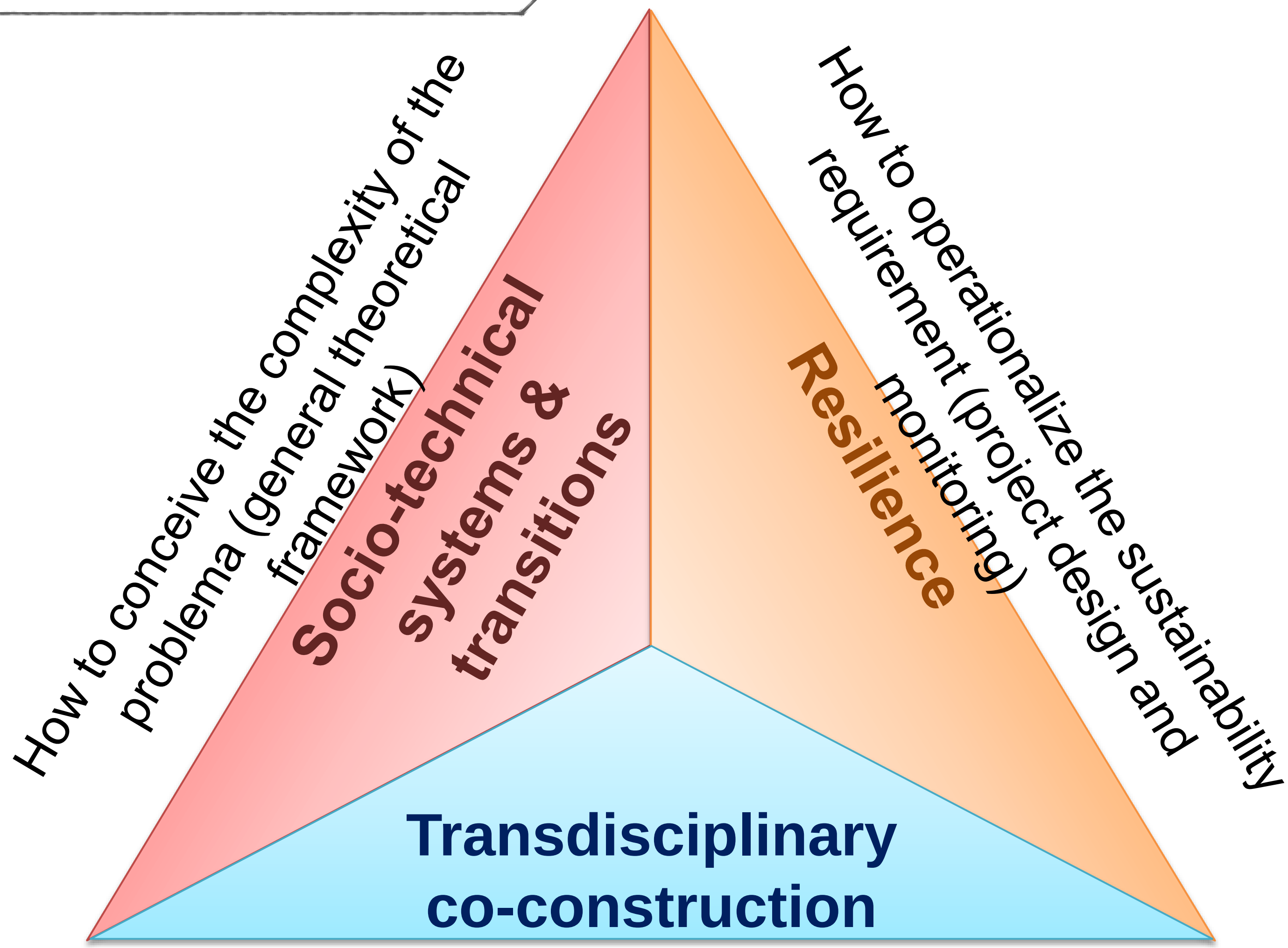
SOCIO-ENVIRONMENTAL AREA

A multi-disciplinary area: agronomist, anthropologist, sociologist, natural resources engineer

Socio-technical systems: Specific organizational systems built around a technological innovation, whose social structures are made of decisions (Luhmann, 2000).

Inter-relation between technology, social actors, and the social structures that develop around their operation (Ropohl, 1999; Ulli-Beer, 2013).

Methodology



How to engage the communities and incorporate the local knowledge (methodology)

Methodology

Co-construction scheme

(Open-framework for microgrid development)

Stage 1
- **SOCIO-TECHNICAL DIAGNOSTICS AND TEAM BUIDING**

Stage 2
- **SOCIO-TECHNICAL DESIGN AND SUSTAINABILITY PLAN**

Stage 3
- **IMPLEMENTATION AND FIRST IMPRESSION**

Stage 4
- **OPERATION, EVALUATION AND DISSEMINATION**

Methodology

Stage 1

- **SOCIO-TECHNICAL DIAGNOSTICS AND TEAM BUIDING**

- Define technical-structural borders (co-construction scope)
- Represent diversity and local leadership
- Share principles of transdisciplinarity

Stage 2

- **SOCIO-TECHNICAL DESIGN AND SUSTAINABILITY PLAN**

- Train participants for informed decision making and acknowledge local knowledge
- Jointly define technical and organizational characteristics
- Development a sustainability plan and resilience indicators

Stage 3

- **IMPLEMENTATION AND FIRST IMPRESSION**

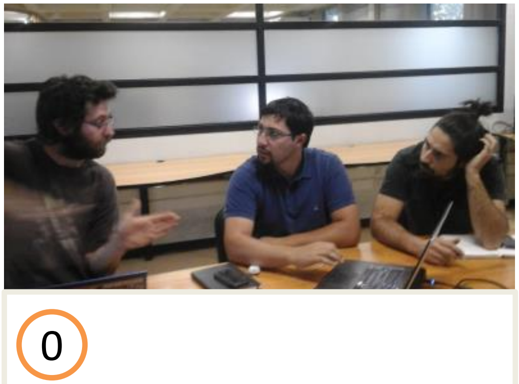
- Implement project with the active participation of the community
- Register first impressions and feedbacks

Stage 4

- **OPERATION, EVALUATION AND DISSEMINATION**

- Follow-up and monitoring
- Develop strategies to tackle weaknesses
- Project dissemination

Methodology: Stage 1



Team Formation

Gathering information

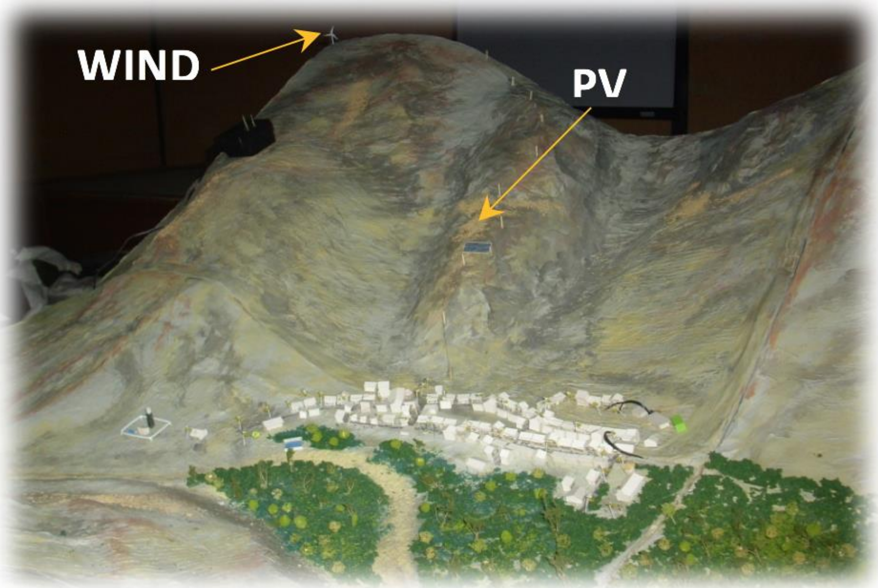
Training / preliminary discussion of alternatives

Training / preliminary discussion of alternatives

Discussion of alternatives

Presentation and discussion of preliminary results

Methodology: Stage 1

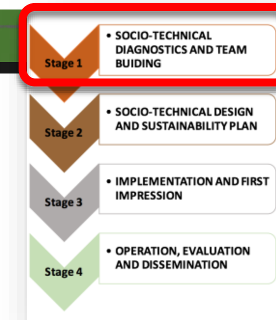


Boundary objects and meetings

Methodology: Stage 1

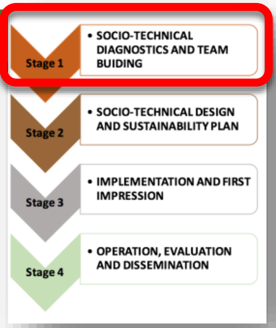
Boundary objects: Scale model of the island.

Methodology: Stage 1



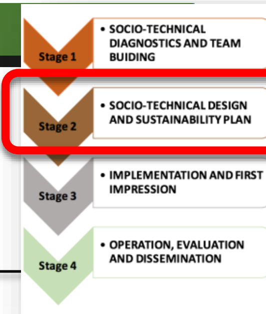
Boundary objects in the Eastern Island.

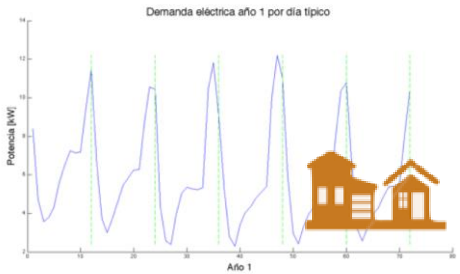
Methodology: Stage 1

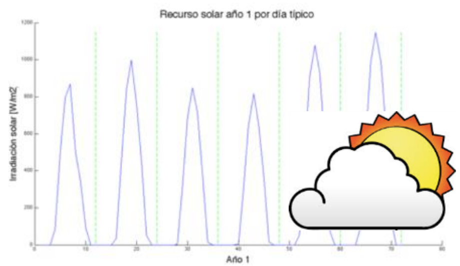


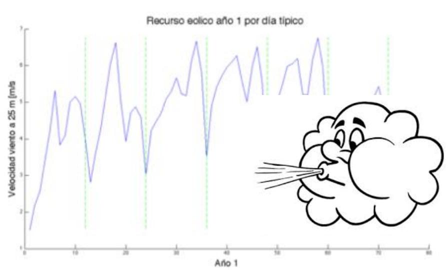
Boundary objects in the Eastern Island.

Methodology: Stage 1









Technology cost

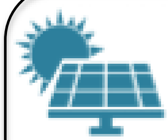
Optimun design tool

$$\min_{\{E_0,\ I_m,\ P_{m,a,d,h}\}} VAC_P + VAC_W + VAC_B + VAC_G$$

Límites de potencia por unidad	$0 \le P_{m,a,d,h} \le I_m \quad m = \{P, W, G\}$ $P_{Bmin} \le P_{B,a,d,h} \le P_{Bmax}$
Límite de energía en las Baterías	$SoC_{min} \cdot E_{max} \le E_{B,a,d,h} \le E_{max}$ $SoC_{min} \cdot E_{max} \le E_{B,0} \le E_{max}$
Suministrar potencia Dda	$P_{D,a,d,h} = \sum_{m=\{P,W,G,B\}} P_{m,a,d,h} \quad \forall a,d,h$
Potencia aerogenerador	$P_{W,a,d,h} = F\left(W_{a,d,h} \cdot \left(\frac{aT}{aD}\right)^k\right)$
Potencia planta fotovoltaica	$P_{P,a,d,h} = cP \cdot G_{a,d,h}$
Ciclo energético bat. nulo	$\sum_{h=1}^{NH} E_{B,a,d,h} = 0 \quad \forall a,d$

Modelo Baterías

$$E_{BMAX} = H_{nom} \cdot I_B$$
$$P_{BMAX} = k_{des} \cdot I_B$$
$$P_{BMIN} = k_{car} \cdot I_B$$
$$E_{B,a,d,h} = E_{B,a,d,h-1} - P_{B,a,d,h} \cdot nB$$



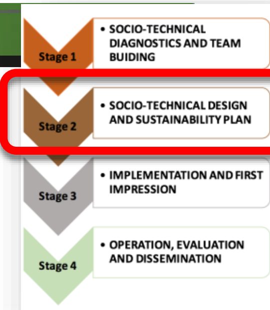
PV
50kW

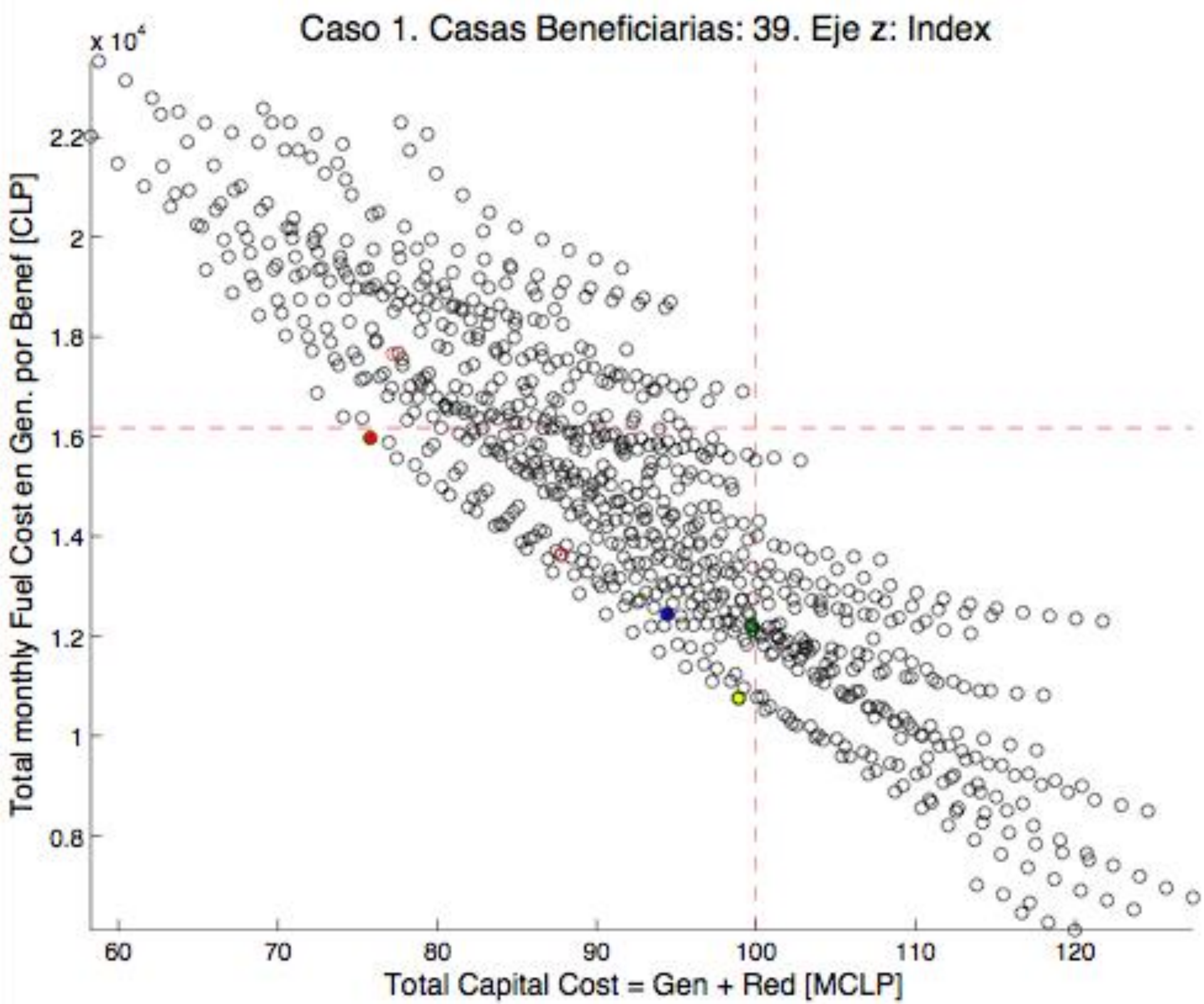
Storage
300kWh

Diesel
70kW

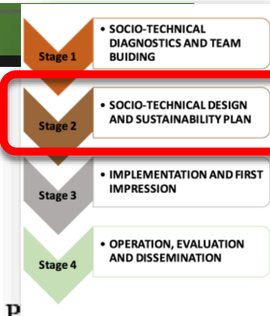
Wind
30kW

Methodology: Stage 2





Methodology: Stage 2



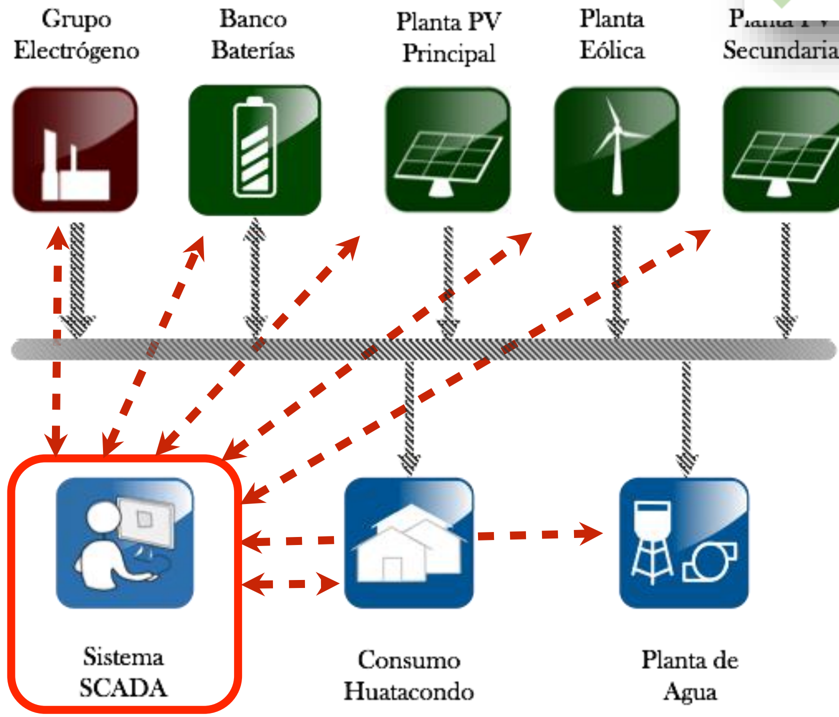
Huatacondo

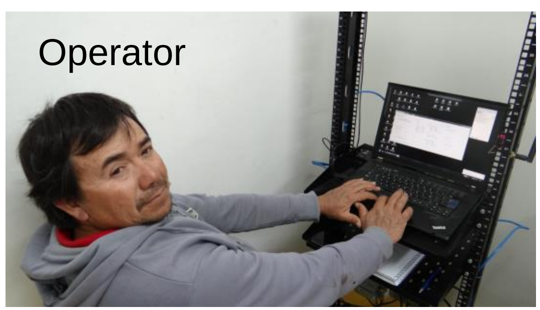
Isolated community- 30 families

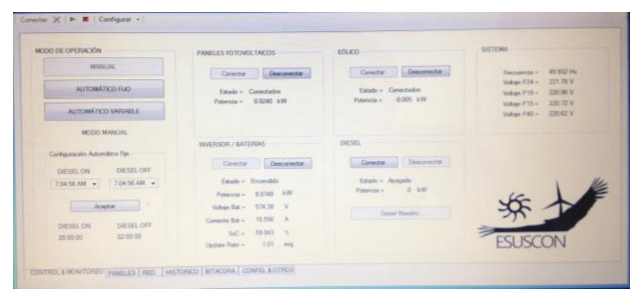
Nov 2009 - Begining

Sep 2010 - Launching

2011 - 2015 - O&M

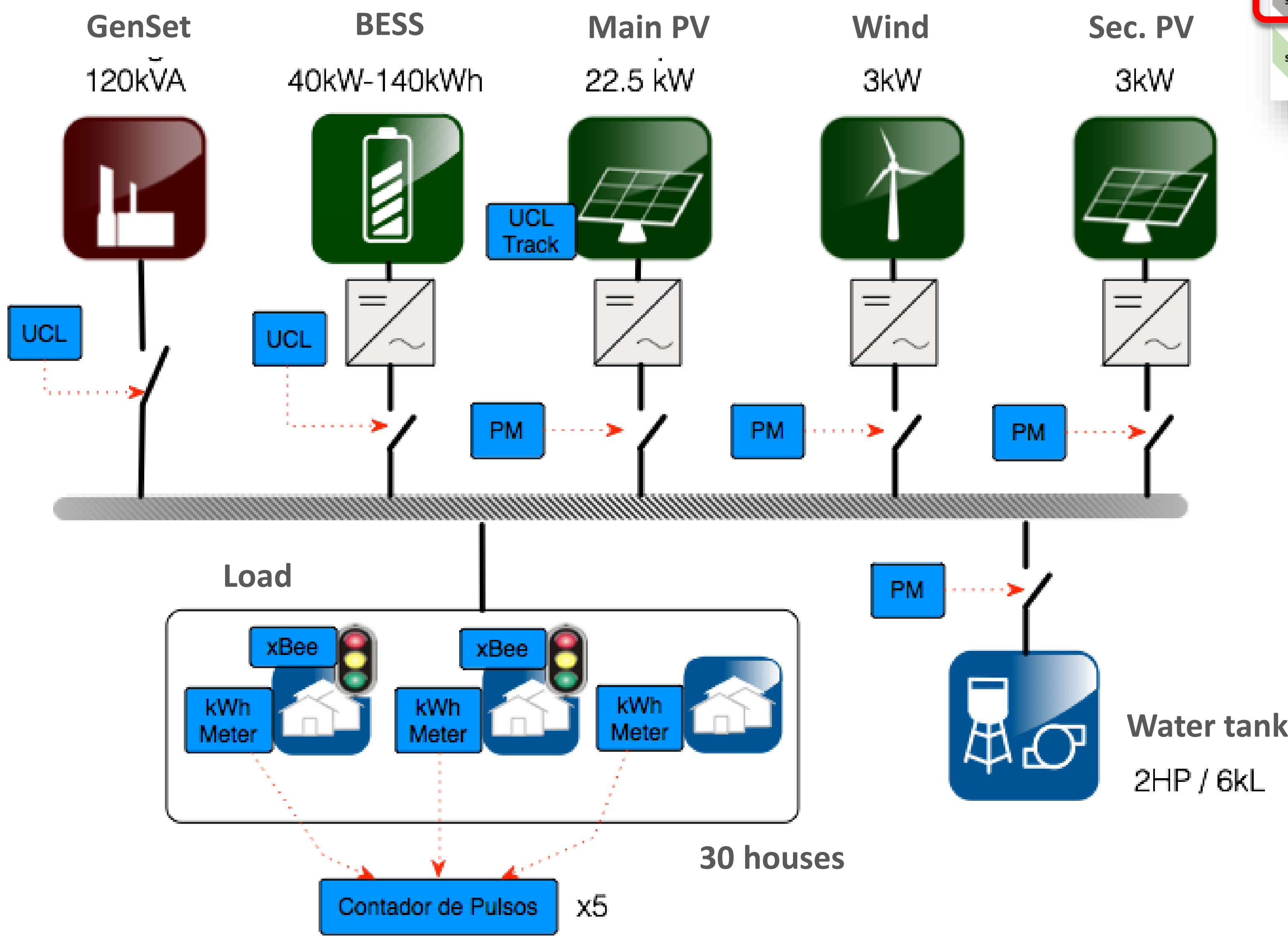




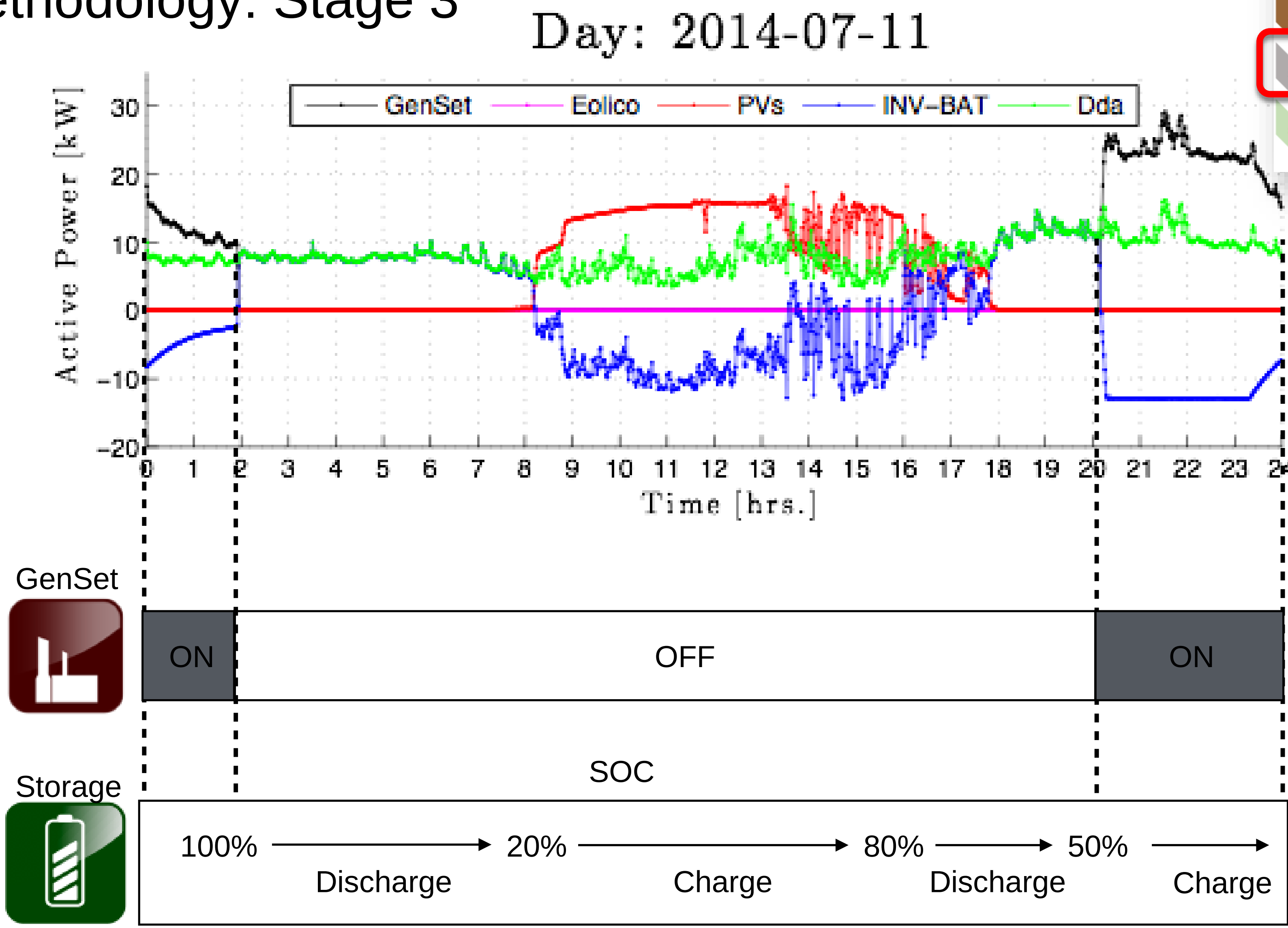


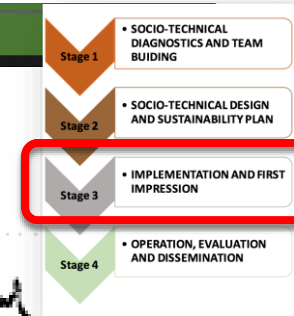
Methodology: Stage 3

Power diagram

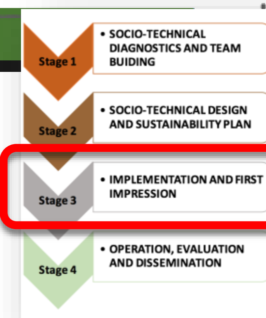


Methodology: Stage 3



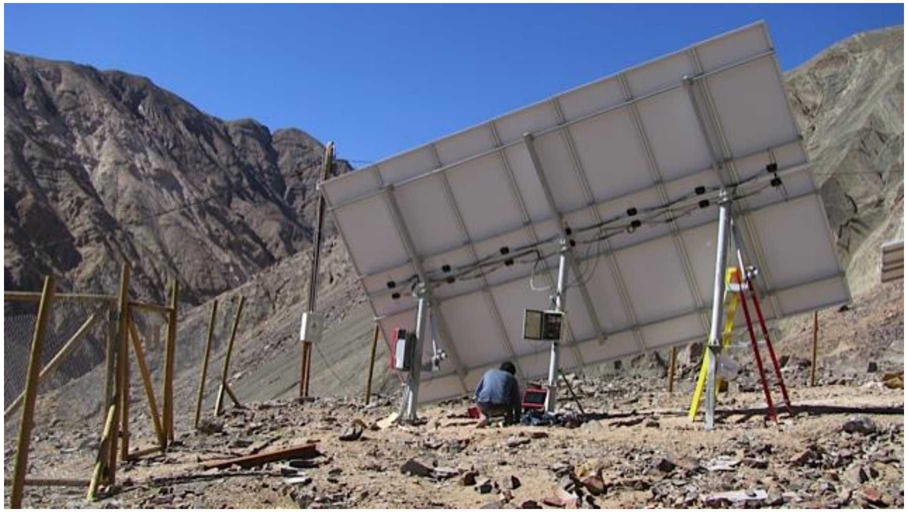


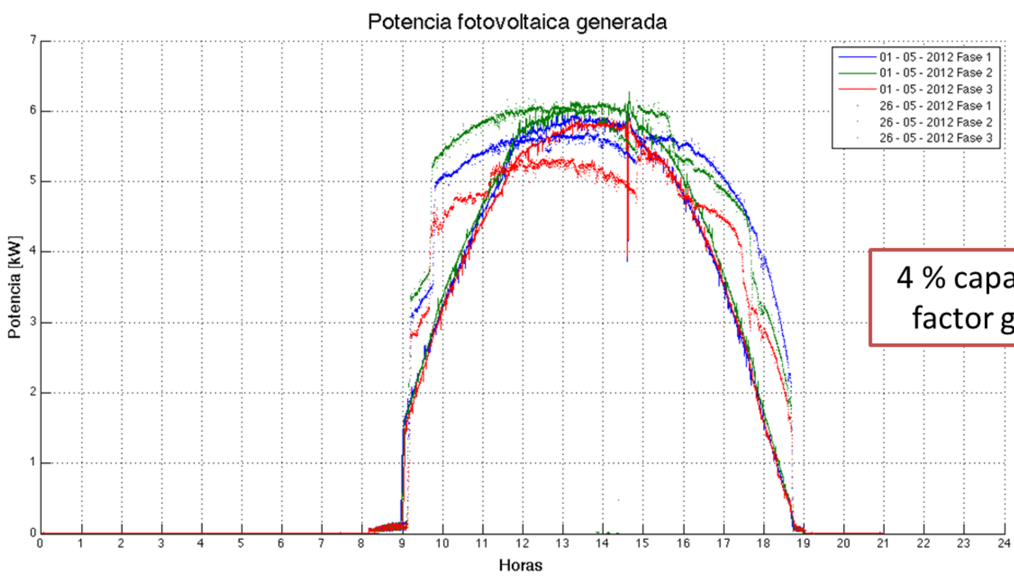
Methodology: Stage 3



PV tracking system

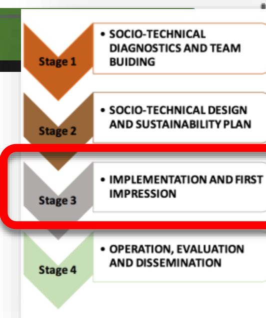
- 2 linear actuators
- No sensors
- Centralized control
- Position feedback
- Intelligent relay local control
- Mechanical constraints considered on EMS





4 % capacity factor gain

Methodology: Stage 3

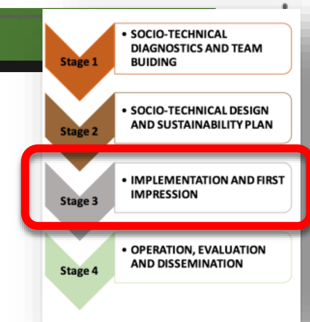


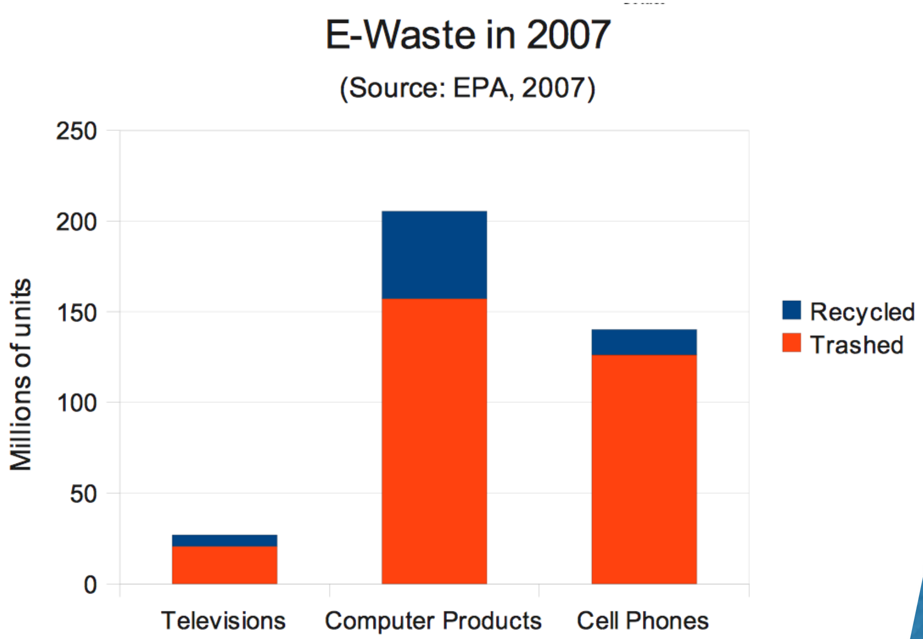
Adjustments

Wind unit protection.

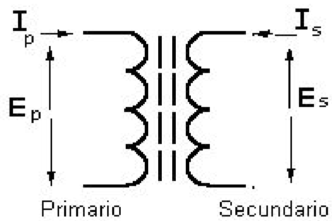
Methodology: Stage 3

Micro-formers



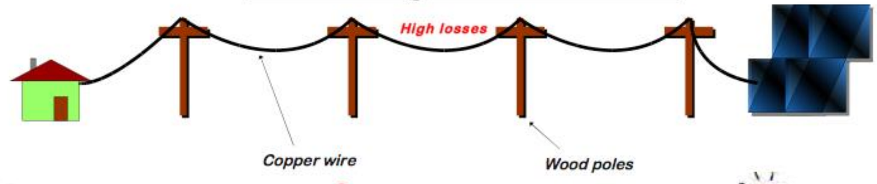


Methodology: Stage 3



Micro-formers

Low voltage transmission

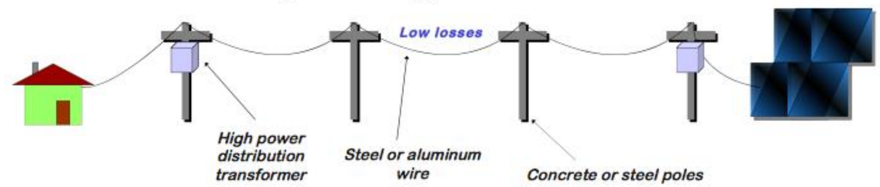


Pros
- Easy to build
- No transformers needed
- Consumers and producers easily connected

Cons
- Expensive, thick copper wire
- High distribution losses, low efficiency
- 100 meter range

Quality:
Cost:
Efficiency:

High voltage transmission

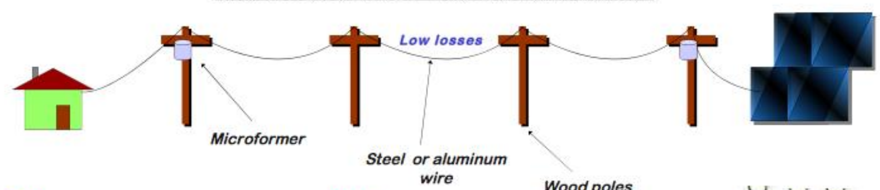


Pros
- Low distribution losses, high efficiency
- Thin wire
- High power capacity (typical)
- 10 to 100 km range

Cons
- Expensive, bulky transformers
- Expensive poles
- Added complexity in connecting consumers and producers

Quality:
Cost:
Efficiency:

Microformer transmission



Pros
- Easy, low-cost construction
- Consumers and producers easily connected
- Low system losses, average to high efficiency

Cons
- Modest amounts of power
- 1 to 5 km range

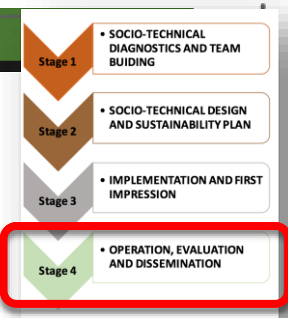
Quality:
Cost:
Efficiency:

Methodology: Stage 4

- Sustainability indicators
- Energy rates / payment!
- Operation and Maintenance
- Local Management Structure
- Communications channels

Methodology: Stage 4

Social SCADA

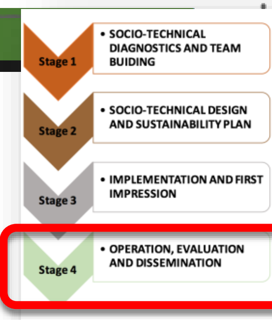


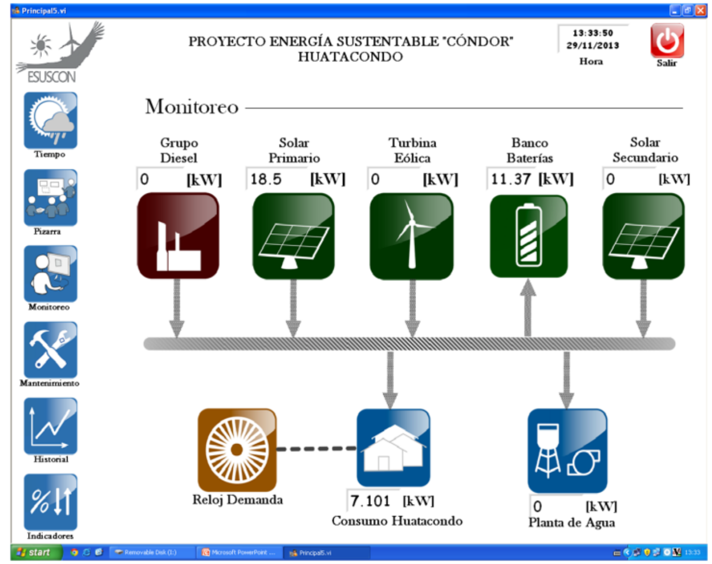
Social SCADA

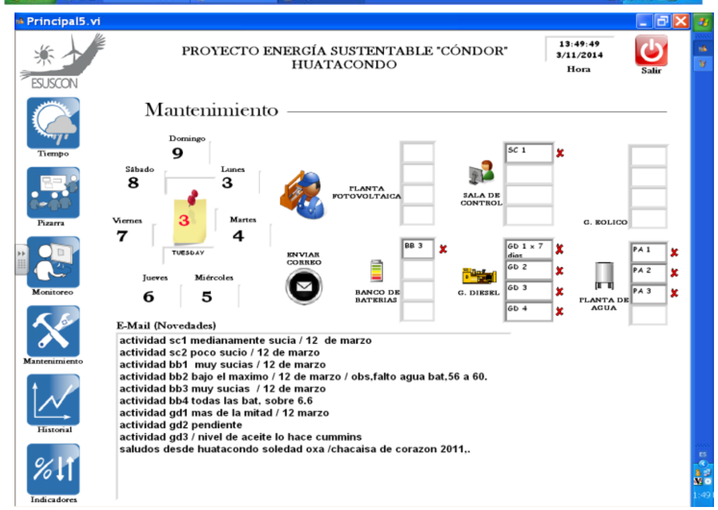
- Interface Design
- EMS Communication
- Design of Indicators

Methodology: Stage 4

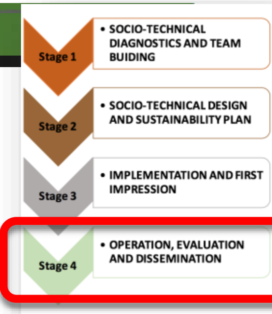
Social SCADA

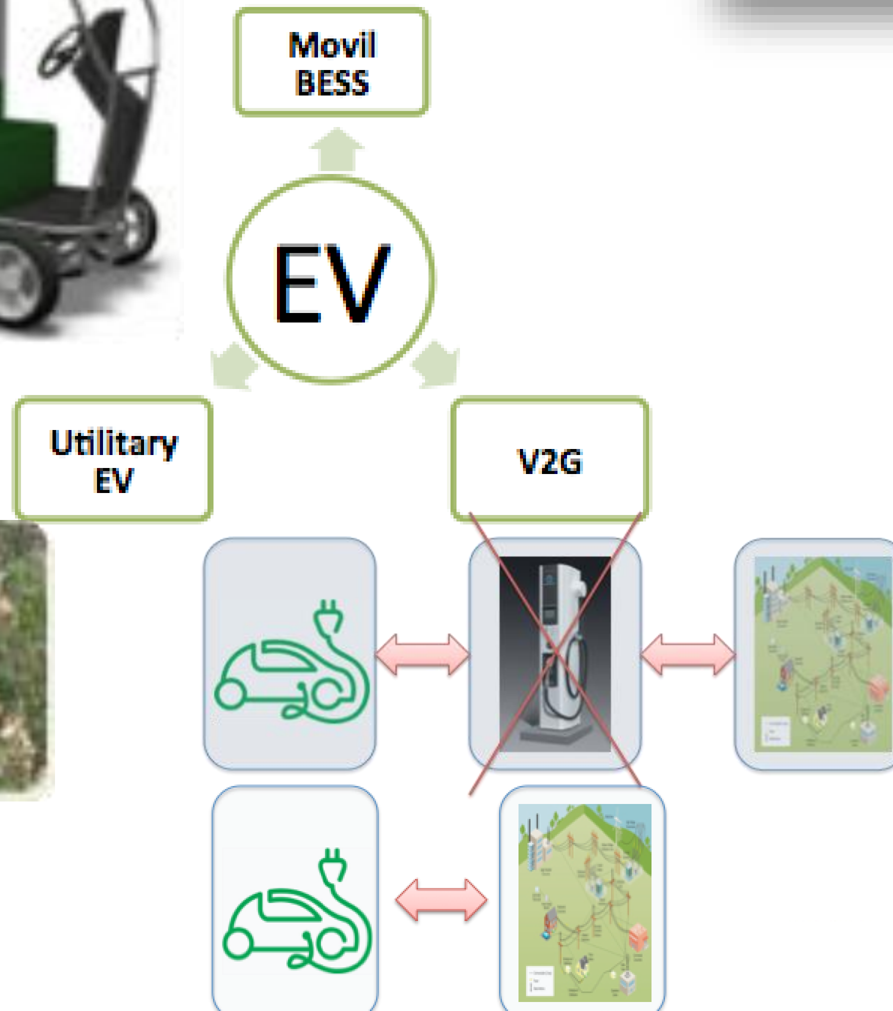




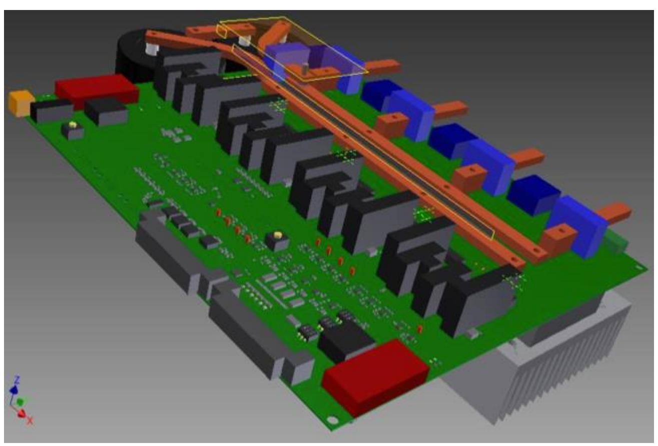


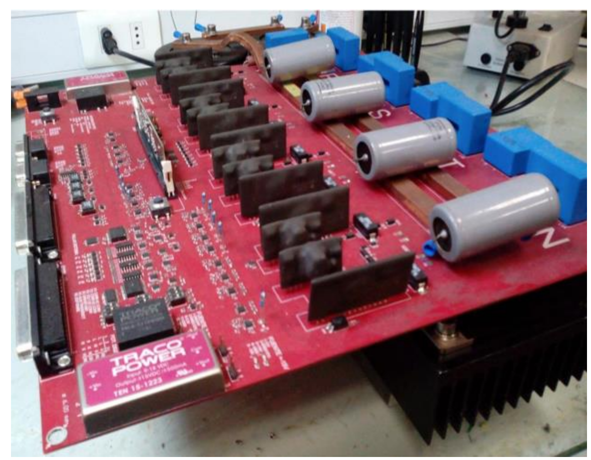
Methodology: Stage 4





Methodology: Stage 4





Methodology: Remarks

	Traditional approach	Co-construction
Design	Developed by the technical team	Developed jointly between the technical team and the community
Operation and maintenance	Dependent on external technical support	Installation of technical capacities in the community to allow the inhabitants of the territory to operate and maintain the project
Management of the technological application	Defined under technical criteria, externalized or not considered	Developed jointly with the community, based and giving relevance to the local reality
Beneficiaries role	The communities are usually passive receivers	The community plays an active role and participates of the fundamental decisions that define the project

Agenda

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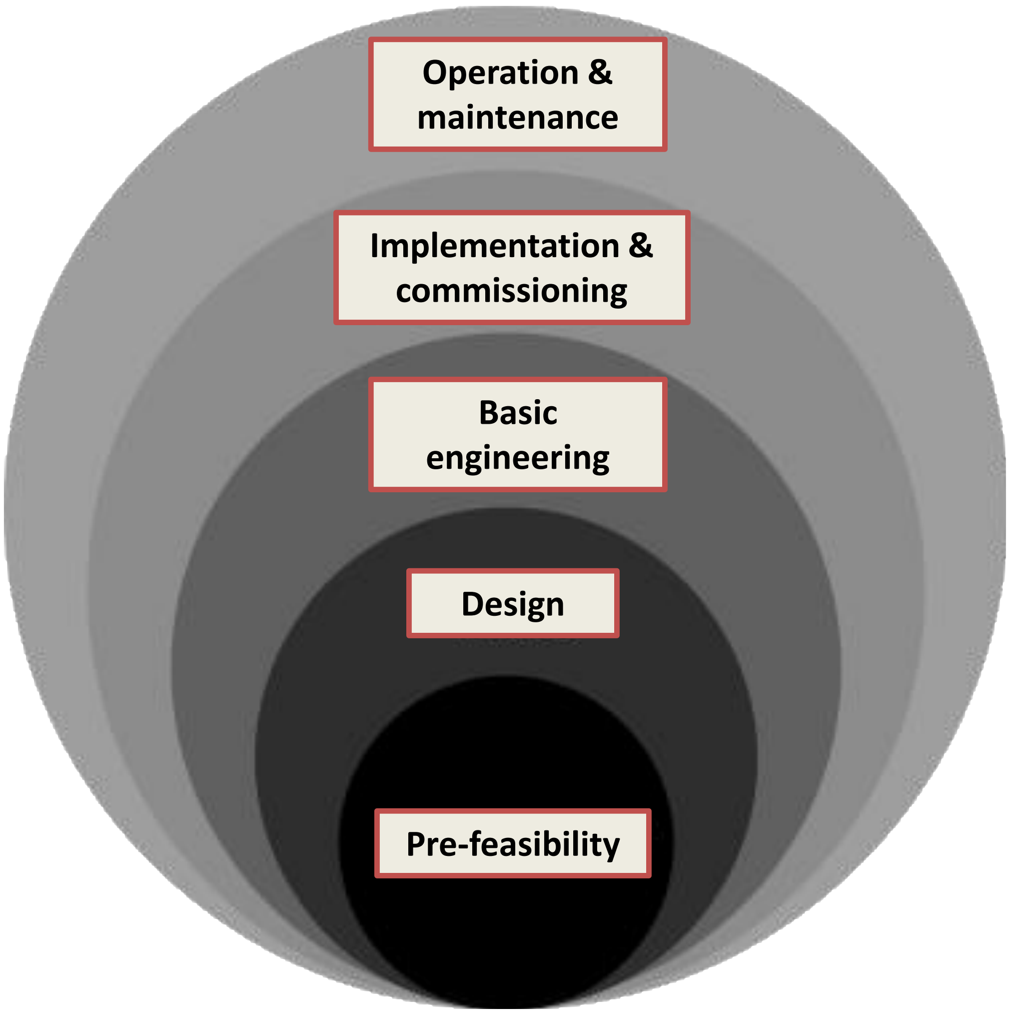
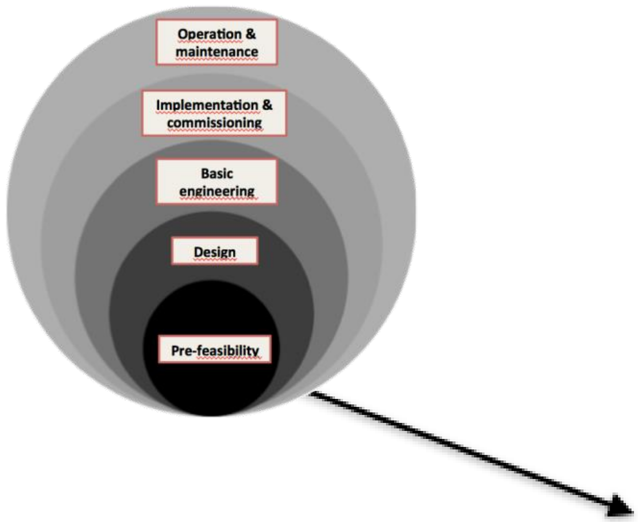
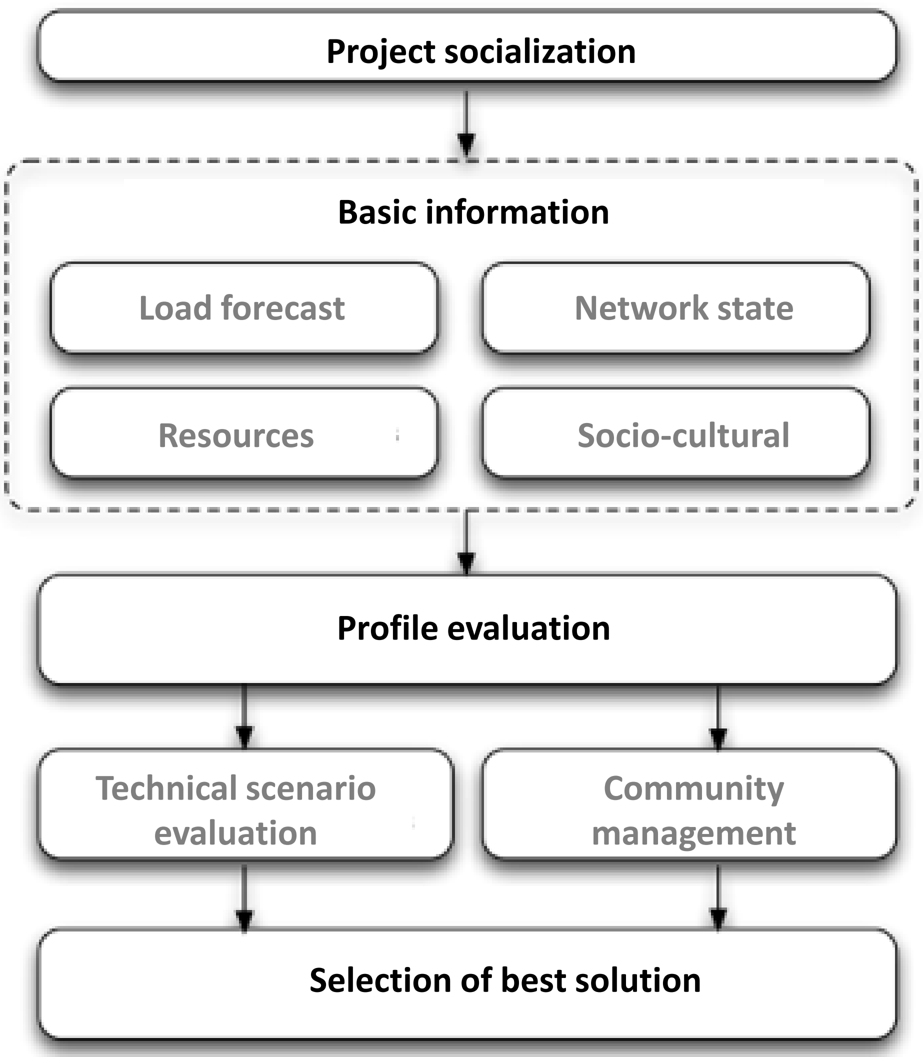
Planning Tools: Approach

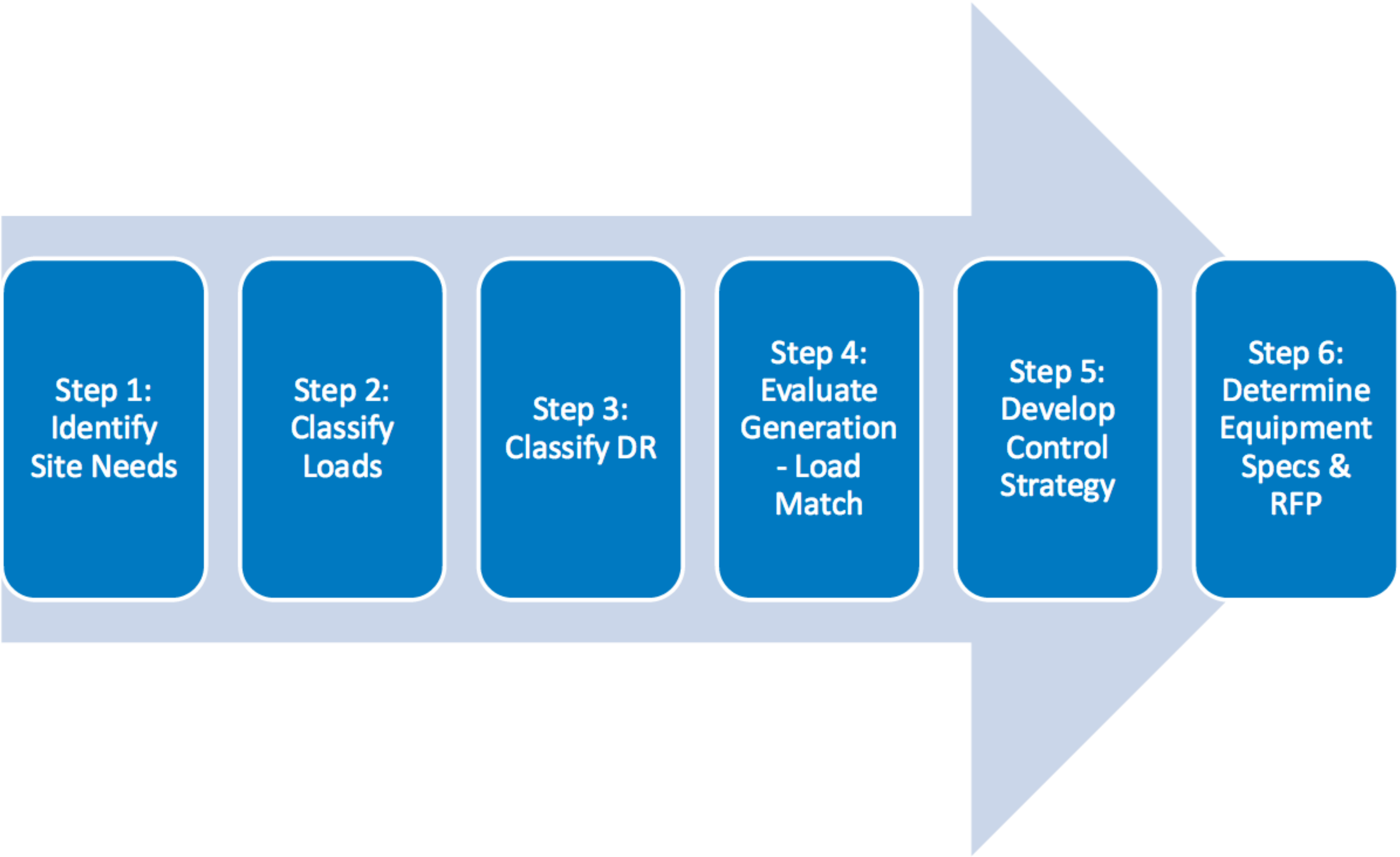


Planning Tools: Feasibility



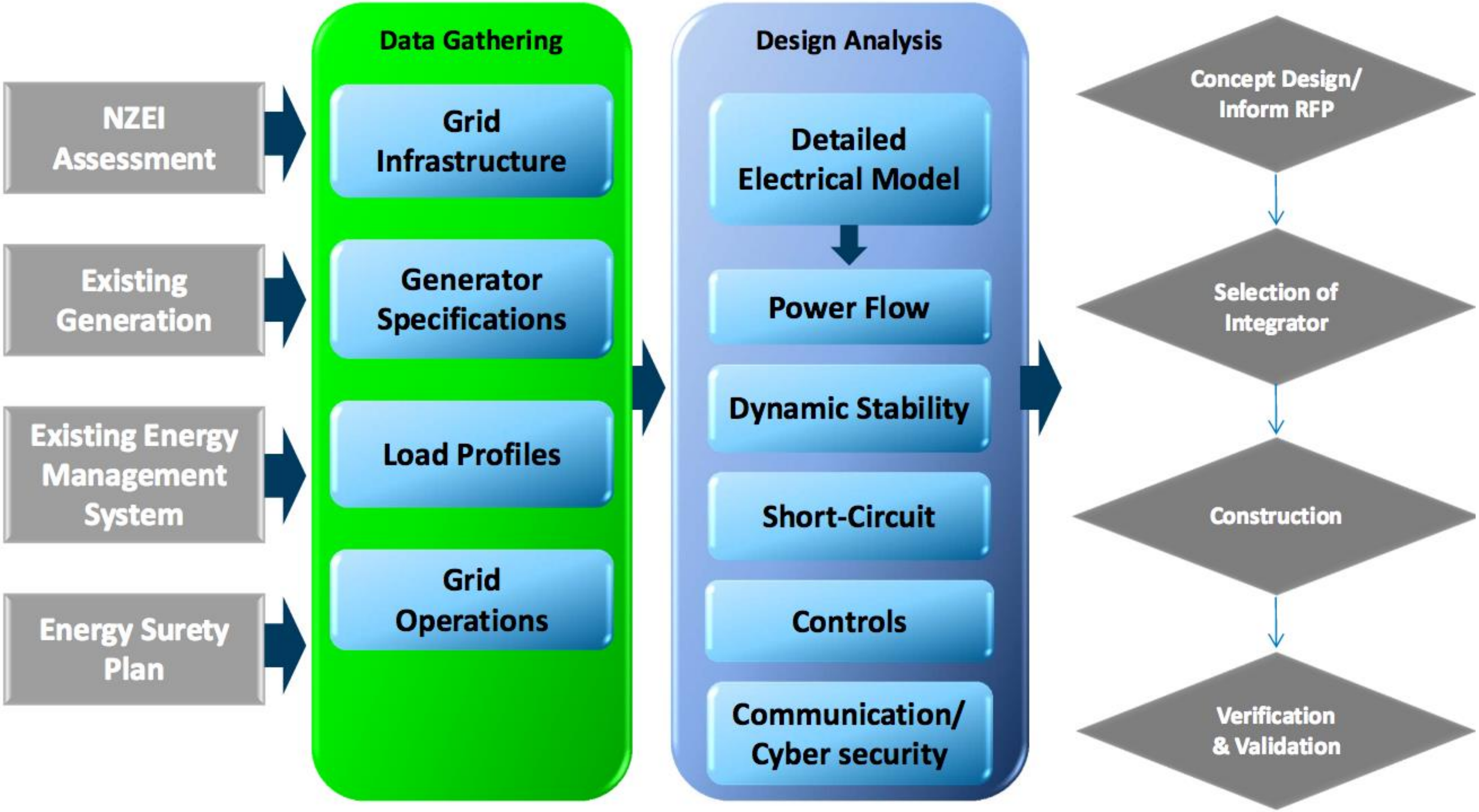


Planning Tools: NREL Approach



Ref: http://e2s2.ndia.org/schedule/Documents/Abstracts/Butt.pdf

Planning Tools: NREL Approach



Ref: http://www.nrel.gov/docs/fy12osti/54985.pdf

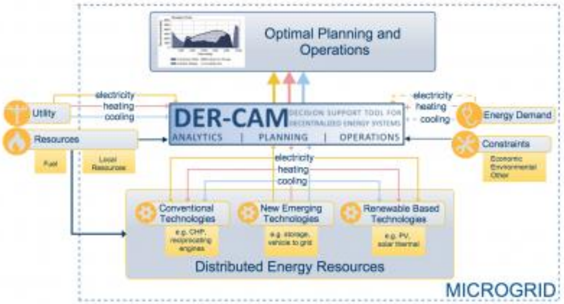
Planning Tools: Software Tools

RetScreen

HOGA (Hybrid Optimization by Genetic Algorithms)

LAP: Low Voltage Electrification Analysis and Planning

Distributed Energy Resources Customer Adoption Model (Der-Cam)



https://building-microgrid.lbl.gov/

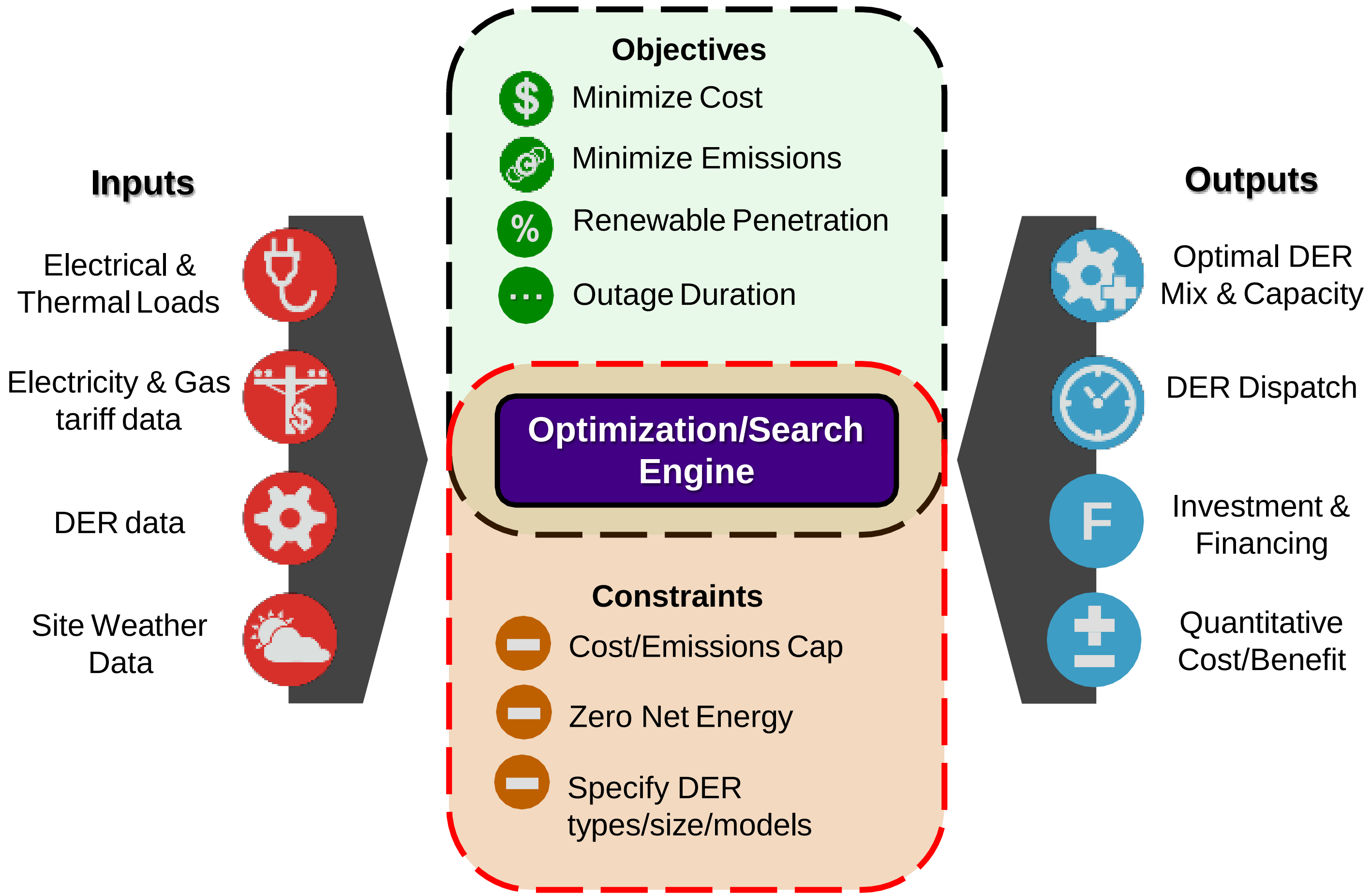
Planning Tools: Software Tools

HOMER

A TRaNsient SYstems Simulation Program

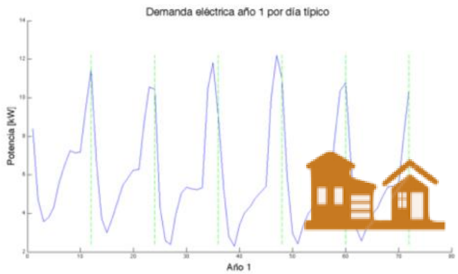
Planning Tools: EPRI Overview

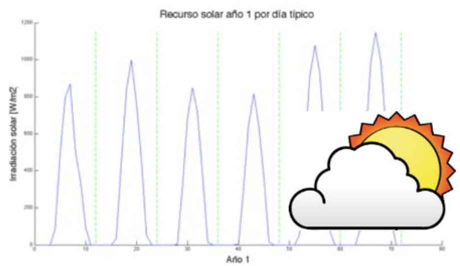
Modeling *Overview*

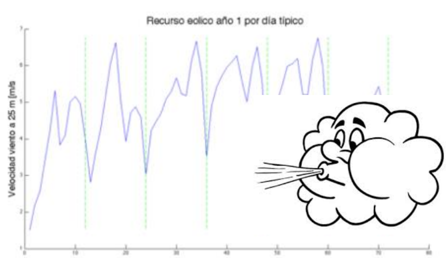


Planning Tools: Example

Romeral







Technology cost

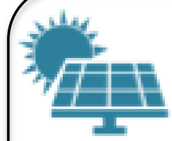
Optimun design tool

$$\min_{\{E_0,\ I_m,\ P_{m,a,d,h}\}} \quad VAC_P + VAC_W + VAC_B + VAC_G$$

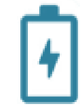
Límites de potencia por unidad	$0 \le P_{m,a,d,h} \le I_m \quad m = \{P, W, G\}$ $P_{Bmin} \le P_{B,a,d,h} \le P_{Bmax}$
Límite de energía en las Baterías	$SoC_{min} \cdot E_{max} \le E_{B,a,d,h} \le E_{max}$ $SoC_{min} \cdot E_{max} \le E_{B,0} \le E_{max}$
Suministrar potencia Dda	$P_{D,a,d,h} = \sum_{m=\{P,W,G,B\}} P_{m,a,d,h} \quad \forall a, d, h$
Potencia aerogenerador	$P_{W,a,d,h} = F\left(W_{a,d,h} \cdot \left(\frac{aT}{aD}\right)^k\right)$
Potencia planta fotovoltaica	$P_{P,a,d,h} = cP \cdot G_{a,d,h}$
Ciclo energético bat. nulo	$\sum_{h=1}^{NH} E_{B,a,d,h} = 0 \quad \forall a, d$

Modelo Baterías

$$E_{BMAX} = H_{nom} \cdot I_B$$
$$P_{BMAX} = k_{des} \cdot I_B$$
$$P_{BMIN} = k_{car} \cdot I_B$$
$$E_{B,a,d,h} = E_{B,a,d,h-1} - P_{B,a,d,h} \cdot nB$$



PV
50kW



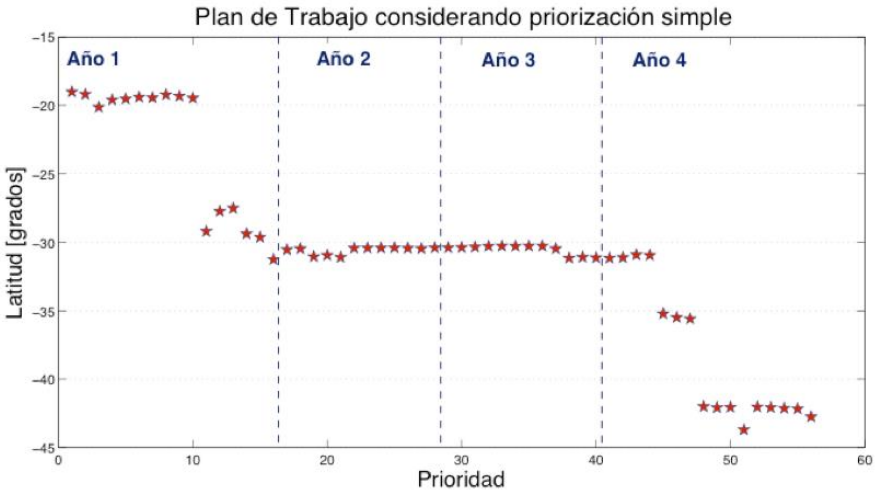
Storage
300kWh

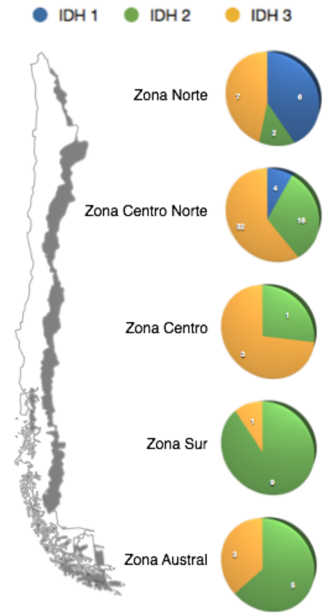
Diesel
70kW

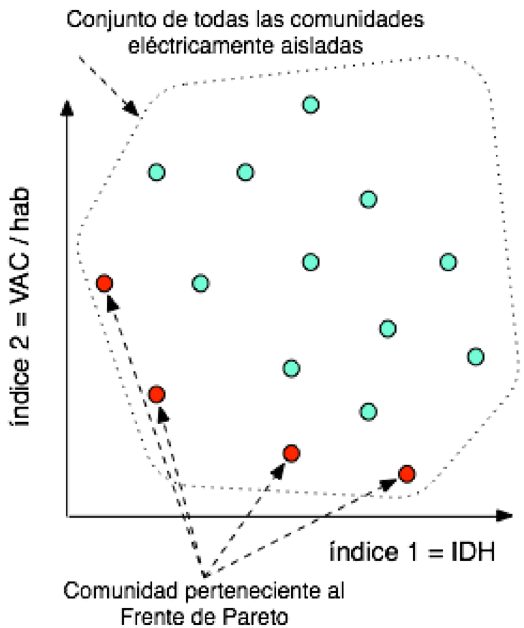
Wind
30kW

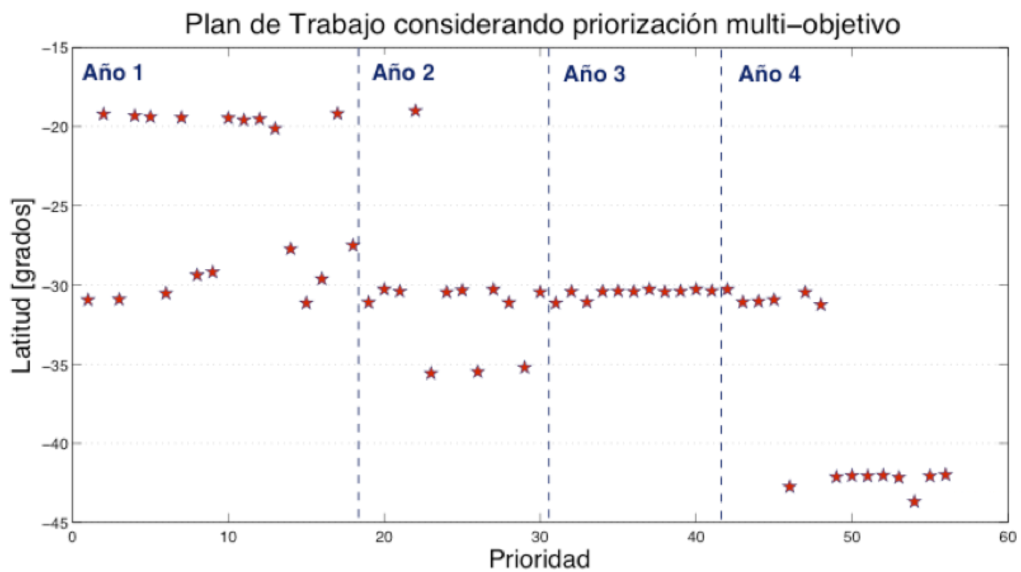
Planning Tools: Example

Romeral



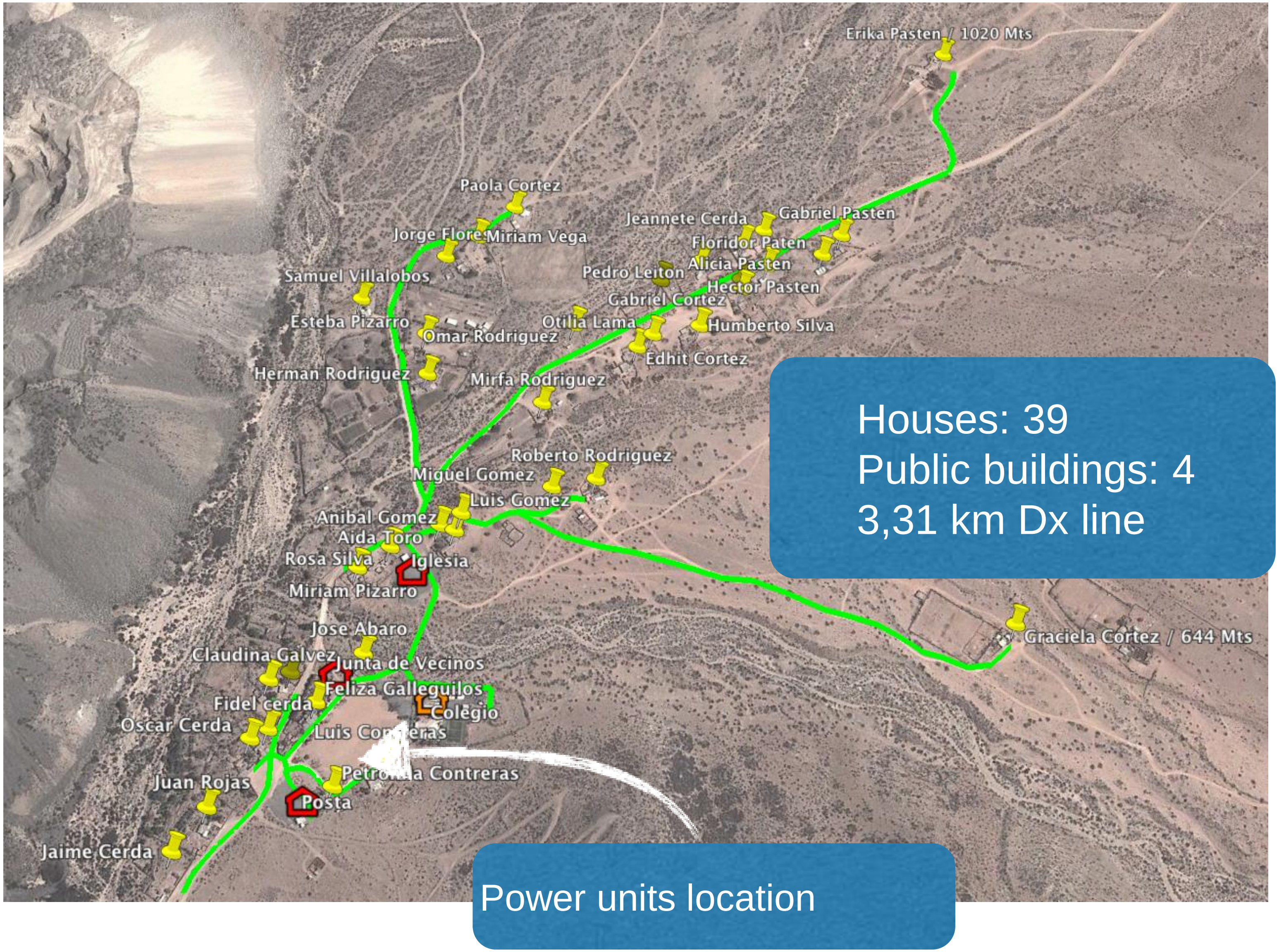




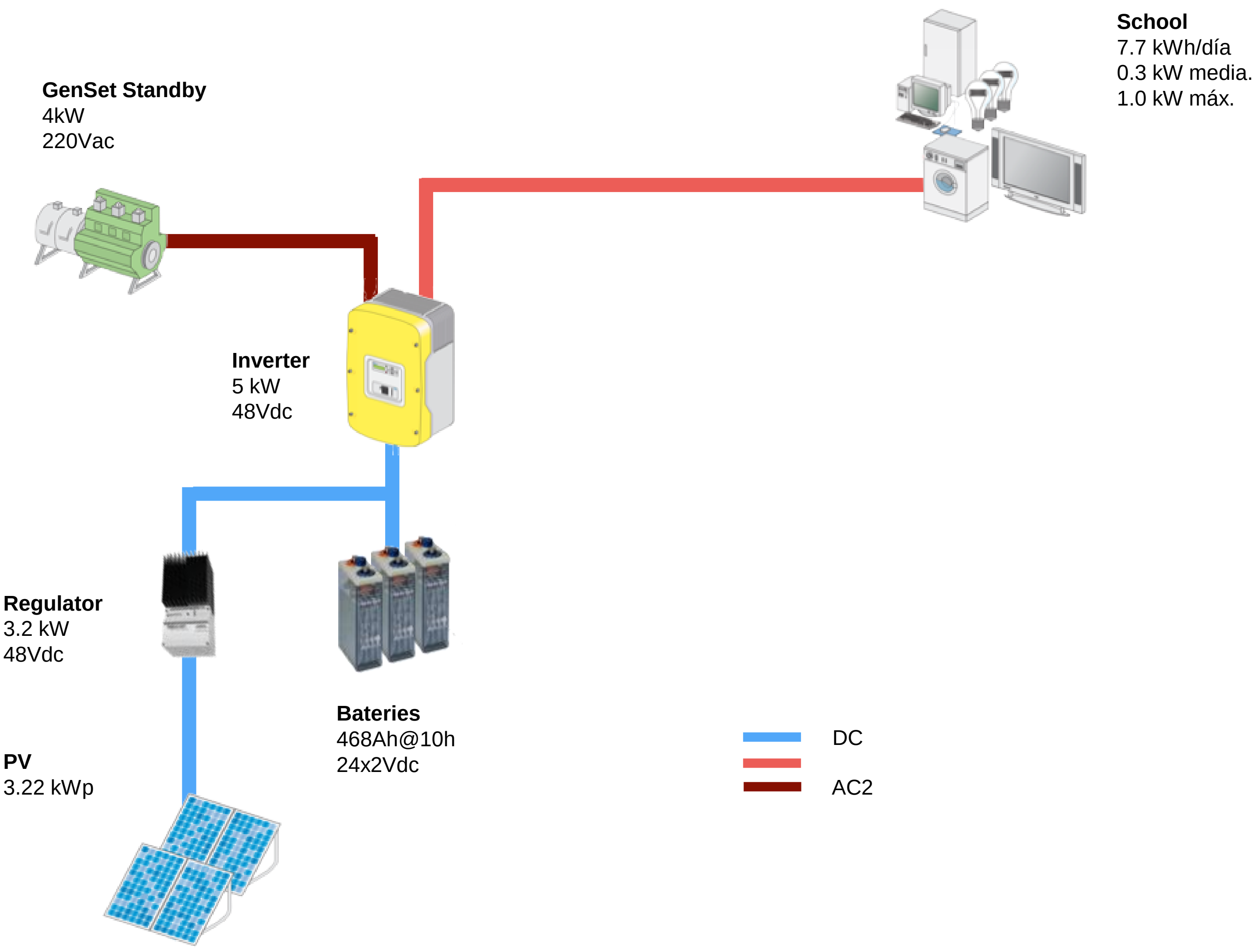


Planning Tools: Example

Romeral

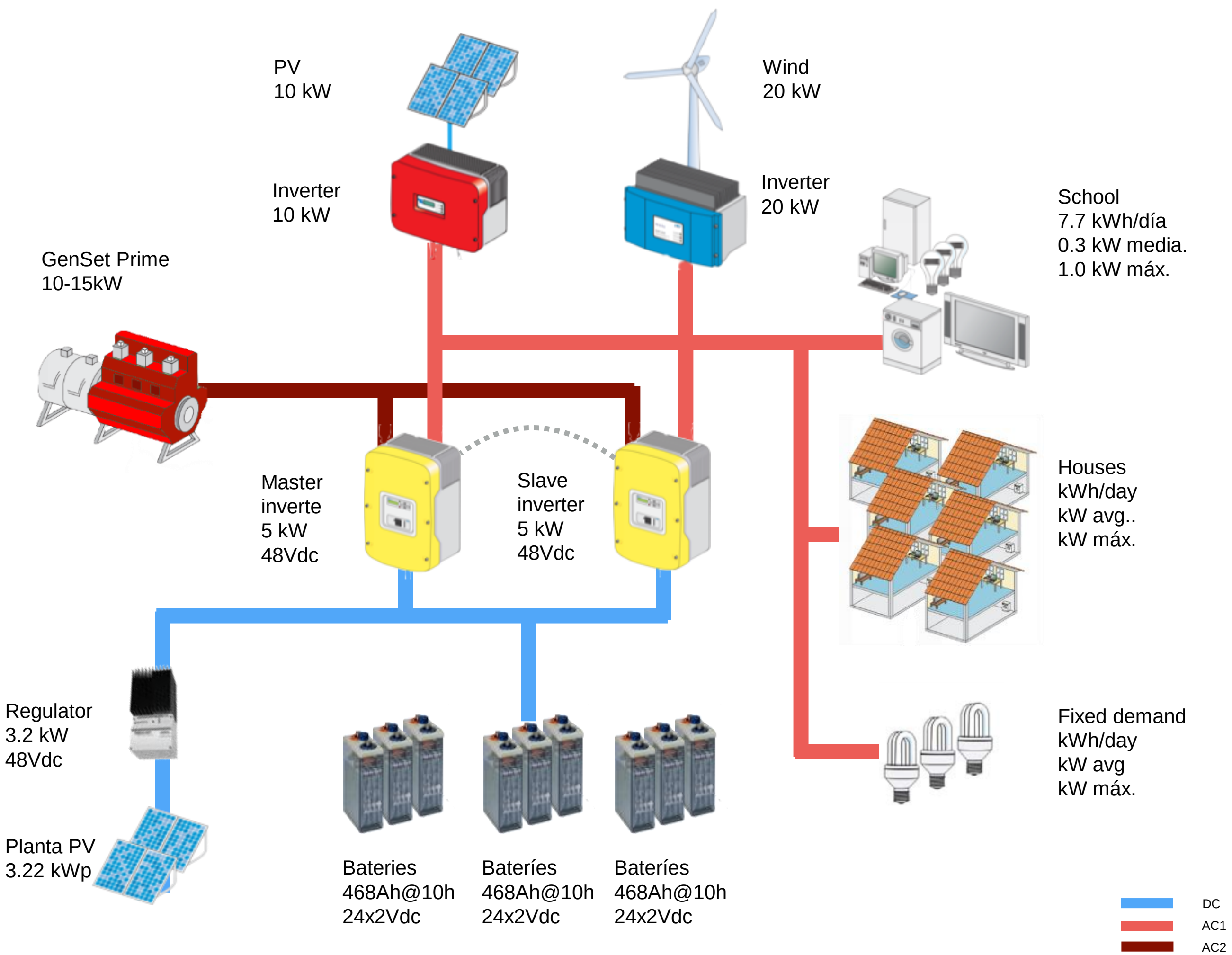


Planning Tools: Example



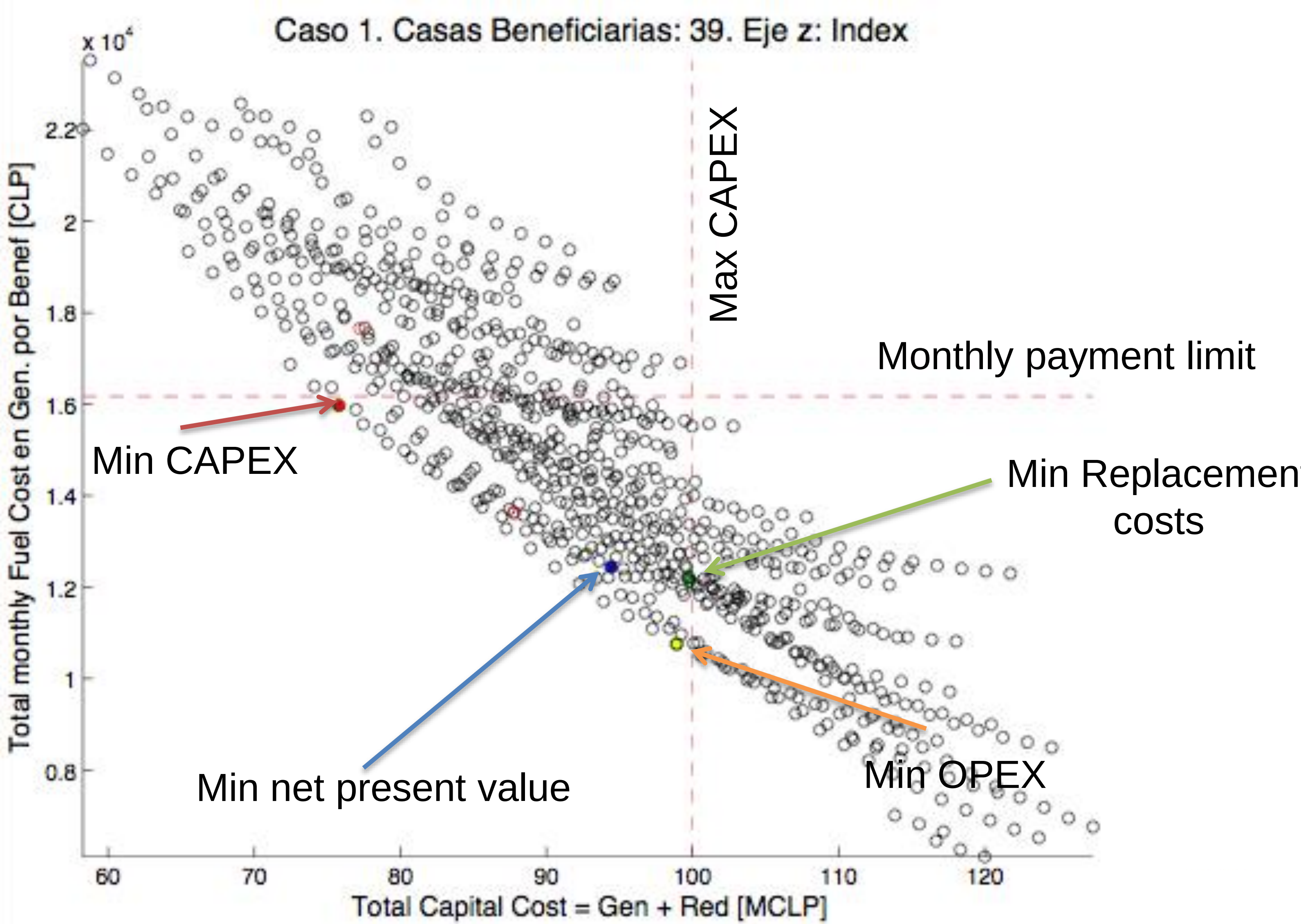
Planning Tools: Example

Romeral



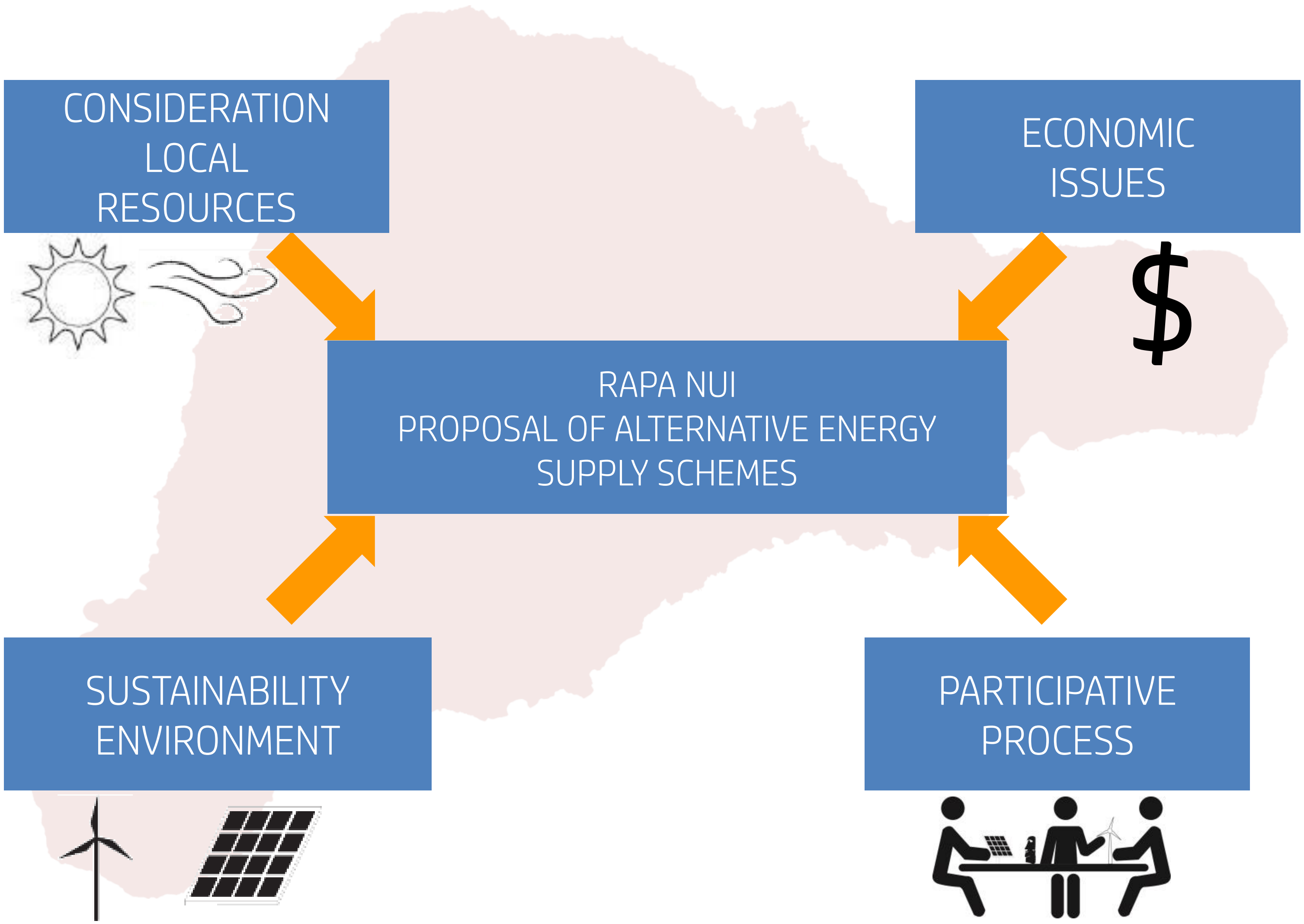
Planning Tools: Example

Romeral



Planning Tools: Example

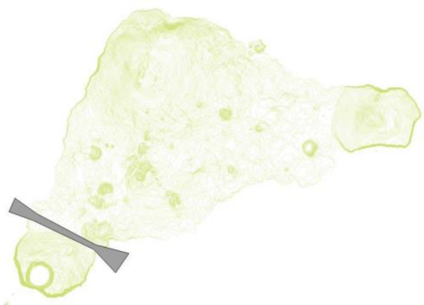
Eastern Island



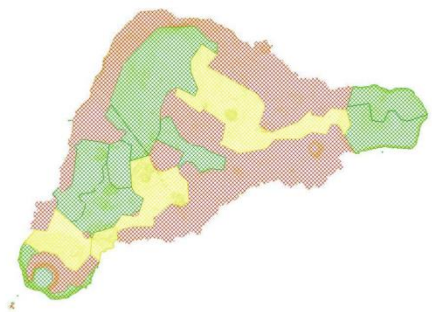
Planning Tools: Example

Eastern Island

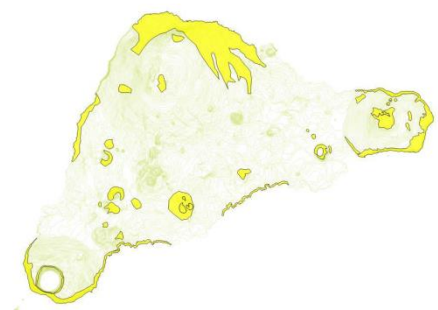
LAND USE CONSTRAINTS



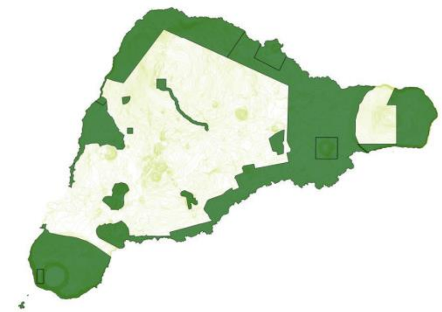
Airport zone constraint



Archaeological density



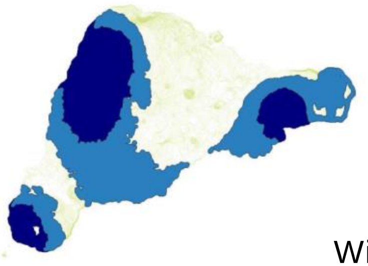
Eroded Zones



National Park Rapa Nui

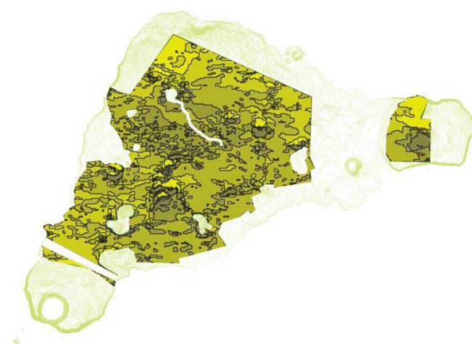
LOCAL ENERGY SOURCES

Shadows at noon

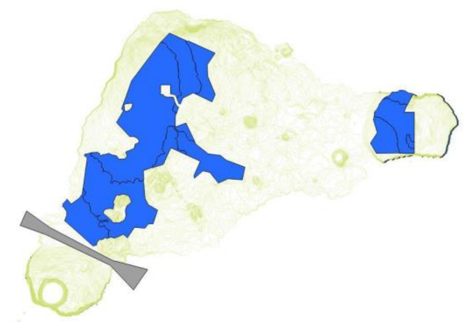


Wind resource

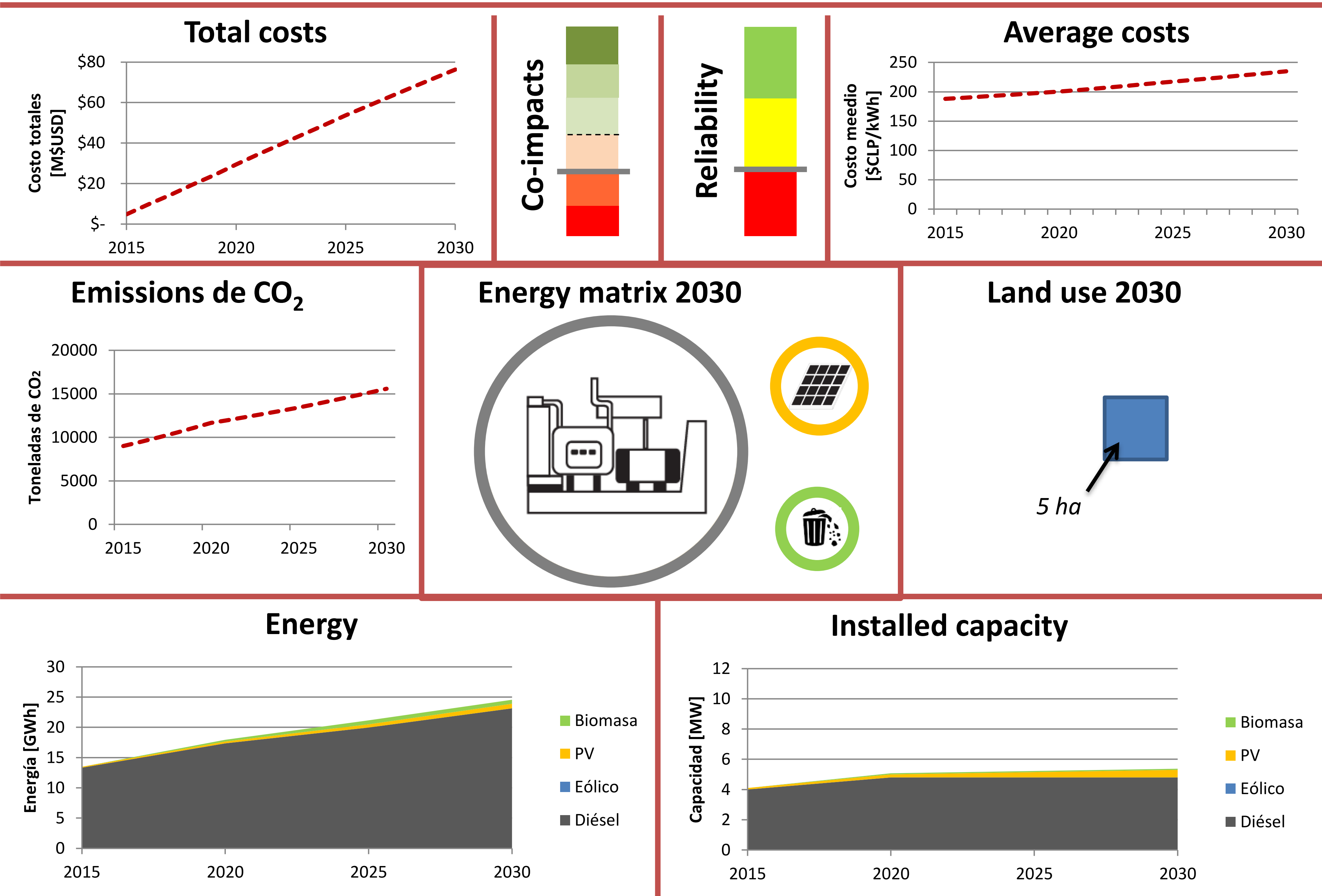
SOLAR RESOURCE AFTER CONSTRAINTS



WIND RESOURCE AFTER CONSTRAINTS

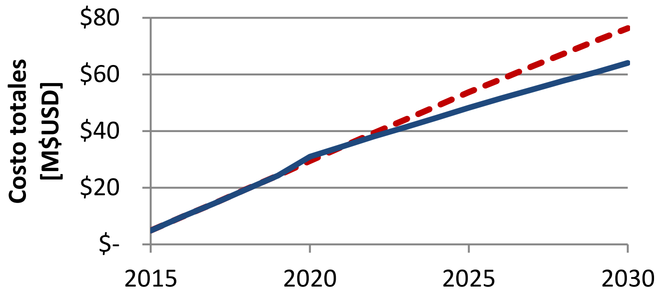


ENERGY SCENARIOS 2030:
BAU

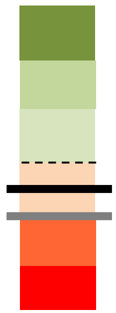


ENERGY SCENARIOS 2030:
30% renewable scenario, centralized

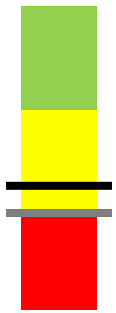
Total costs



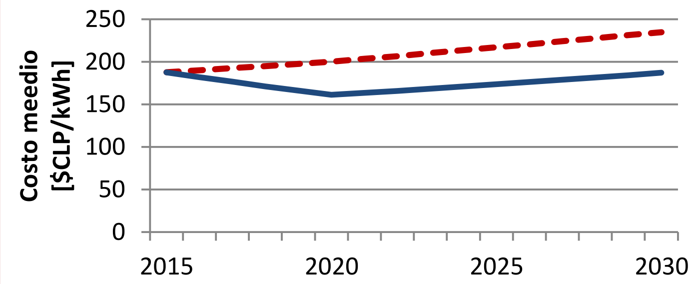
Co-impacts



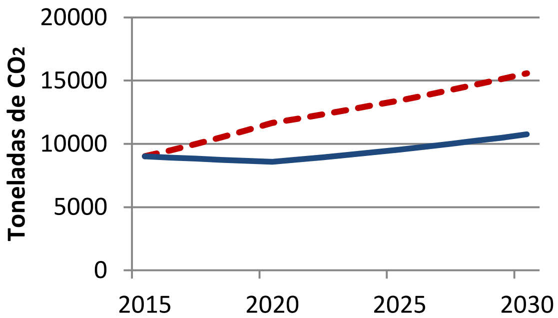
Reliability



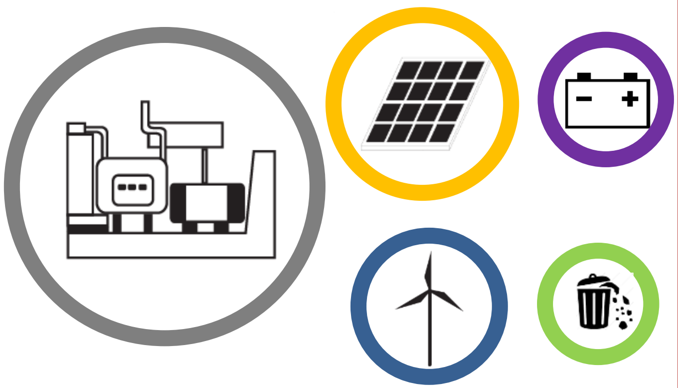
Average costs



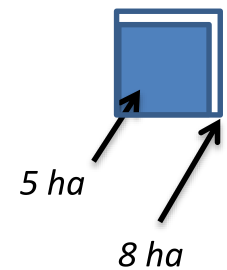
Emissions de CO_2



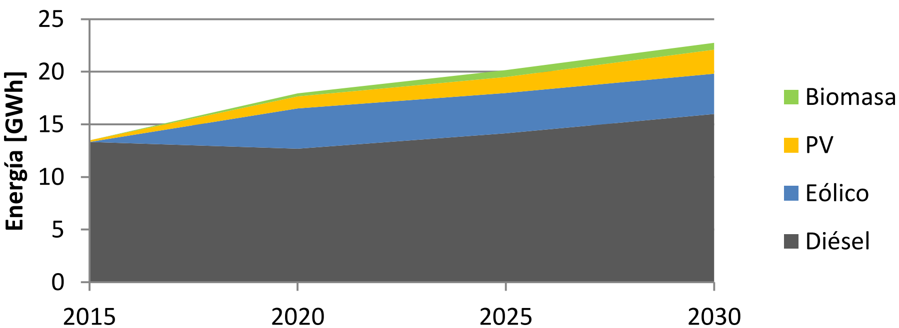
Energy matrix 2030



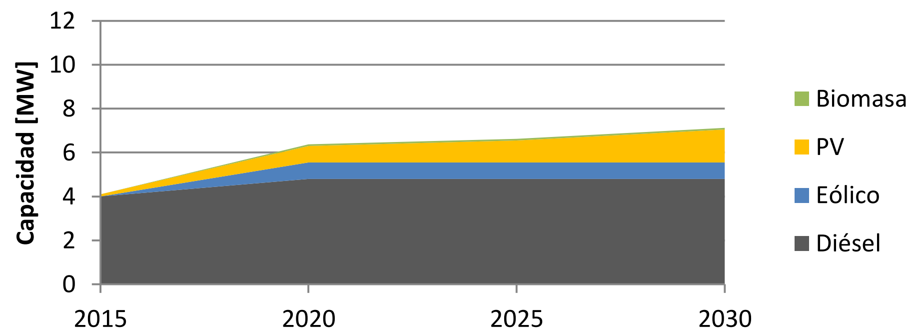
Land use 2030



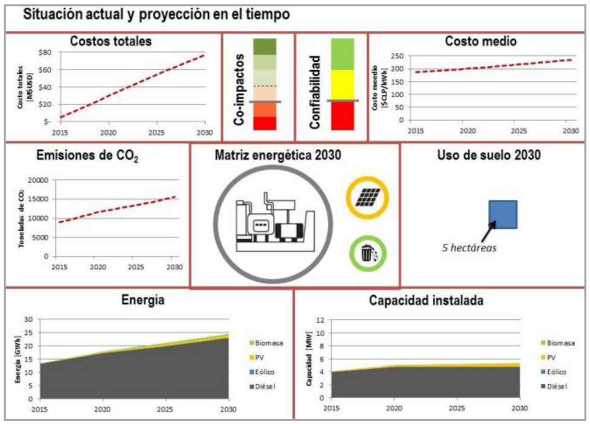
Energy



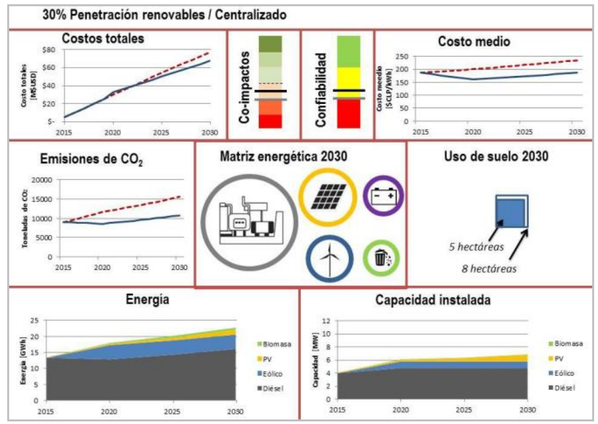
Installed capacity



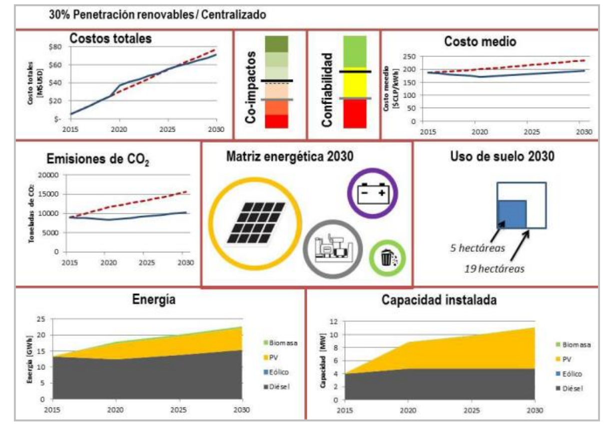
SET OF ENERGY SCENARIOS, 2030



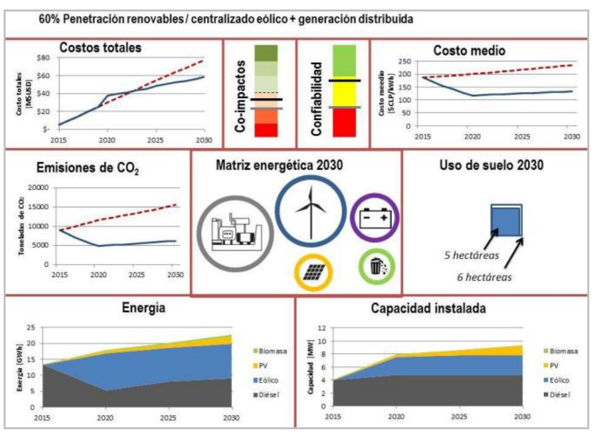
BAU



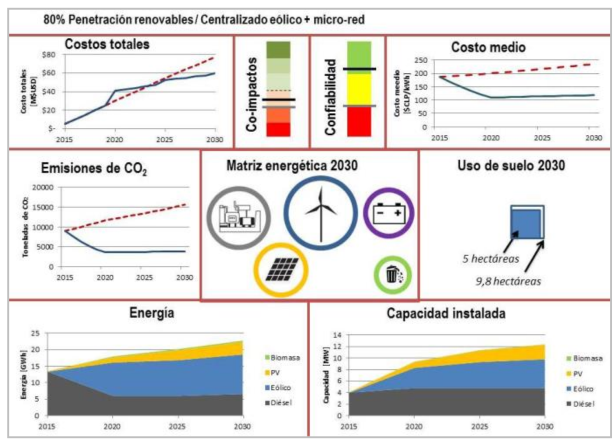
30% renewable centralized



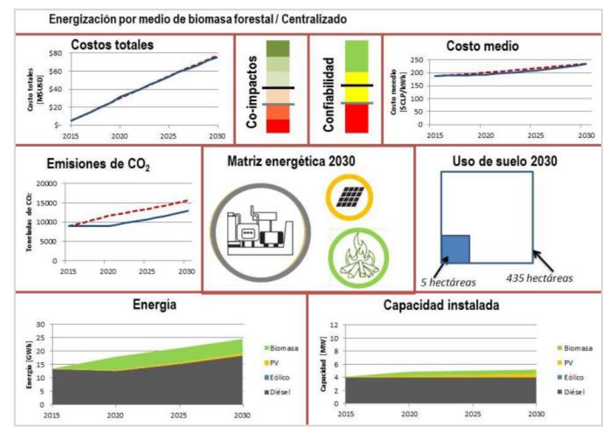
30% renewable cetralized – PV



60% renewable centralized



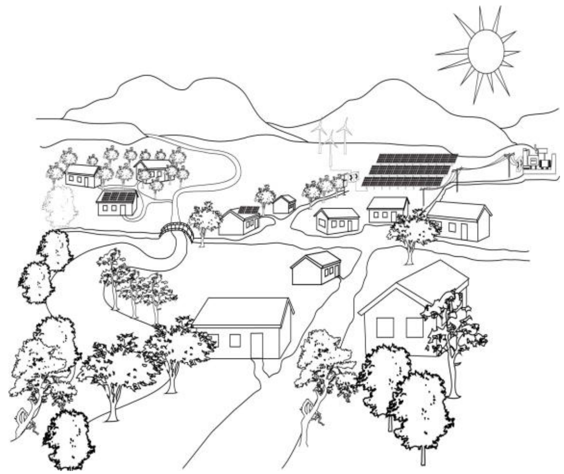
80% renewable centralized



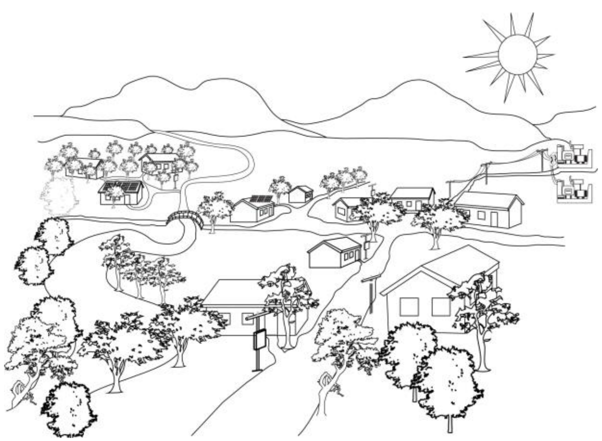
Forest biomass

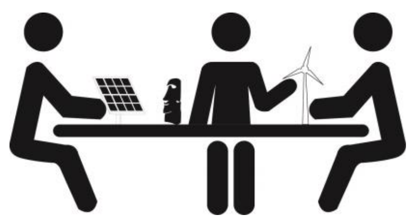
SET OF ENERGY SCENARIOS, 2030

Renewable centralized

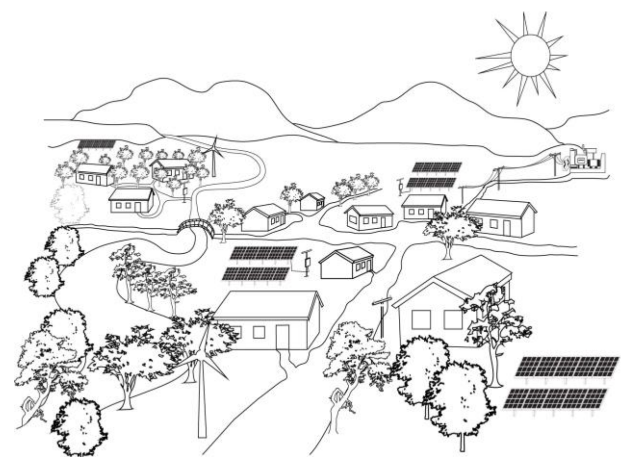


Following current paradigm





Renewable Micro-islands



Online Numerical Example

Agenda

- Introduction
- Co-construction methodology
- Planning tools
- Conclusions and challenges

Conclusions

Need of **co-construction** scheme combined with adapted tools
→ **Microgrid development framework**.

In the Latin American case, **funding** is mostly lead by private companies (**Social responsibility**). Academic institutions assume the role of developers. Promote strategic alliances among different actors. Local actors are key in terms of maintenance.

Microgrid **funding** is associated to **CAPEX**, supporters are not interested on assuming OPEX → Develop business models that may ensure that OPEX can be covered in time.

Even though **Energy Efficiency** can be promoted at community level, significative energy demand rise should be considered as a design and planning criterion.

Definition with the community of a local **management structure** to ensure correct operation and maintenance practices.

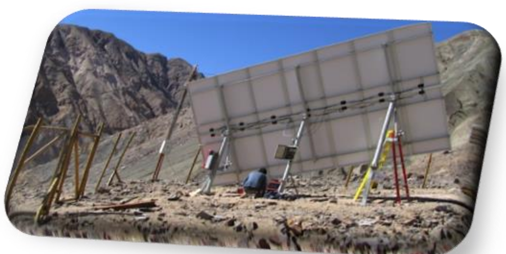
New distribution regulation → options for microgrids and innovative associative models.

Conclusions

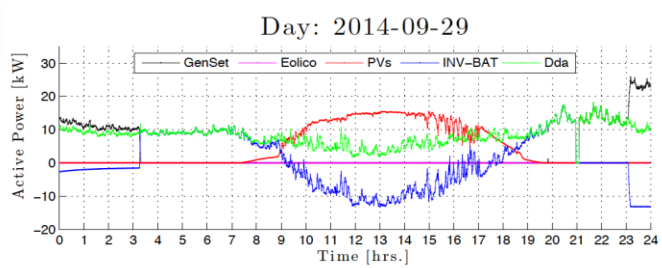
Bird protective device

V2G solutions

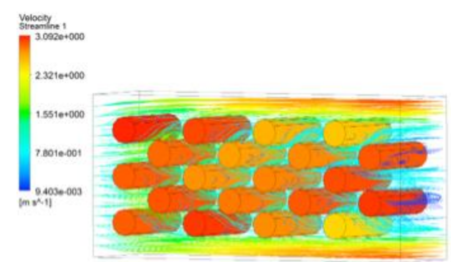
Demand response



Tracking system



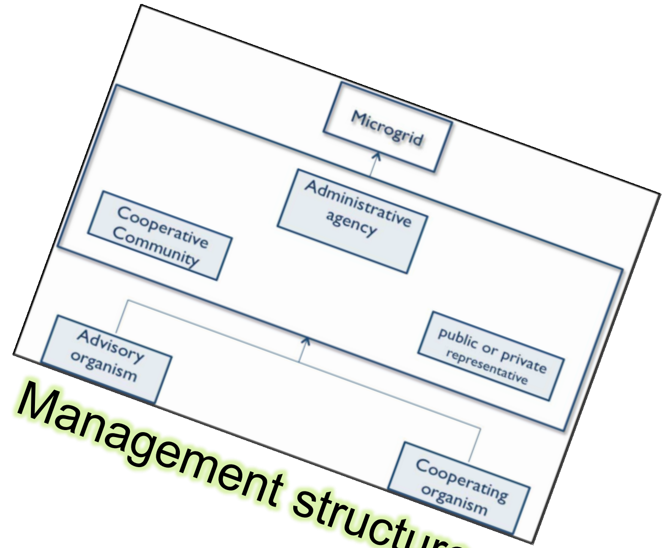
Energy Management Systems



Battery pack design

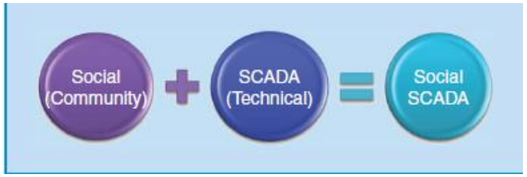
Conclusions

Participative processes



Management structures

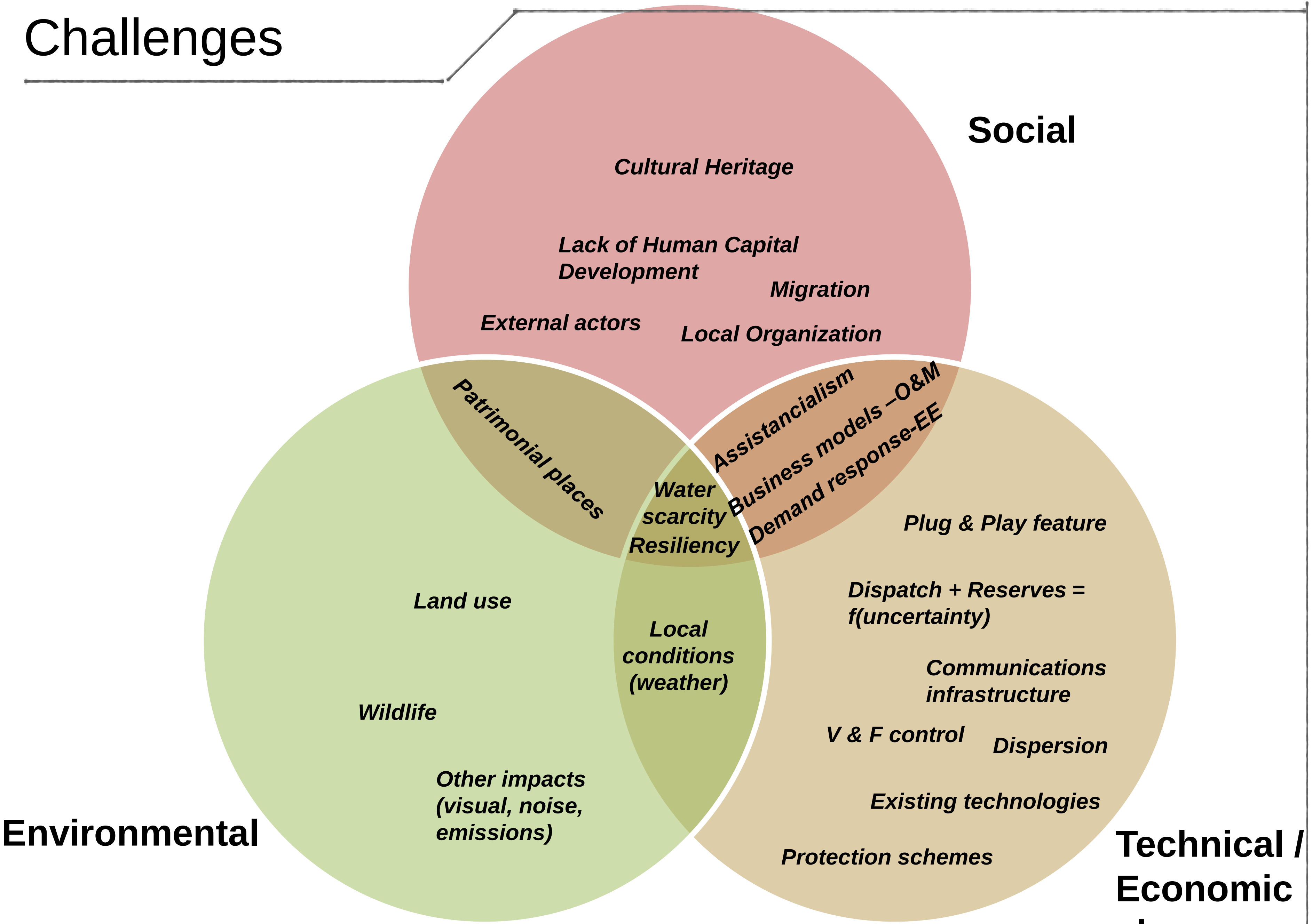
Education, training



Social SCADA

"Science from and for the community "

Challenges


Social
Cultural Heritage
Lack of Human Capital Development
Migration
External actors
Local Organization
Patrimonial places
Assistancialism
Business models –O&M
Demand response-EE
Water scarcity
Resiliency
Plug & Play feature
Dispatch + Reserves = f(uncertainty)
Land use
Local conditions (weather)
Communications infrastructure
Wildlife
V & F control
Dispersion
Other impacts (visual, noise, emissions)
Existing technologies
Environmental
Technical / Economical
Protection schemes

Cooperation

Comunidad Solar IEEE – R9 (www.comunidadsolar.cl)

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EPER Lab Electric Power and Energy Research Laboratory

References research group

- Jimenez-Estevez, Guillermo; Navarro-Espinosa, Alejandro; Palma-Behnke, Rodrigo; et al., "**Achieving Resilience at the distribution Level**", IEEE Power & Energy Magazine, Vol 15, Issue 3, pp. 64-73, 2017.

- Reyes-Marambio, J.; Moser, F.; Gana, F.; Severino, B.; Calderón-Muñoz, W.; Palma-Behnke, R.; Estevez, P.; Orchard, M.; Cortés, M., "**A fractal time thermal model for predicting the surface temperature of air-cooled cylindrical Li-ion cells based on experimental measurements**," Journal of Power Sources, Vol 306, pp. 636-645, 2016.

- Merino J., Mendoza-Araya P., Venkataramanan G., Baysal M.: "**Islanding Detection in Microgrids Using Harmonic Signature**", Power Delivery, IEEE Transactions on, Vol 30 , Issue 5, pp. 2102 – 2109, 2015.

- M.E. Orchard, M.S. Lacalle, B.E. Olivares, J.F. Silva, R. Palma-Behnke, P.A. Estevez, B. Severino, W. Calderon-Munoz, M. Cortes-Carmona: "**Information-Theoretic Measures and Sequential Monte Carlo Methods for Detection of Regeneration Phenomena in the Degradation of Lithium-Ion Battery Cells**", IEEE Transactions on Reliability, Vol. 64, Issue: 2, pp. 701-709, June, 2015.

- Jimenez-Estevez, G.; Palma-Behnke, R.; Roman Latorre, R.; Moran, L., "**Heat and Dust: The Solar Energy Challenge in Chile**," Power and Energy Magazine, IEEE , Volume: 13, Issue: 2, pp. 71-77, March-April 2015.

- Mendoza-Araya P.A., Venkataramanan G., "**Stability Analysis of AC Microgrids Using Incremental Phasor Impedance Matching**", Electric Power Components and Systems, Volume: 43, Issue: 4, pp.473-484, Feb. 25, 2015.

- Merino J., Mendoza-Araya P., Veganzones C., "**State of the Art and Future Trends in Grid Codes Applicable to Isolated Electrical Systems**", Energies, Volume. 7, Issue. 12, pp. 7936-7954, 2014.

References research group

- K. Ubilla, G. Jiménez, R. Hernández, L. Reyes-Chamorro, C. Hernández, B. Severino, R. Palma-Behnke: "**Smart microgrids as a solution for Rural Electrification: Ensuring long-term sustainability through cadastre and business models**", IEEE Transactions on Sustainable Energy, (10.1109/TSTE.2014.2315651), 2014.

- B. Severino, F. Gana, R. Palma-Behnke, P. Estévez, W. Calderón, M. Orchard, M. Cortés, J. Reyes: "**Multi-objective optimal design of lithium-ion battery packs based on evolutionary algorithms**", Journal of Power Sources, Volume 267, 1 December 2014, pp: 288–299, 2014.

- G. Jiménez-Estévez, R. Palma-Behnke, D. Ortiz-Villalba, O. Nuñez, and C. Silva.: "**It Takes a Village: Social SCADA and Approaches to Community Engagement in Isolated Microgrids**", IEEE Power and Energy Magazine, Volume: 12, Issue: 4, pp: 60-69, 2014.

- Palma-Behnke R., Benavides C., Lanas F., Severino B., Reyes L., Llanos J., Sáez D.: "**A Microgrid Energy Management System Based on the Rolling Horizon Strategy**", IEEE Transactions on Smartgrids, Volume 4, Issue 2, pp: 996-1006, junio 2013.

- Alvial-Palavicino C., Garrido-Echeverría N., Jiménez-Estévez G., Reyes L., Palma-Behnke R.: "**A Methodology for Community Engagement in the Introduction of renewable Based Smart Microgrid**", Energy for Sustainable Development, Vol. 15, Issue 3, Special Issue: SI, pp: 314-323, septiembre, 2011.

- Palma-Behnke R., Jiménez G., **Microgrids Architectures and Control (Nikos Hatziargyriou), "Chapter: An off-grid Microgrid in Chile**", Wiley, 2013

3DMicroGrid

DESIGN, DEVELOPMENT AND DEMONSTRATION OF A SMART MICRO GRID

Workshop: Design of Smart Micrografts

8th November 2017

Escuela Técnica Superior de Ingeniería, Sala Juan Larrañeta

Microgrid Planning and Operation
Part 2

Rodrigo Palma Behnke
Guillermo Jiménez Estévez, Patricio Mendoza, Marcia Montedonico, Lorenzo Reyes, Bernardo Severino, Ignacio Polanco, Felipe Valencia.

CE-FCFM / Universidad de Chile

Claudio Cañizares
With content from Mariano Arriaga, Mostafa Farrokhabadi, Jose Lara, Ehsan Nasr, Daniel Olivares, Mehrdad Pirnia, David Romero, and Bharat Solanki.

Department of Electrical and Computer Engineering
University of Waterloo, Canada

November 8th, 2017

Outline

- Introduction
- Definitions
- Stability and control
- Energy management systems:

Introduction

- Rapid development and increase penetration of distributed generation (DG) being integrated through microgrids.
- Transition from a passive grid containing only loads to an active grid, including loads and DGs.
- This affects the dynamics of both transmission and distribution systems.

Introduction

- DG stability:
  - There is a lack of understanding of the dynamics of DGs, particularly under unbalanced conditions.
  - A full characterization of the unbalanced system in stability studies would allow a better understanding of the dynamic behaviour of DGs.
  - Most DGs nowadays are equipped with small Synchronous Generators (SGs) (e.g. diesel generators, CHP).
  - Converter-based sources (solar, wind, and energy storage systems) are being deployed.

Introduction

Microgrid challenges:

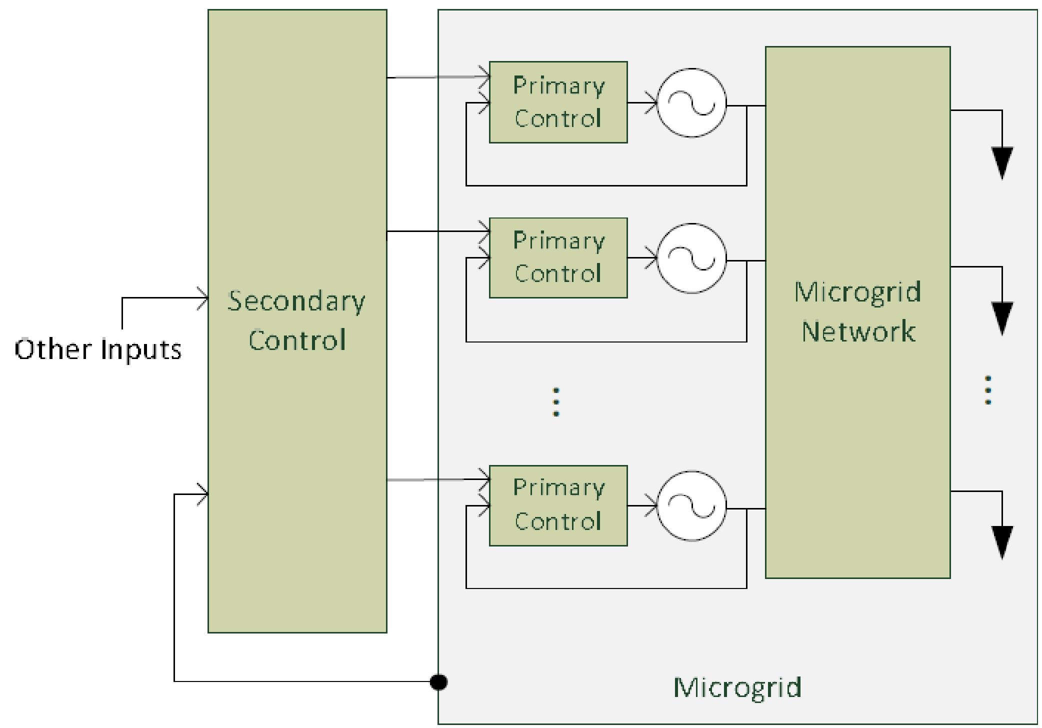
- Integrate high penetration of renewable energy (RE) sources.
- Low system's inertia.
- Rapid output fluctuations of converter-based RE sources, which yield high frequency variations.
- Need for expensive energy storage systems (ESS).

Introduction

Basic understanding of microgrids:

- Definitions
- Components
- Stability
- Controls
- Energy management

V and F Control

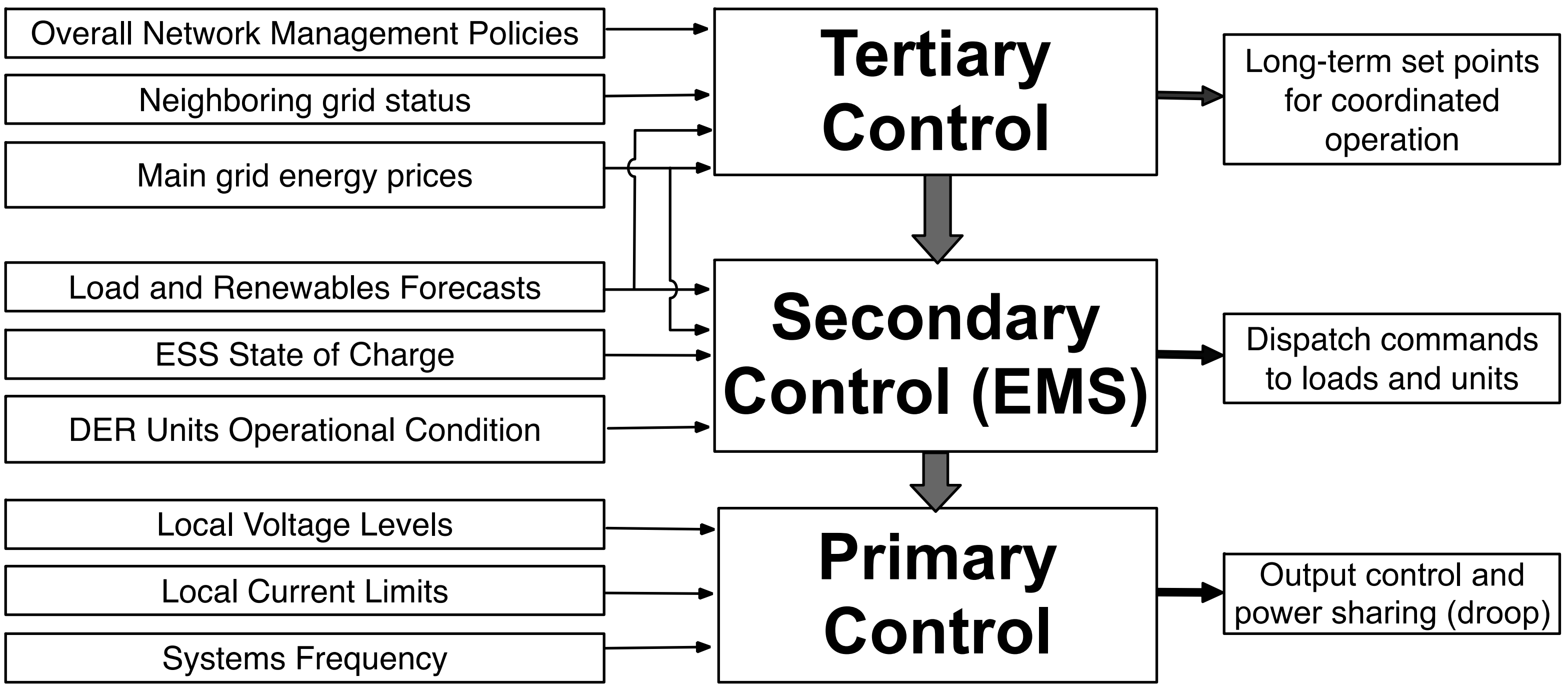


Outline

- Introduction
- **Definitions**
- Stability and control
- Energy management systems:

Definitions

- IEEE PES TF in Microgrid Control, “Trends in Microgrid Control,” *IEEE Transactions on Smart Grid*, vol. 6, no. 4, July 2014, pp. 1905-1919:



Definitions

V and F Control

- Grid-connected microgrids:
  - V and particularly f control is not a major issue, as the grid provides these “services”.
  - DGs on PQ control mode is the current “standard” in this case, including non-dispatchable DGs (solar PV and some wind generators).
  - V control is being considered/implemented by LDCs when DGs allow (e.g. solar PV).

Definitions

V and F Control

- Isolated/islanded (e.g. remote) microgrids:
  - V and f control are a major issue and must be implemented.
  - V control is prevalent in most DG technologies.
  - F control is available and “dependable” only in diesel generators, microturbines/CHP turbines and energy (battery) storage systems.

Definitions

V and F Control

- As more DGs of various technologies are added to microgrids (on- or off-grid), the need to coordinate controls is important:
  - Primary controls:
    - Isochronous:
      - Control is shared proportionally to unit ratings.
      - Works well for small number of units.
    - Droop:
      - Control is allocated based on a droop constant, so that some react faster than others.
      - Necessary with many units, similar to large grids.

Definitions

V and F Control

- Secondary controls:
  - Hierarchical, centralized controls similar to those found in large grids (e.g. SVR, AGC).
  - Distributed controls:
    - Agent based controls.
    - Distributed OPF approaches.
- Tertiary controls:
  - The main objective is to optimize the control with an "overall" (central or distributed) optimization of the grid.
  - Not widely implemented in large grids in practice, where is only applied to V control.
  - It can be viewed as optimal control coordination of multiple microgrids and their common grid.

Definitions

V and F Control

- These controls depend on the DG technology:
  - V controls:
    - Available in diesel gen. sets, microturbines, CHP turbines, VSC-based DGs (solar PV, some wind generators, fuel cells), DFIG-based wind generators (usually found in farms and not “individually” as part of microgrids), battery storage systems.
    - Not available in IM-based wind turbines (old, but somewhat prevalent technology in remote, small microgrids).

Definitions

V and F Control

- F controls:
  - Available and dependable in diesel gen. sets, microturbines/CHP turbines and battery storage systems, given their dispatchability and relatively fast response.
  - Not available in non-dispatchable sources, i.e. solar PV, wind, small hydro.

Outline

- Introduction
- Definitions
- **Stability and control**
- Energy management systems:

Stability and control

KLFN Microgrid

Kasabonika Lake

Stability and control

KLFN Microgrid

- Community:
  - 914 people.
  - 500 km north of Thunder Bay.
  - Winter-road access.
- Electricity generation:
  - 0.4 MW, 0.6MW, and 1 MW diesel generator in operation.
  - 1.5 MW diesel generator replacing 0.4 MW generator is being installed.
  - 3x10 kW Bergey WTs.
  - 1x30 kW Wenvor WT.
  - 10 kW solar PV array.

Stability and control

KLFN Microgrid

Local grid dataloggers:

1. Diesel generator plant.
2. 3x Bergey WTs.
3. Store.
4. Water treatment plant.

Dent meters:

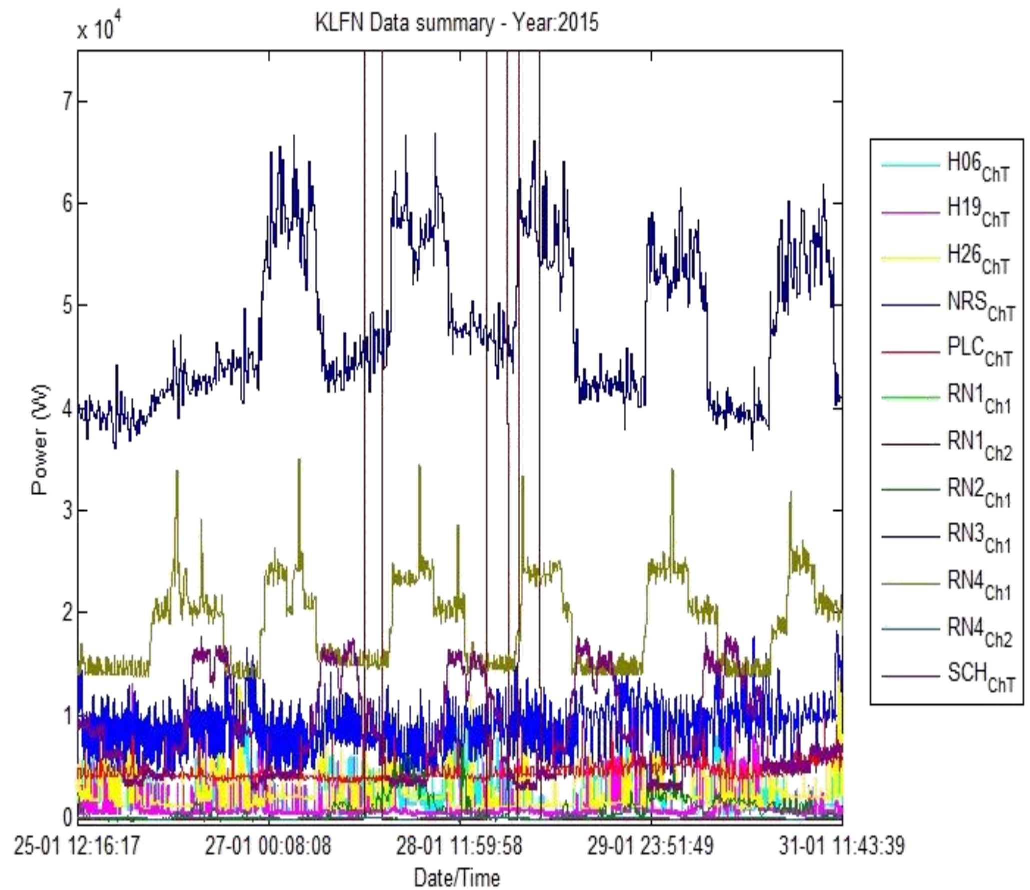
5. Sewage plant.
6. School.
7. Police station.
8. Nursing station.
9. Wenvor WT.

Laptop dataloggers:

10. 13 Houses across the community.

Stability and control
KLFN Microgrid

- Data summary:
  - Dataloggers collected information for approximately one year.
  - Some information missing but a representative sample for all locations has been collected.



Stability and control

KLFN Microgrid

Diesel generator plant RN1 Channel 1 - Lower load Timeframe: Jun/14 - Oct/14		Percetile												
		50th	1st		5th		25th		75th		95th		99th	
Description	Units	Value	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.
Active Power_A+B+C	kW	458.41	206.32	-55.0%	231.29	-49.5%	327.44	-28.6%	527.86	15.1%	622.19	35.7%	678.74	48.1%
Reactive Power_A+B+C	kVAR	78.69	36.34	-53.8%	43.59	-44.6%	56.42	-28.3%	91.87	16.8%	105.38	33.9%	115.17	46.4%
Voltage_A_RMS	V	605.09	598.09	-1.2%	599.96	-0.8%	602.76	-0.4%	607.48	0.4%	611.87	1.1%	620.35	2.5%
Voltage_B_RMS	V	600.01	593.97	-1.0%	596.18	-0.6%	598.44	-0.3%	601.88	0.3%	605.84	1.0%	614.22	2.4%
Voltage_C_RMS	V	593.58	587.05	-1.1%	588.31	-0.9%	591.48	-0.4%	596.43	0.5%	599.41	1.0%	603.06	1.6%
Frequency_A	Hz	60.06	59.94	-0.2%	59.97	-0.1%	60.01	-0.1%	60.09	0.1%	60.12	0.1%	60.15	0.1%
Total power factor	-	0.99	0.97	-1.1%	0.98	-0.7%	0.98	-0.3%	0.99	0.2%	0.99	0.5%	0.99	0.6%
Current A RMS	A	172.50	71.86	-58.3%	84.64	-50.9%	128.19	-25.7%	213.44	23.7%	290.10	68.2%	333.92	93.6%
Current B RMS	A	333.07	147.19	-55.8%	172.97	-48.1%	235.89	-29.2%	387.92	16.5%	453.70	36.2%	501.62	50.6%
Current C RMS	A	247.14	109.47	-55.7%	127.18	-48.5%	181.32	-26.6%	298.45	20.8%	369.60	49.6%	409.64	65.8%
Voltage Imbalance (neg seq)	V	1.58	0.75	-52.8%	0.88	-44.1%	1.20	-24.2%	2.03	28.7%	2.65	67.7%	3.15	99.5%
Voltage Imbalance (zero seq)	V	0.00	0.00	-76.3%	0.00	-59.4%	0.00	-31.2%	0.00	15.7%	0.00	44.5%	0.00	51.9%
Current Imbalance (neg seq)	A	18.70	3.56	-81.0%	5.98	-68.0%	12.35	-34.0%	22.39	19.7%	26.97	44.2%	30.26	61.8%
Current Imbalance (zero seq)	A	20.74	5.88	-71.6%	7.79	-62.4%	13.86	-33.2%	24.54	18.3%	29.36	41.6%	32.96	58.9%
Voltage_A_FFT_THD	-	1.74	1.14	-34.5%	1.31	-24.4%	1.50	-13.7%	2.07	19.1%	3.02	73.8%	3.28	88.6%
Voltage_B_FFT_THD	-	1.75	1.11	-36.5%	1.28	-27.2%	1.47	-16.0%	2.05	17.2%	2.73	55.9%	2.94	67.5%
Voltage_C_FFT_THD	-	1.40	0.94	-32.5%	1.09	-22.0%	1.27	-9.0%	1.60	14.5%	2.50	78.4%	2.77	98.1%
Current_A_FFT_THD	-	7.49	4.46	-40.5%	5.11	-31.7%	6.31	-15.7%	9.19	22.7%	11.55	54.3%	12.96	73.1%
Current_B_FFT_THD	-	5.63	3.06	-45.7%	3.66	-35.0%	4.65	-17.4%	6.97	23.7%	9.07	61.1%	10.33	83.5%
Current_C_FFT_THD	-	5.25	3.10	-40.9%	3.54	-32.6%	4.44	-15.3%	6.12	16.5%	7.37	40.5%	8.38	59.8%

Stability and control

KLFN Microgrid

Diesel generator plant RN1 Channel 1 - Higher load Timeframe: Nov/14-May/15		Percetile													
		50th	1st		5th		25th		75th		95th		99th	
Description	Units	Value	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.
Active Power_A+B+C	kW	642.43	358.22	-44.2%	415.74	-35.3%	534.17	-16.9%	721.34	12.3%	800.97	24.7%	842.21	31.1%
Reactive Power_A+B+C	kVAR	96.80	55.76	-42.4%	62.19	-35.7%	76.14	-21.3%	110.44	14.1%	124.38	28.5%	132.32	36.7%
Voltage_A_RMS	V	603.84	598.88	-0.8%	600.29	-0.6%	602.41	-0.2%	605.20	0.2%	607.22	0.6%	608.65	0.8%
Voltage_B_RMS	V	599.97	595.49	-0.7%	596.79	-0.5%	598.70	-0.2%	601.22	0.2%	603.07	0.5%	604.41	0.7%
Voltage_C_RMS	V	597.62	593.78	-0.6%	594.92	-0.5%	596.52	-0.2%	598.68	0.2%	600.04	0.4%	600.92	0.6%
Frequency_A	Hz	60.07	59.98	-0.1%	60.01	-0.1%	60.05	0.0%	60.09	0.0%	60.12	0.1%	60.14	0.1%
Total power factor	-	0.99	0.98	-0.4%	0.99	-0.3%	0.99	-0.1%	0.99	0.1%	0.99	0.2%	0.99	0.3%
Current A RMS	A	313.48	173.02	-44.8%	203.09	-35.2%	265.05	-15.4%	360.34	14.9%	416.25	32.8%	448.64	43.1%
Current B RMS	A	402.49	223.70	-44.4%	261.39	-35.1%	336.55	-16.4%	454.22	12.9%	512.77	27.4%	548.37	36.2%
Current C RMS	A	357.52	195.40	-45.3%	228.59	-36.1%	291.15	-18.6%	405.22	13.3%	454.92	27.2%	483.86	35.3%
Voltage Imbalance (neg seq)	V	0.99	0.59	-40.6%	0.67	-32.2%	0.85	-14.4%	1.14	14.7%	1.37	38.2%	1.56	56.5%
Voltage Imbalance (zero seq)	V	0.00	0.00	-77.0%	0.00	-58.2%	0.00	-33.2%	0.00	53.7%	0.00	71.5%	0.00	74.1%
Current Imbalance (neg seq)	A	7.94	2.04	-74.2%	3.37	-57.5%	5.96	-24.9%	10.00	26.0%	13.13	65.5%	15.47	95.0%
Current Imbalance (zero seq)	A	8.80	3.99	-54.7%	4.83	-45.2%	6.89	-21.7%	10.94	24.2%	14.23	61.7%	16.72	90.0%
Voltage_A_FFT_THD	-	1.36	1.11	-18.1%	1.18	-13.0%	1.28	-5.8%	1.43	5.5%	1.55	14.0%	1.65	21.3%
Voltage_B_FFT_THD	-	1.31	1.04	-20.6%	1.12	-14.7%	1.23	-6.1%	1.39	5.8%	1.49	13.4%	1.56	19.2%
Voltage_C_FFT_THD	-	1.25	1.00	-20.0%	1.12	-10.3%	1.19	-4.5%	1.31	5.0%	1.39	11.9%	1.45	16.6%
Current_A_FFT_THD	-	4.89	3.29	-32.7%	3.70	-24.3%	4.34	-11.2%	5.56	13.5%	6.70	36.9%	7.61	55.6%
Current_B_FFT_THD	-	3.98	2.43	-38.9%	2.80	-29.5%	3.46	-12.9%	4.53	13.9%	5.43	36.7%	6.13	54.2%
Current_C_FFT_THD	-	4.53	2.93	-35.2%	3.30	-27.1%	3.99	-11.8%	5.08	12.3%	5.96	31.5%	6.68	47.5%

Stability and control

KLFN Microgrid

10kW Solar Array at the Water Treatment Plant RN4 Channel 2 - Higher load Timeframe: Nov/14-May/15		Percetile												
		50th	1st		5th		25th		75th		95th		99th	
Description	Units	Value	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.	Value	% w.r.t. 50th per.
Active Power_A+B+C	kW	1.51	0.17	-88.8%	0.23	-84.9%	0.55	-63.4%	3.11	105.8%	5.04	233.9%	5.83	285.6%
Reactive Power_A+B+C	kVAR	0.56	0.02	-96.0%	0.05	-91.8%	0.16	-71.8%	1.20	113.6%	1.97	251.8%	2.28	308.0%
Voltage_A_RMS	V	117.12	115.35	-1.5%	115.85	-1.1%	116.61	-0.4%	117.61	0.4%	118.33	1.0%	118.77	1.4%
Voltage_B_RMS	V	117.93	116.14	-1.5%	116.60	-1.1%	117.35	-0.5%	118.51	0.5%	119.28	1.1%	119.92	1.7%
Voltage_C_RMS	V	116.88	115.41	-1.3%	115.85	-0.9%	116.46	-0.4%	117.32	0.4%	117.97	0.9%	118.41	1.3%
Frequency_A	Hz	60.05	59.97	-0.1%	60.00	-0.1%	60.03	0.0%	60.07	0.0%	60.11	0.1%	60.13	0.1%
Current A RMS	A	6.16	1.02	-83.4%	1.09	-82.2%	2.31	-62.5%	12.63	105.3%	20.42	231.7%	23.48	281.4%
Current B RMS	A	6.20	1.04	-83.2%	1.16	-81.3%	2.40	-61.2%	12.58	102.8%	20.23	226.2%	23.32	275.9%
Current C RMS	A	3.71	0.58	-84.2%	0.64	-82.6%	1.38	-62.8%	7.65	106.0%	12.40	234.1%	14.30	285.2%
Voltage Imbalance (neg seq)	V	0.99	0.61	-38.1%	0.68	-31.3%	0.82	-16.6%	1.20	20.9%	1.55	56.2%	1.84	85.6%
Voltage Imbalance (zero seq)	V	0.46	0.33	-29.0%	0.36	-22.9%	0.42	-10.4%	0.48	3.4%	0.51	10.3%	0.53	15.1%
Current Imbalance (neg seq)	A	123.60	106.93	-13.5%	109.67	-11.3%	118.22	-4.4%	124.95	1.1%	125.56	1.6%	125.95	1.9%
Current Imbalance (zero seq)	A	99.41	79.41	-20.1%	84.70	-14.8%	95.05	-4.4%	101.11	1.7%	103.82	4.4%	107.50	8.1%
Voltage_A_FFT_THD	-	1.41	1.05	-25.7%	1.19	-15.4%	1.33	-5.6%	1.48	5.2%	1.60	13.2%	1.68	19.4%
Voltage_B_FFT_THD	-	1.44	1.13	-21.7%	1.22	-15.4%	1.36	-5.6%	1.52	5.4%	1.62	12.6%	1.70	17.9%
Voltage_C_FFT_THD	-	1.23	1.03	-16.1%	1.09	-11.2%	1.17	-4.5%	1.28	4.4%	1.36	10.9%	1.42	15.7%
Current_A_FFT_THD	-	10.95	2.53	-76.9%	3.39	-69.1%	5.89	-46.2%	24.20	121.1%	48.09	339.4%	62.33	469.5%
Current_B_FFT_THD	-	8.21	1.75	-78.7%	2.39	-70.9%	4.49	-45.3%	17.91	118.1%	38.96	374.3%	57.27	597.1%
Current_C_FFT_THD	-	11.21	2.59	-76.9%	3.46	-69.2%	6.00	-46.4%	25.11	124.0%	51.07	355.5%	66.44	492.6%

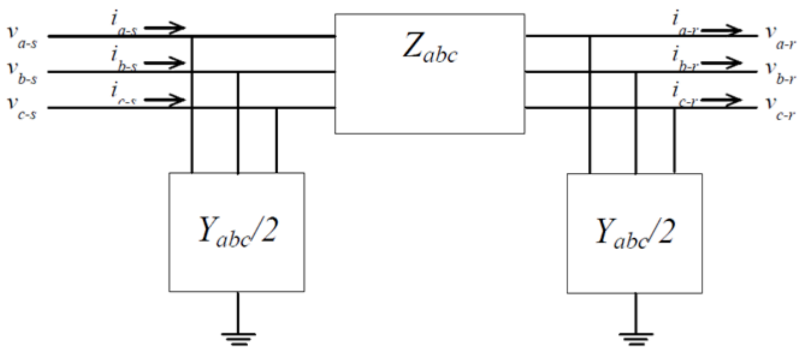
Stability and control
KLFN Microgrid

- Observations:
  - Current imbalances:
    - Significant, particularly in the summer.
    - Seasonal changes do not allow to change transformer connections at generation plant to correct them.
  - Voltage profiles:
    - Flat: 3-phase averages of 600.5 V at the gen. plant and 117.3 V (586.6 V) at the water treatment plant at the end of the feeder, i.e. ~2 % drop.
  - Frequency:
    - Small variations: in a 59.95-60.15 Hz range practically all the time.
    - Renewable sources' impact is small, given the relatively low capacity penetration level of 7% at peak load (70/1000 kW).

Stability and control

Stability Issues and Modeling

- References:
  - E. Nasr, C. A. Cañizares, and K. Bhattacharya, “Stability Analysis of Unbalanced Distribution Systems With Synchronous Machine Based Distributed Generators,” *IEEE Transactions on Smart Grid*, vol. 5, no. 5, September 2014, pp. 2326-2338.
  - M. Farrokhabadi, S. König, C. A. Cañizares, K. Bhattacharya, and T. Leibfried, “Energy Storage System Models for Microgrid Stability Analysis and Dynamic Simulation,” IEEE Transactions on Power Systems, accepted July 2017, 10 pages.
  - IEEE PES TF Microgrid Stability Analysis and Modeling, draft report/paper.
- Modeling due to unbalanced loads:
  - Static model:
    - Three-phase power flow.
  - Dynamic model:
    - Time domain simulations using PSCAD/EMTDC.
    - Detailed device models with associated controls.



$$Z_{al} = (1+k)Z_l$$

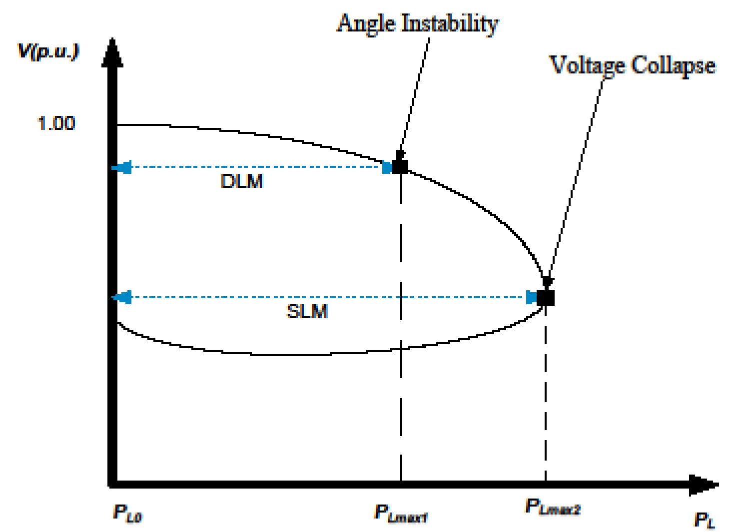
$$Z_{bl} = Z_l$$

$$Z_{cl} = (1-k)Z_l$$

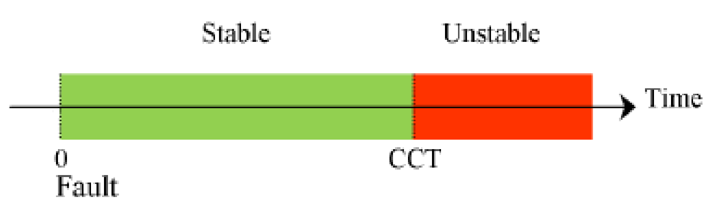
Stability and control

Stability Analysis

- Voltage profiles (V-Parameter curves):
  - Loading margins:



- Transient stability:
  - Time-domain simulations.
  - Critical Clearing Times (CCTs) give a sense of how stable the system is.



Stability and control

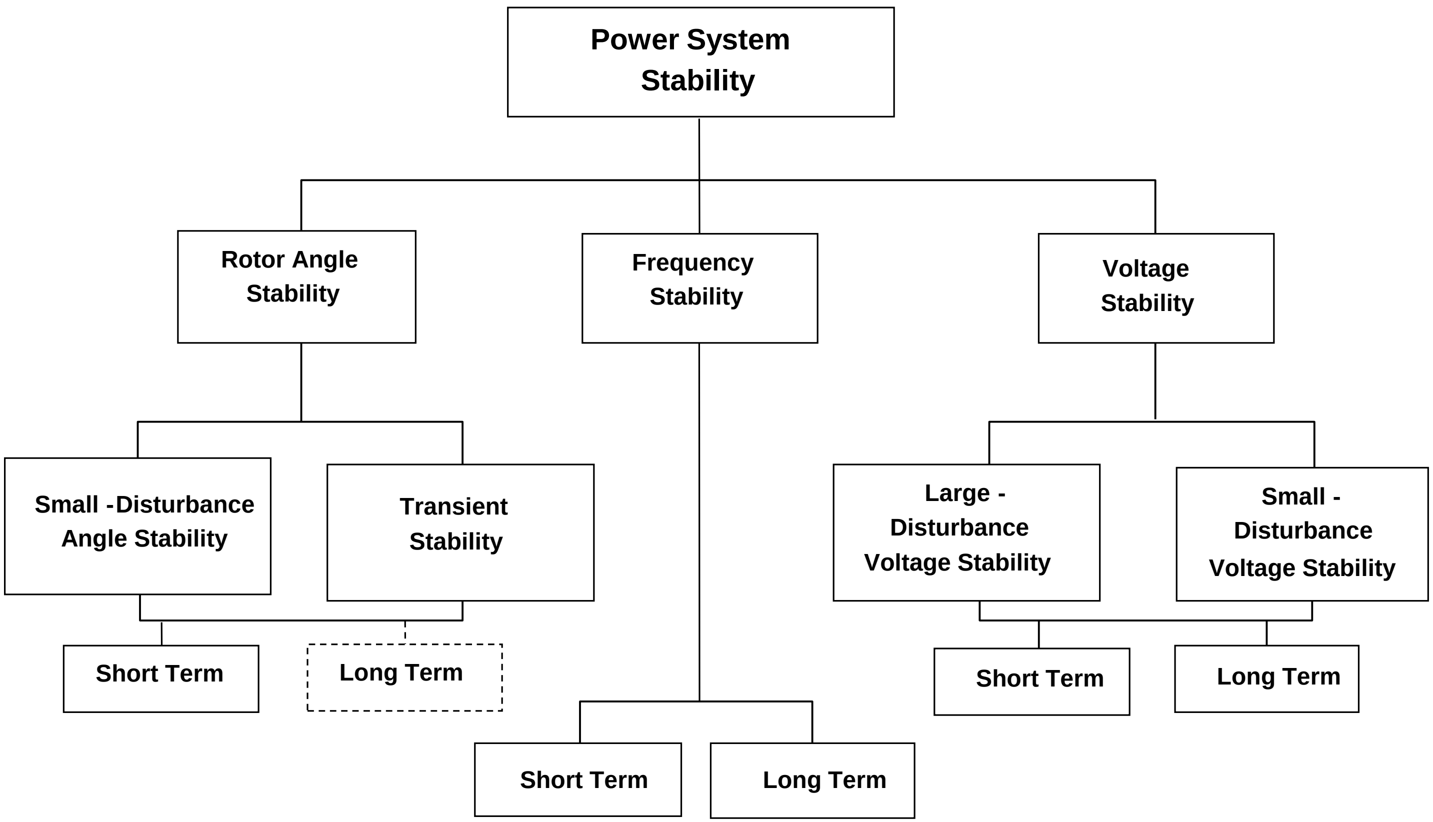
Stability Analysis

- Eigenvalues:
  - Many commercial programs use phasor models for small-perturbation stability studies.
  - Unbalanced generators show sustained small oscillations in steady state conditions, and thus standard phasor-based linearization techniques are not applicable.
  - A simulation based approach is necessary to study the problem using modal estimation:
    - Prony method.
    - Steiglitz-McBride iteration method.

Stability and control

Stability Classification

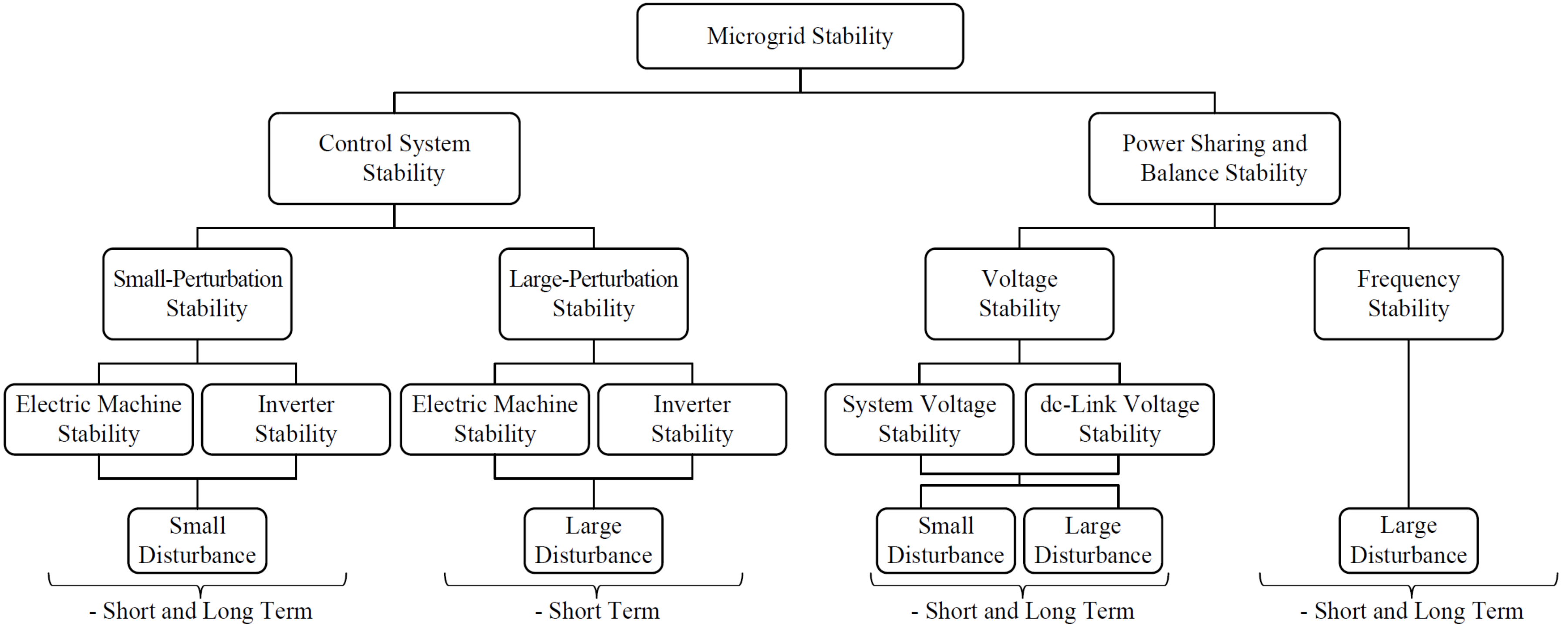
- Power system classification as per IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, "Definition and Classification of Power System Stability", IEEE Trans. Power Systems and CIGRE Technical Brochure 231, 2003:



Stability and control

Stability Classification

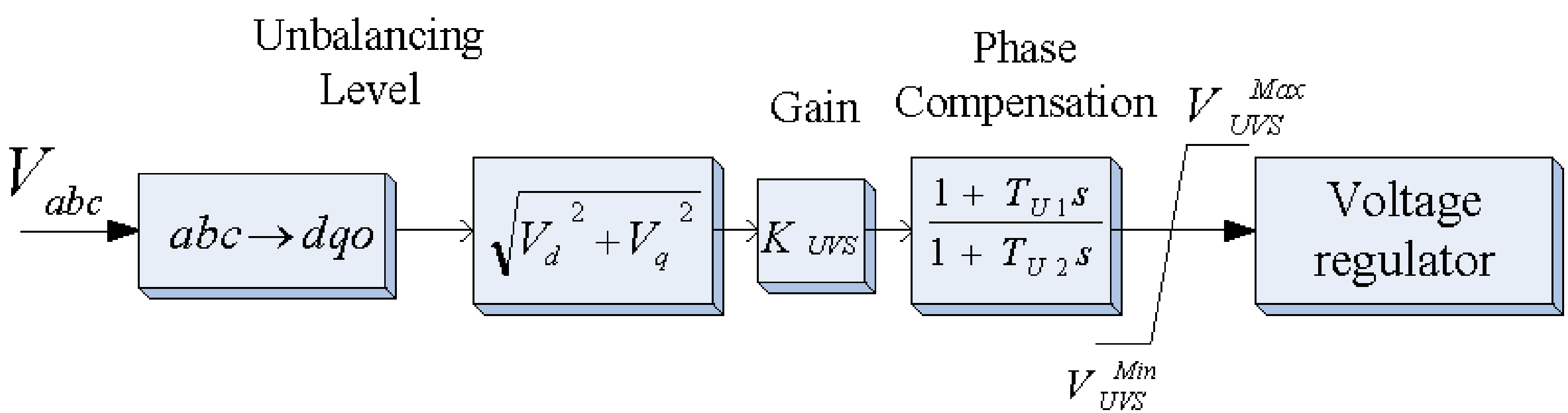
- Proposed IEEE PES TF Microgrid Stability Analysis and Modeling classification:



Stability and control

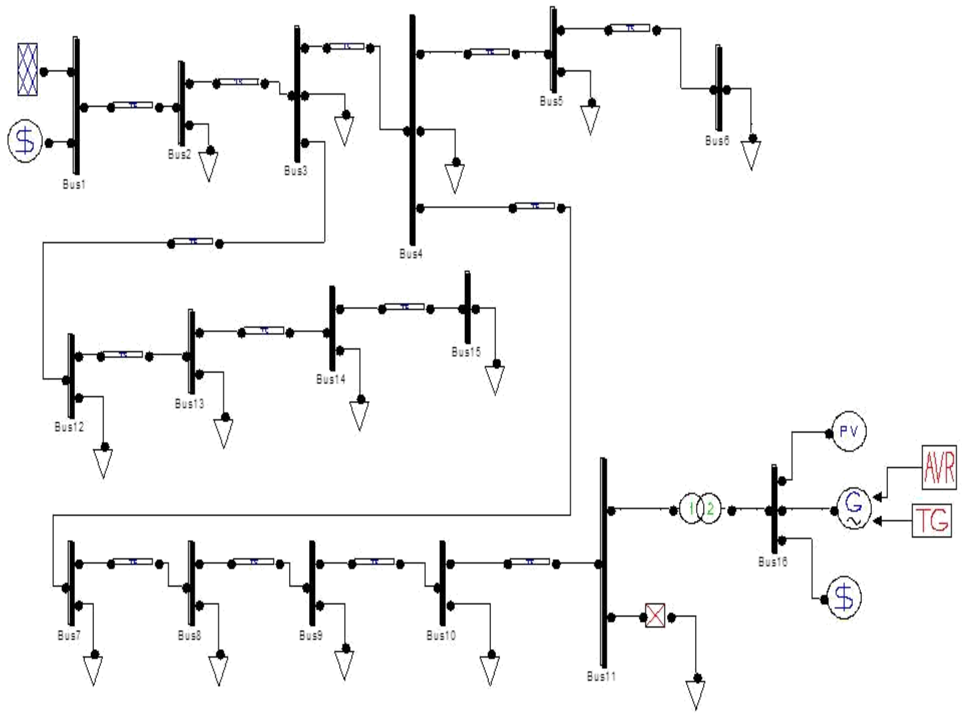
SG-based Microgrid Stability

- Unbalancing may lead to stability problems in SG-based microgrids.
- Introducing an Unbalanced Voltage Stabilizer (UVS) to the SG voltage regulator improves microgrid stability:

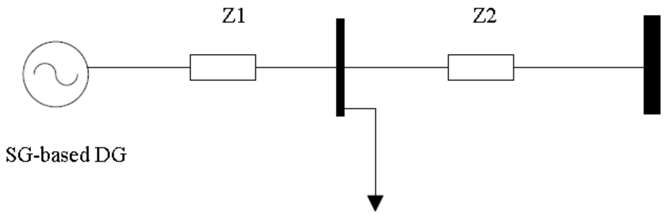


SG-based Microgrid Stability Example

- Japanese test system:



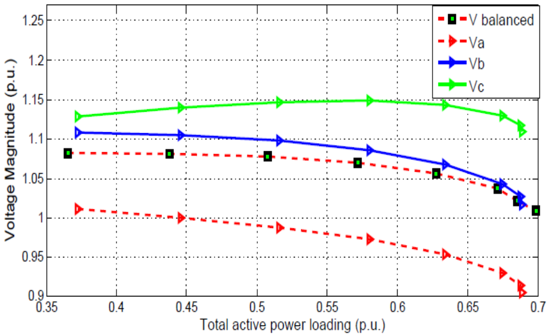
- Resulting reduced DG test system:



SG-based Microgrid Stability Example

- When the system unbalancing increases, the loadability of the system decreases:

$k(\%)$	Maximum loading factor (p.u.)		Maximum active power loadability (p.u.)	
	Time-domain simulations	Three-phase power flow	Time-domain simulations	Three-phase power flow
0	2.2	2.24	0.692	0.6925
5	2.2	2.24	0.692	0.6925
10	2.2	2.22	0.691	0.6923
15	2.2	2.22	0.691	0.6917
20	2.15	2.20	0.689	0.6912
25	2.1	2.18	0.687	0.6903

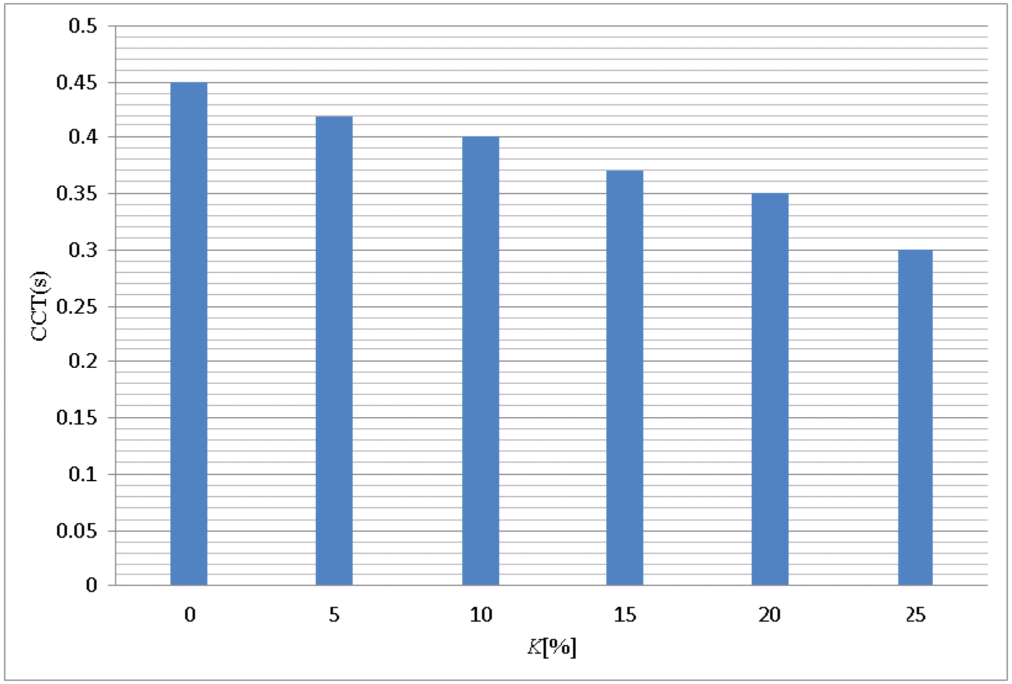


$k(\%)$	Maximum active power loadability (p.u.)	V_a(p.u.)	V_b(p.u.)	V_c(p.u.)
0	0.692	1.0089	1.0089	1.0089
5	0.692	0.9836	1.0076	1.0337
10	0.691	0.9554	1.0058	1.0558
15	0.691	0.9199	0.9985	1.0709
20	0.689	0.9050	1.0172	1.1097
25	0.687	0.8826	1.0292	1.1310

Stability and control

SG-based Microgrid Stability Example

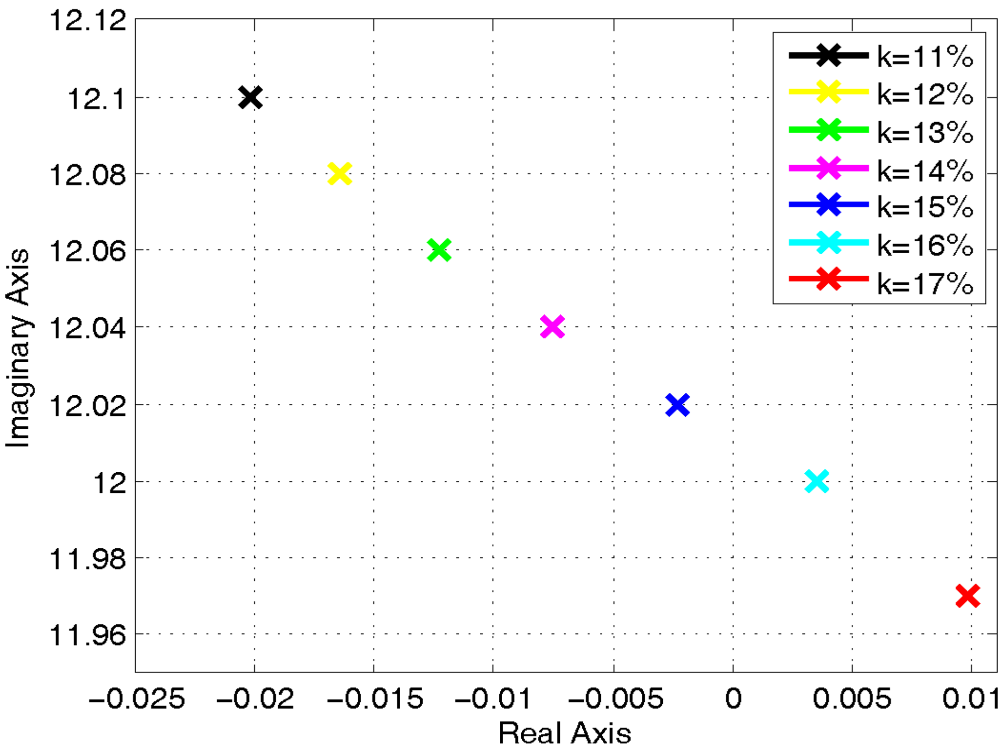
- CCT at base load for a three-phase-to-ground fault decreases as unbalancing increases:



Stability and control

SG-based Microgrid Stability Example

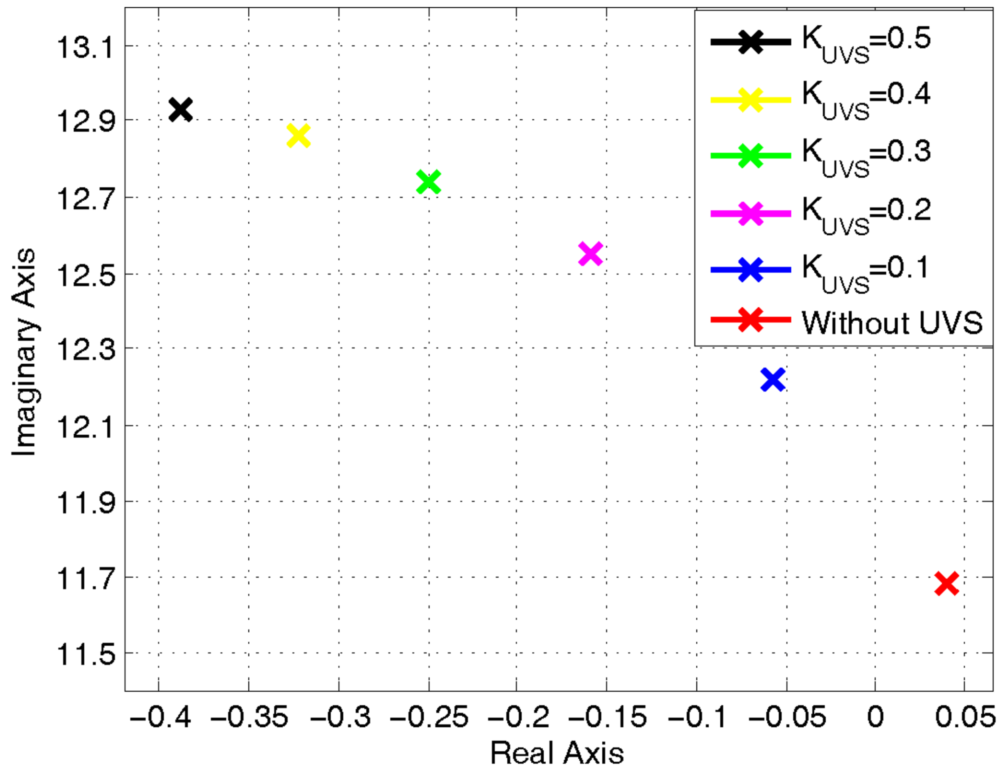
- At high loading and with some unbalancing (k = 15%), the system experiences a Hopf bifurcation with 1.91 Hz frequency:



Stability and control

SG-based Microgrid Stability Example

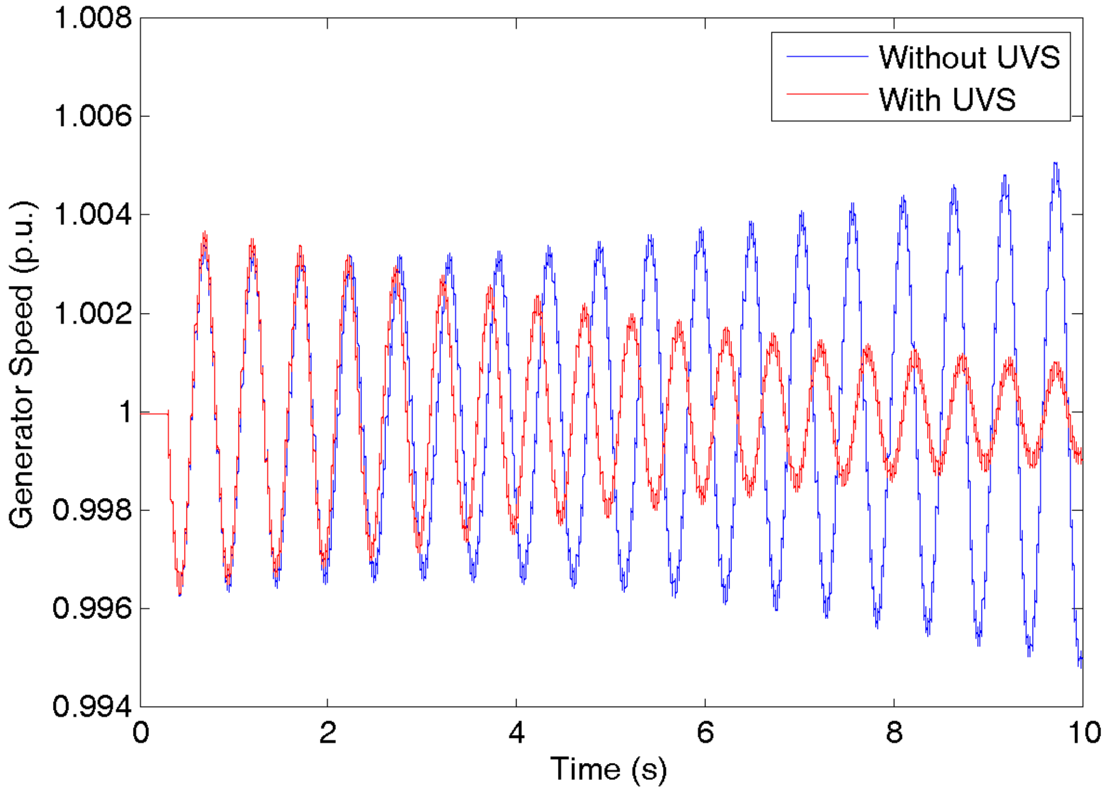
- System becomes stable with UVS (unbalanced voltage stabilizer)) at high loading and unbalancing (k =25%) levels:



Stability and control

SG-based Microgrid Stability Example

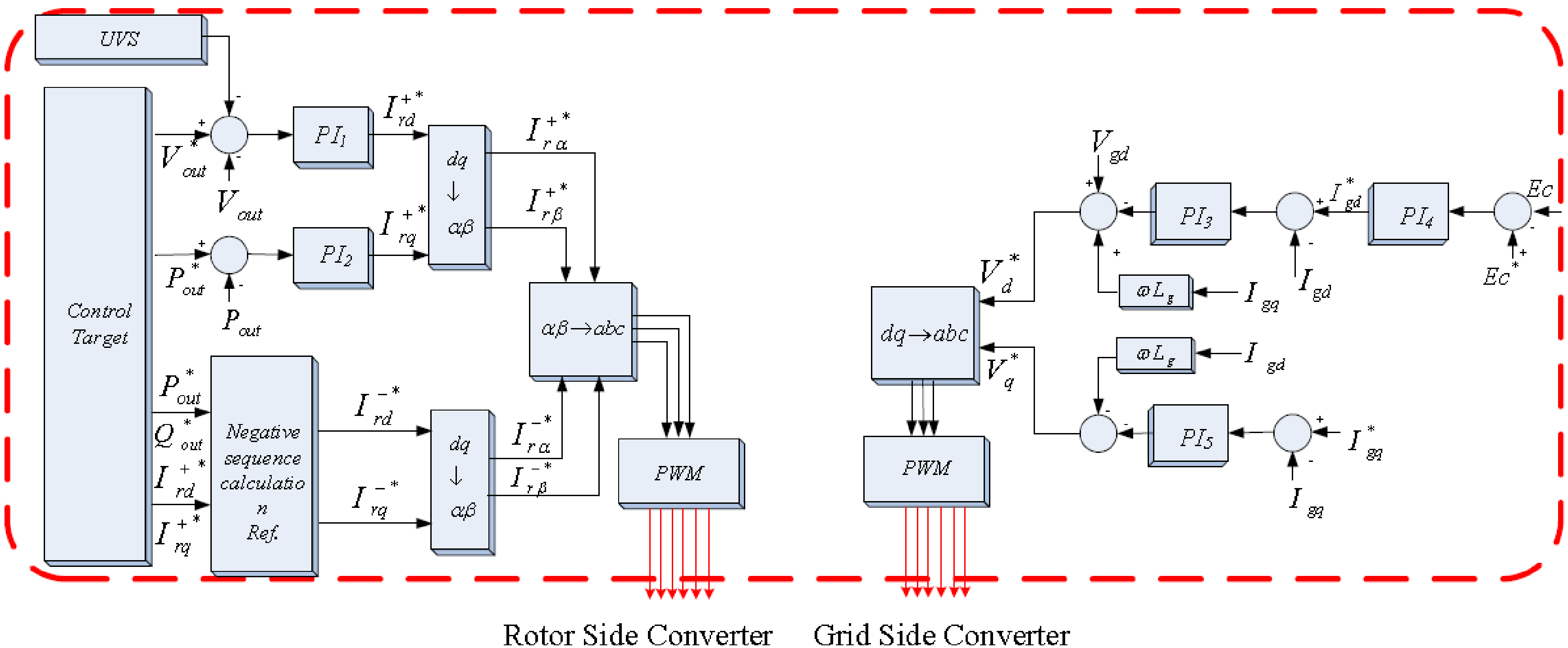
- System is stable at high loading conditions with UVS:



Stability and control

DFIG-based Microgrid Stability

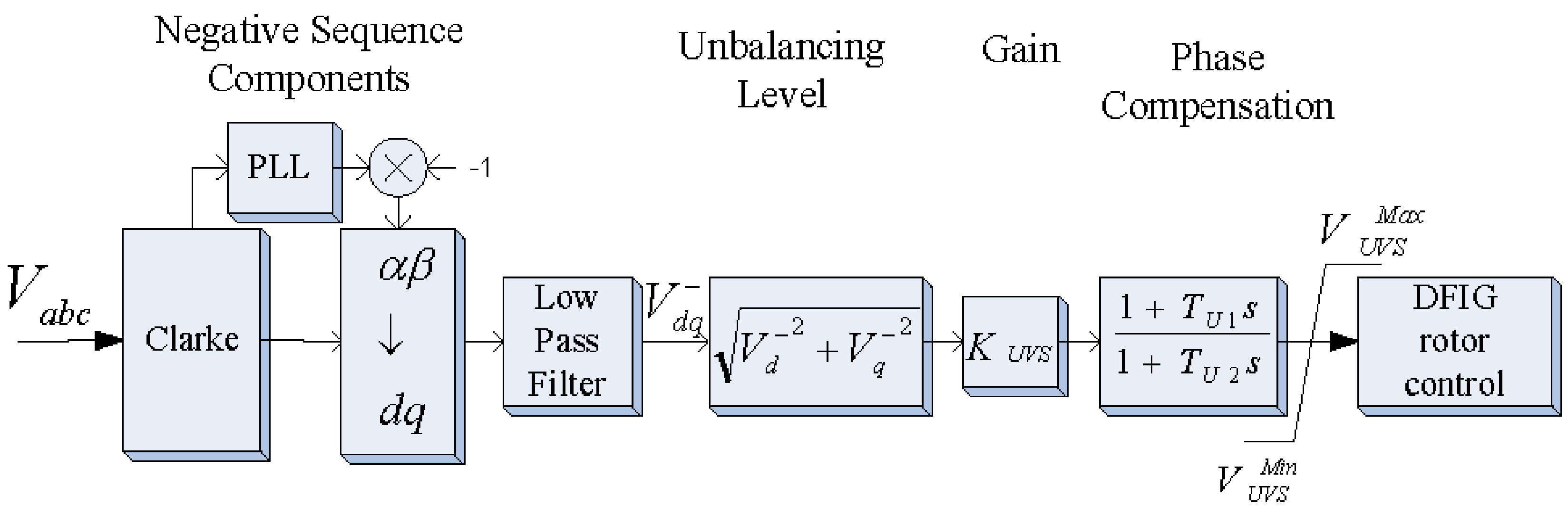
- DFIG control with UVS:



Stability and control

DFIG-based Microgrid Stability

- UVS:

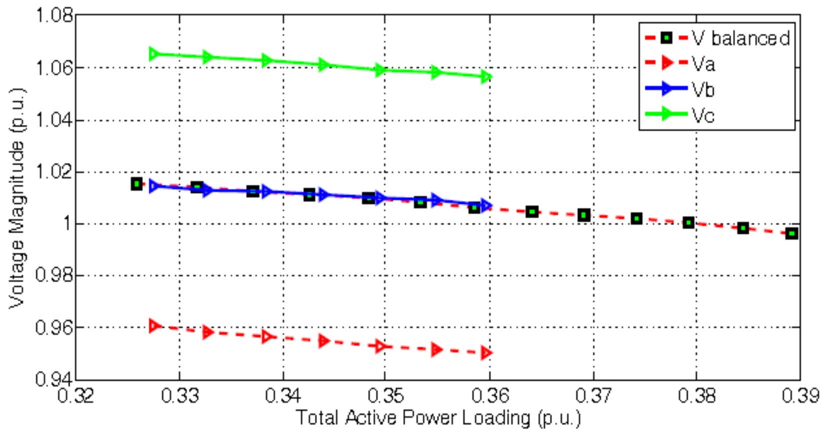


Stability and control

DFIG-based Microgrid Stability Example

- When the system unbalancing increases, the maximum loadability of the system decreases:

$k(\%)$	Maximum active power loadability (p.u.)	V_a (p.u.)	V_b (p.u.)	V_c (p.u.)
0	0.389	0.996	0.996	0.996
5	0.384	0.978	0.998	1.015
10	0.379	0.962	0.998	1.035
15	0.359	0.950	1.007	1.056
20	0.350	0.935	1.011	1.073
25	0.335	0.921	1.016	1.090

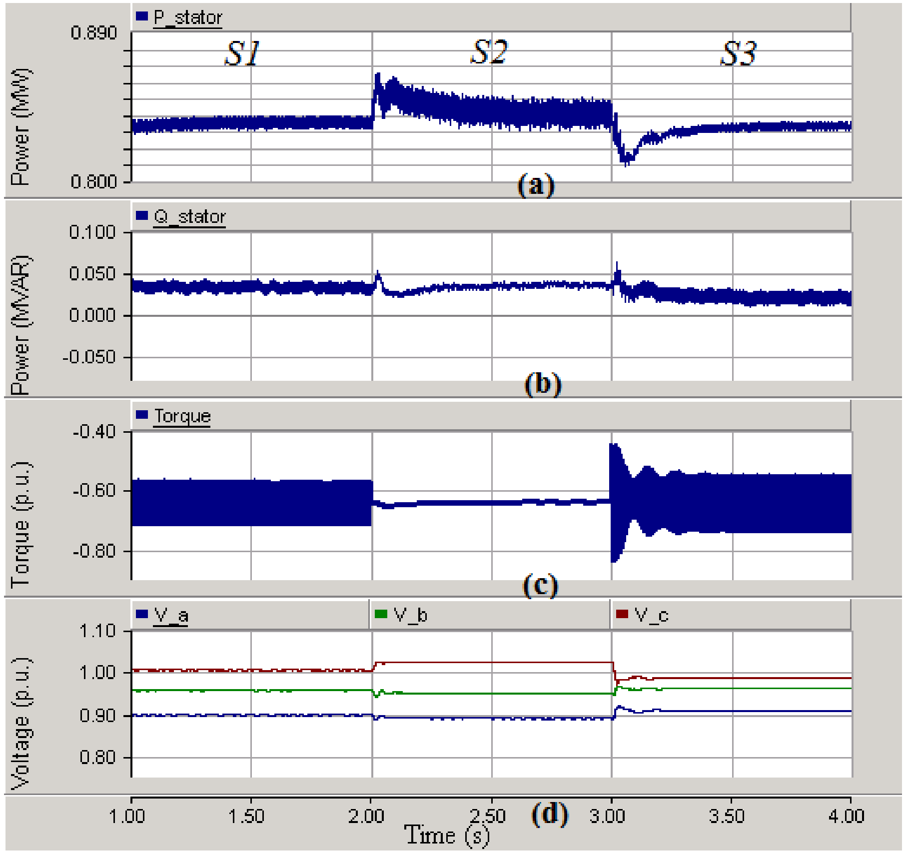


Stability and control

DFIG-based Microgrid Stability Example

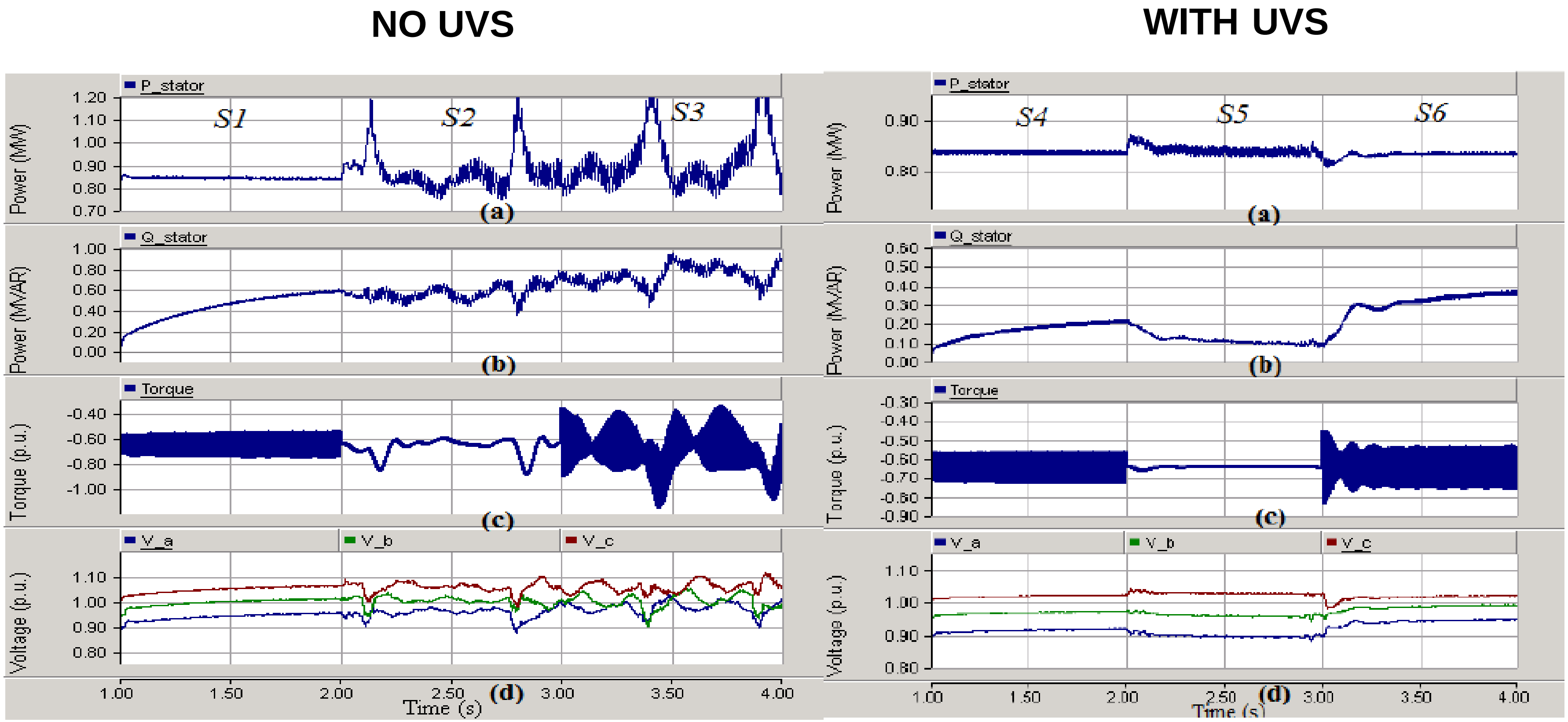
UVS impact on DFIG:

- S1: Classical control balanced approach.
- S2: Limiting the electrical torque oscillations.
- S3: Limiting the stator active power oscillations.
- S4: S1 with the UVS added.
- S5: S2 with the UVS added.
- S6: S3 with the UVS added.



DFIG-based Microgrid Stability Example

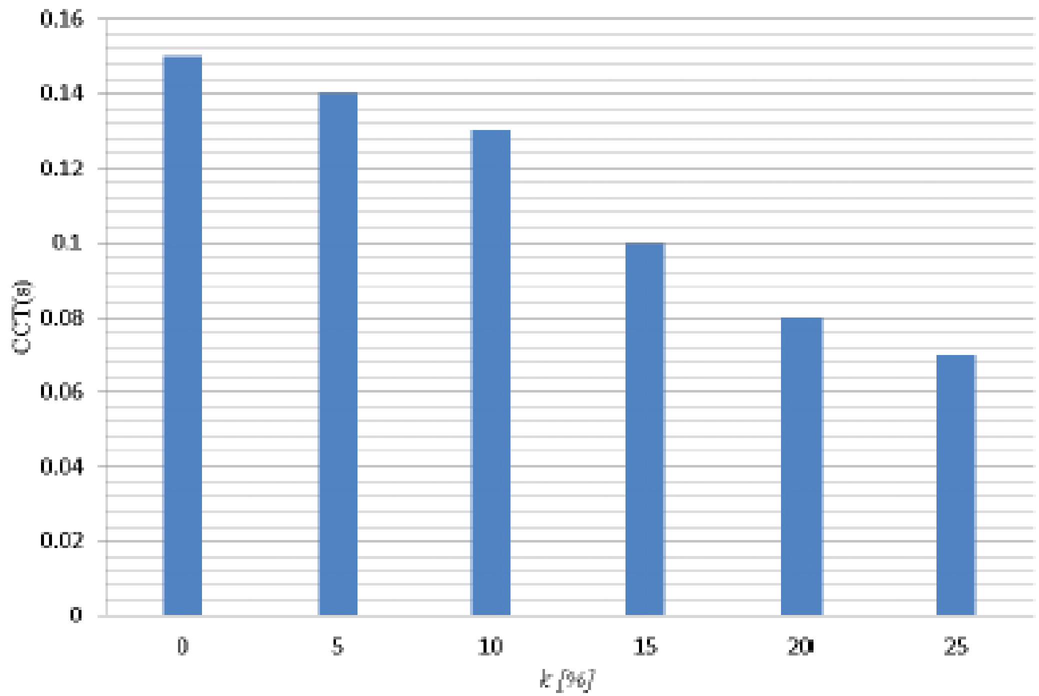
- Transient behavior:



Stability and control

DFIG-based Microgrid Stability Example

- CCT at base load for a three-phase-to-ground fault decreases with increased unbalancing:



Stability and control

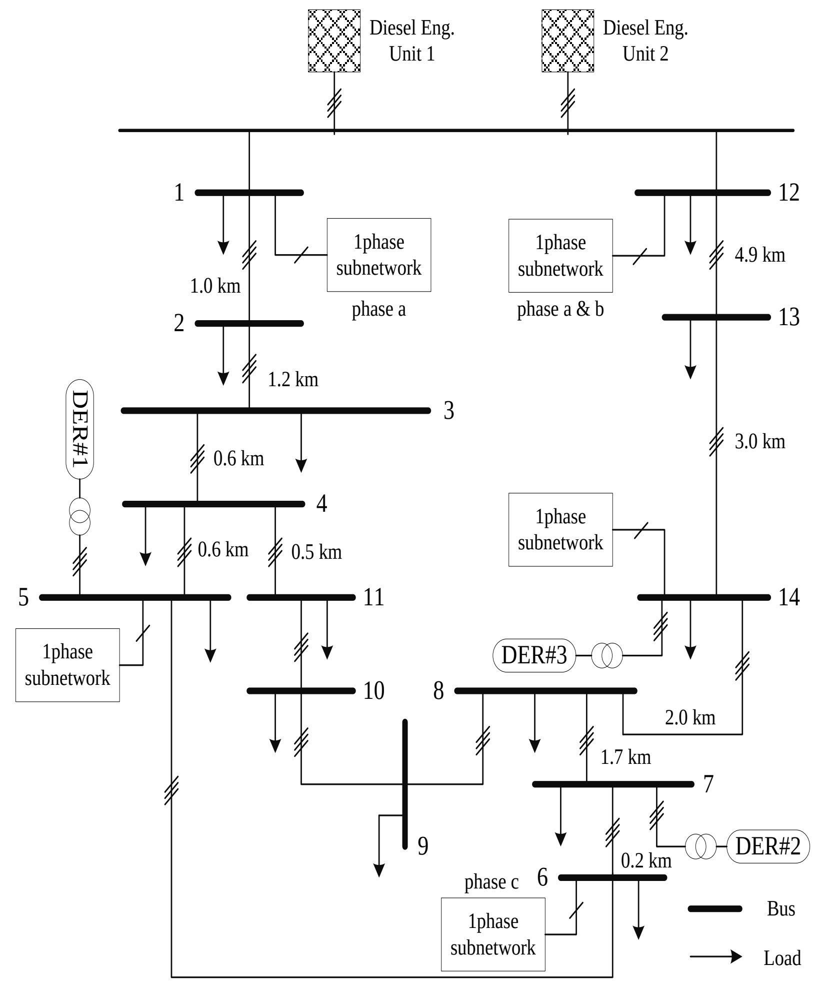
Frequency Stability and Control

- Gen. set reserves are required, especially with variable renewable sources; typically:
  - 10% of load without renewables.
  - 25% of solar PV power output.
  - 50% of wind power output.
- With high penetration of renewables, ESS is required to help regulate variations.
- Isochronous and droop controls are commonly used to share load among gen. plants, and droop control has been proposed for EES.

Stability and control

FC Test System

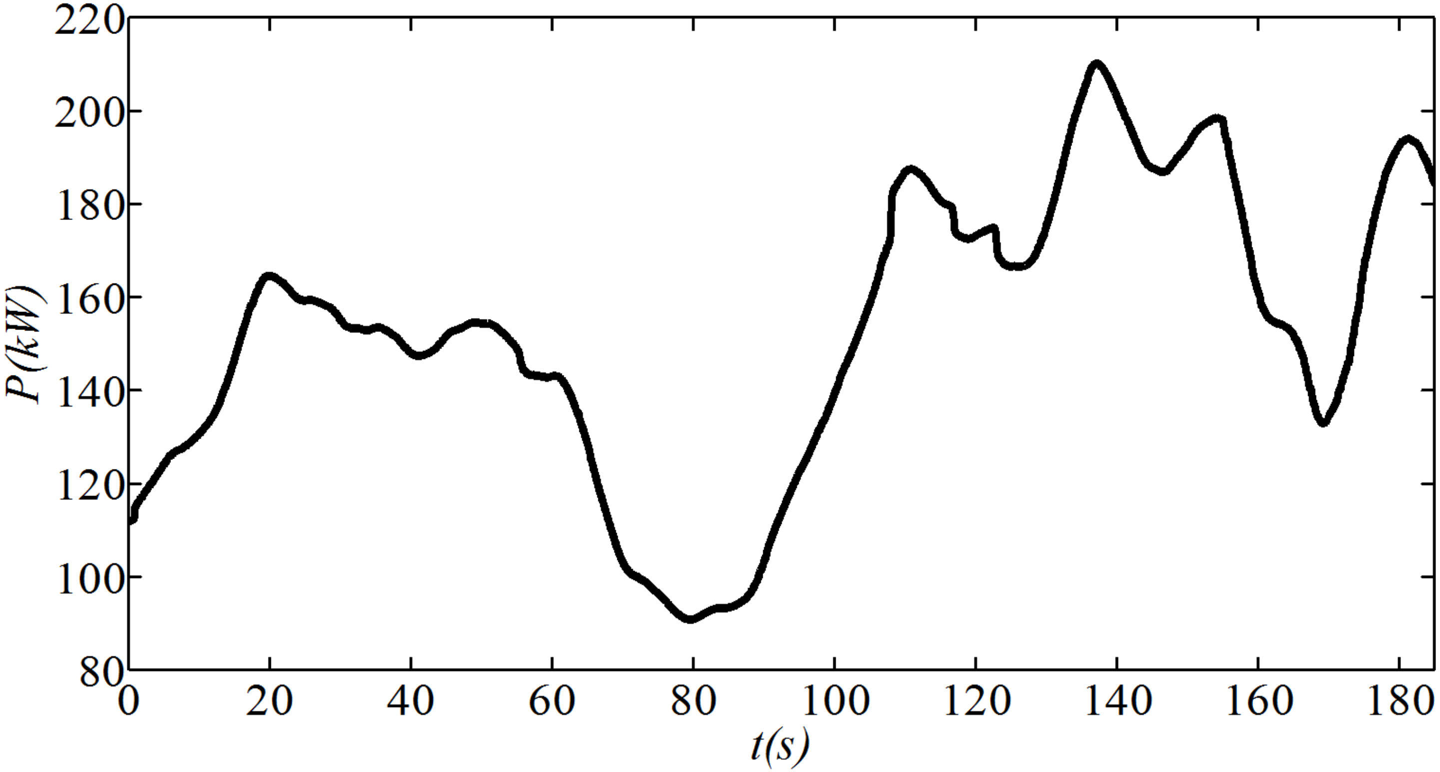
- Based on CIGRE benchmark system.
- Total load of 7 MVA.
- 2 sync. machines (diesel gens).
- 3 DERs.
- Sync. machines are master controls.
- VFC on sync. machines.
- PSCAD/EMTDC detailed modeling.



Stability and control

FC Test System

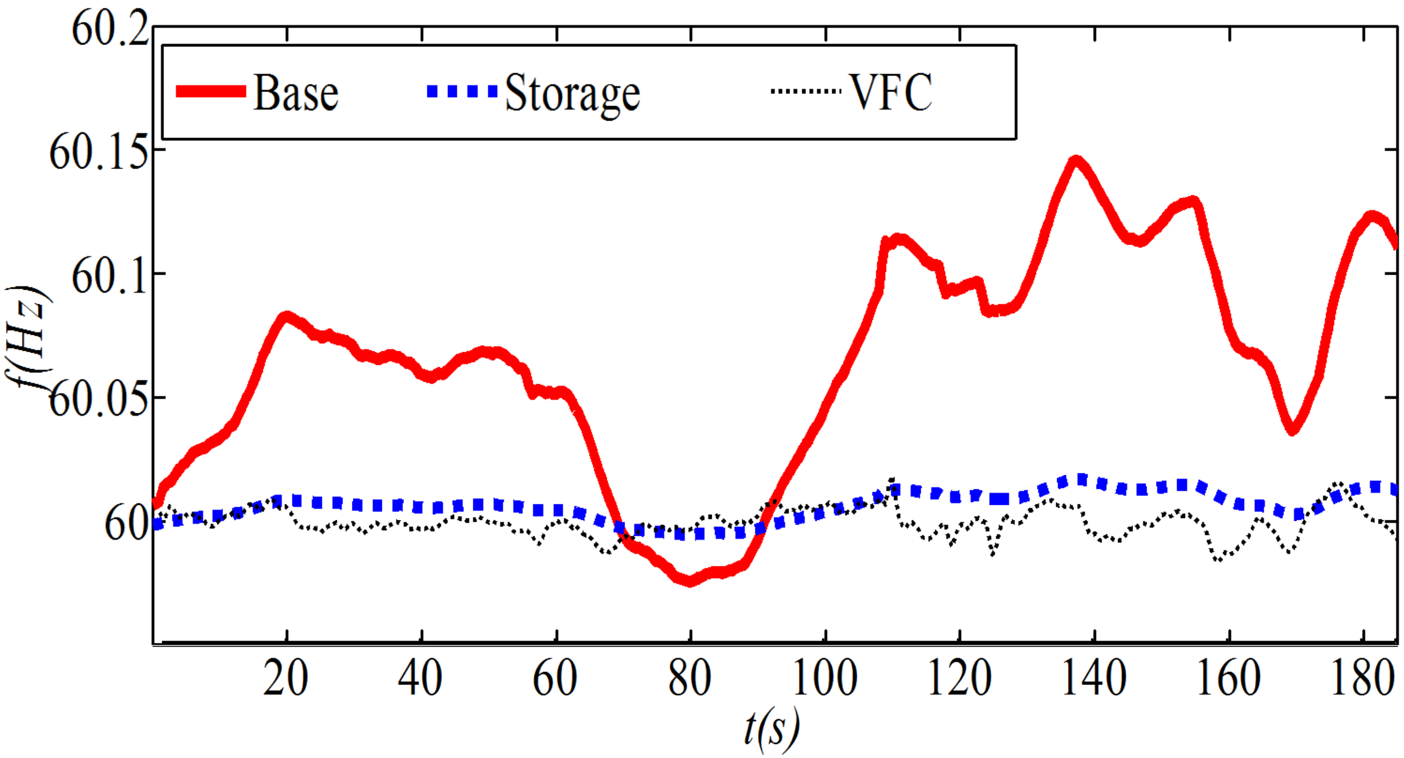
- Aggregate wind power realistic output:



Stability and control

FC Test System

- Resulting frequency variations with gen. set governors:



Stability and control

Voltage-Frequency Control (VFC)

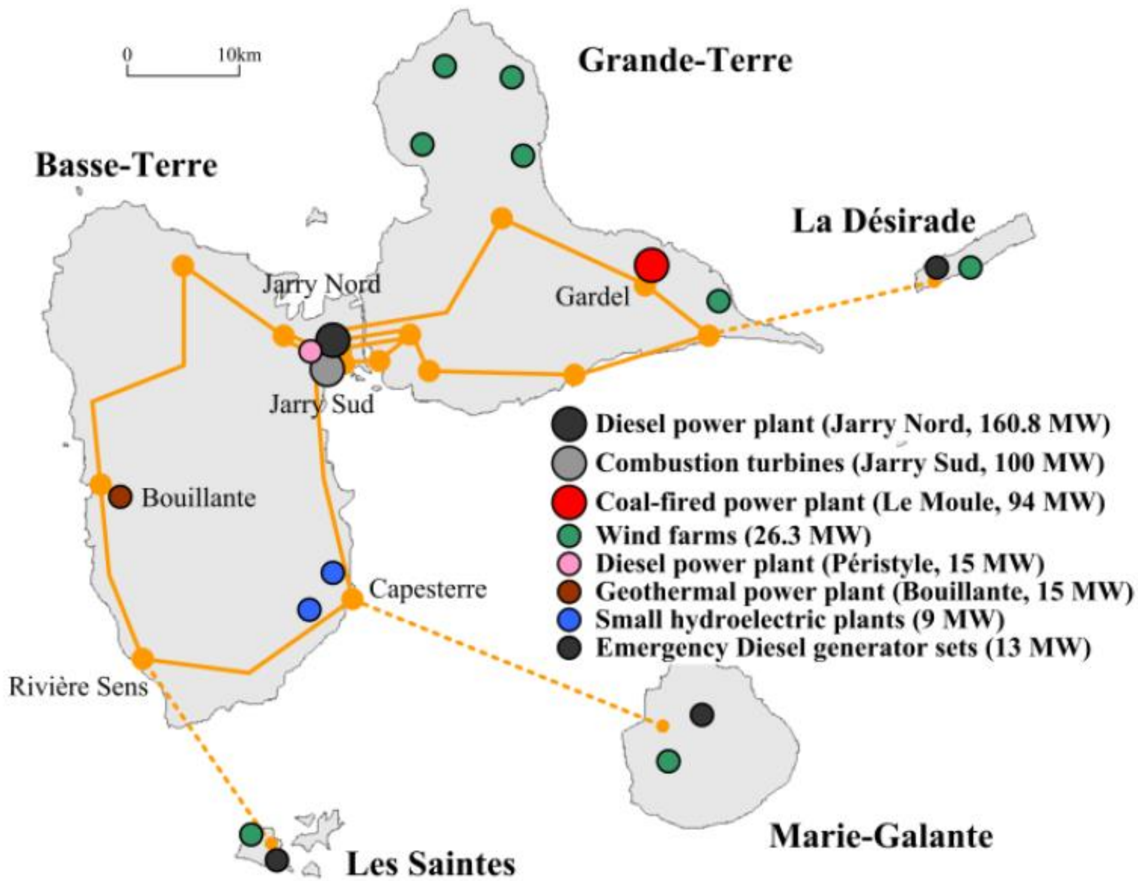
- Studies have been carried out by EDF at the archipelago of Guadeloupe of impact of gen. set voltage on frequency:

G. Delille, L. Capely, D. Souque, and C. Ferrouillat, “Experimental validation of a novel approach to stabilize power system frequency by taking advantage of load voltage sensitivity,” in *Proc. of IEEE PowerTech Eindhoven*, June 2015.

Stability and control

VFC

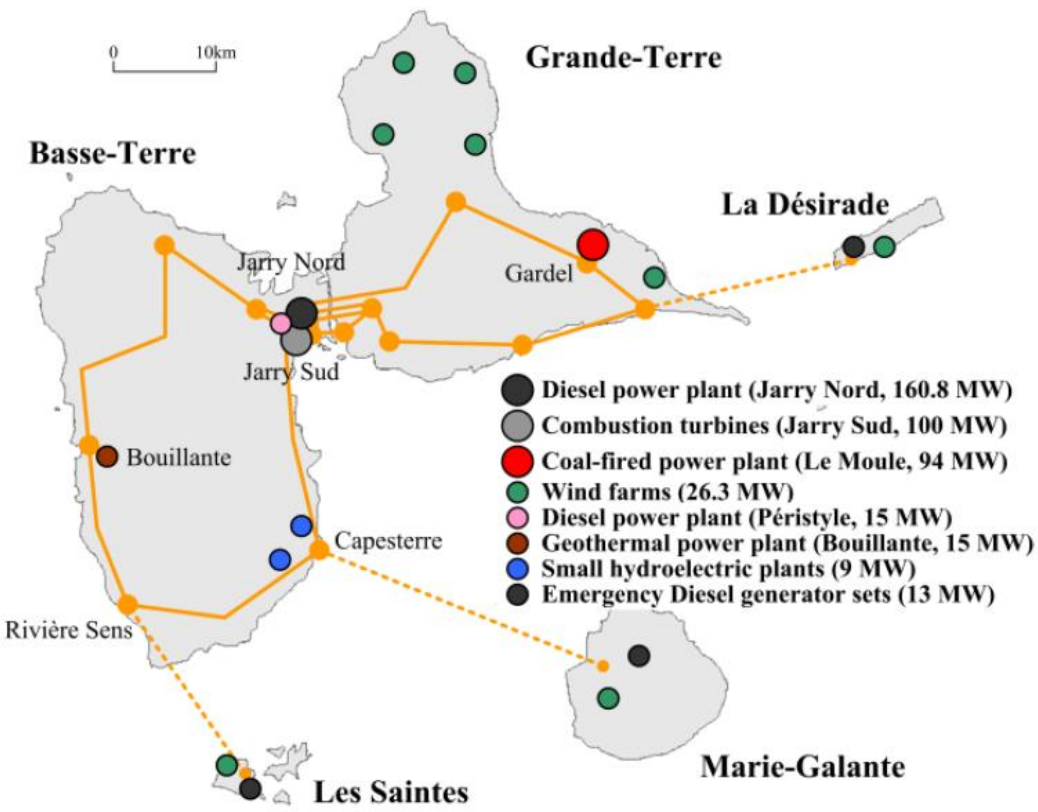
- Microgrid:

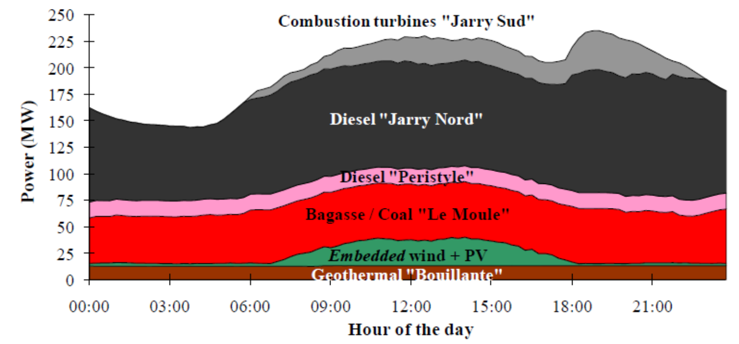


Stability and control

VFC

- Microgrid:

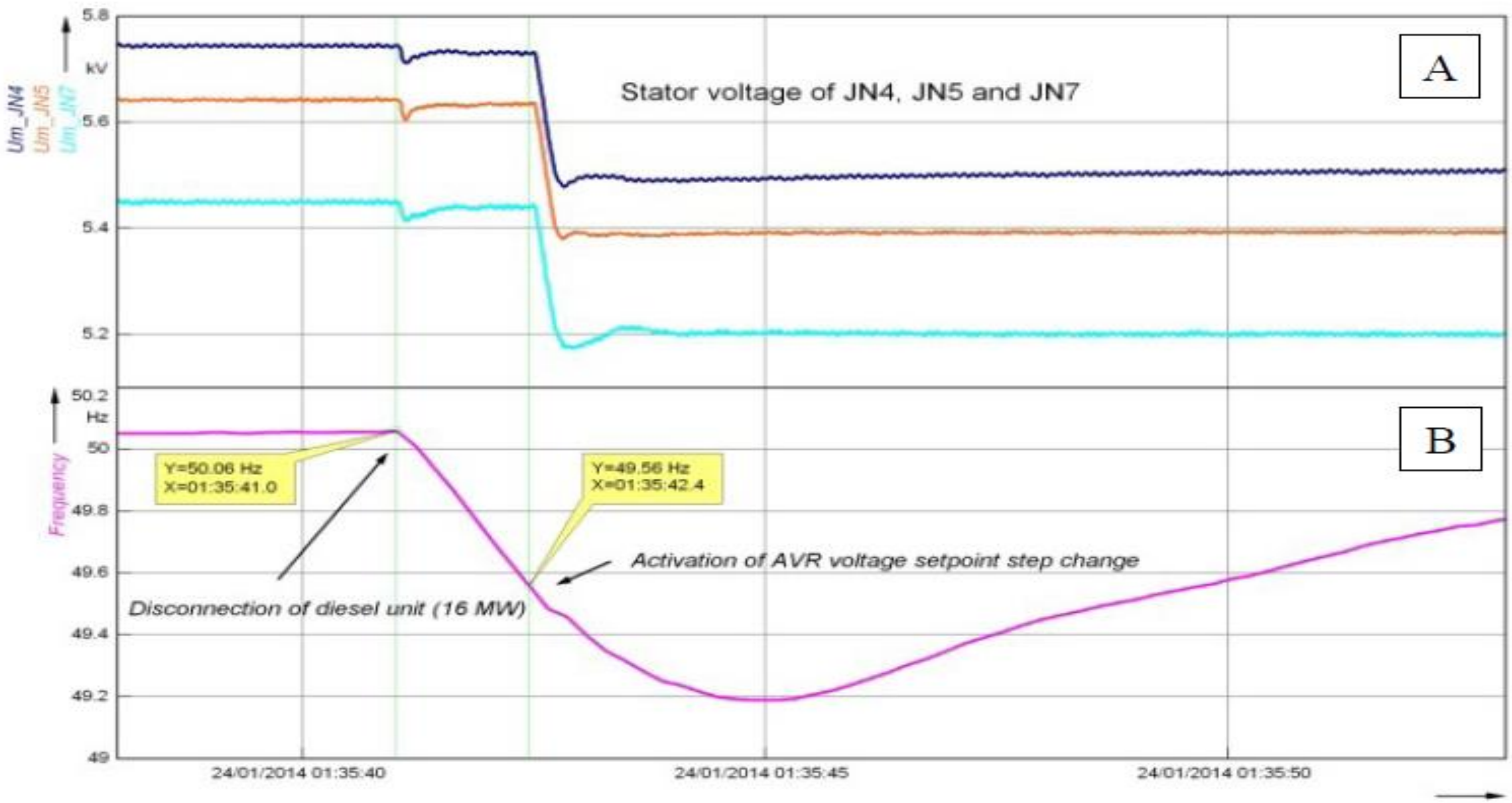




Stability and control

VFC

- Effect of voltage changes at Jarry Nord plant :



Stability and control

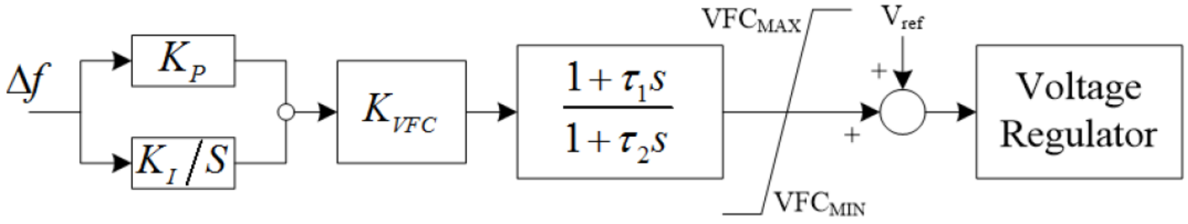
VFC

- M. Farrokhabadi, C. A. Cañizares, and K. Bhattacharya, “Frequency Control in Isolated/Islanded Microgrids Through Voltage Regulation,” *IEEE Transactions on Smart Grid*, accepted September 2015, 10 pages.
- Based on voltage dependency of microgrids loads:

$$P = P_0\left(\frac{V}{V_0}\right)^{n_p} \xrightarrow{n_p=1.5} \Delta P_D = \left(\left(V+\Delta V\right)^{1.5} - V^{1.5}\right)\frac{P_0}{V_0^{1.5}}$$

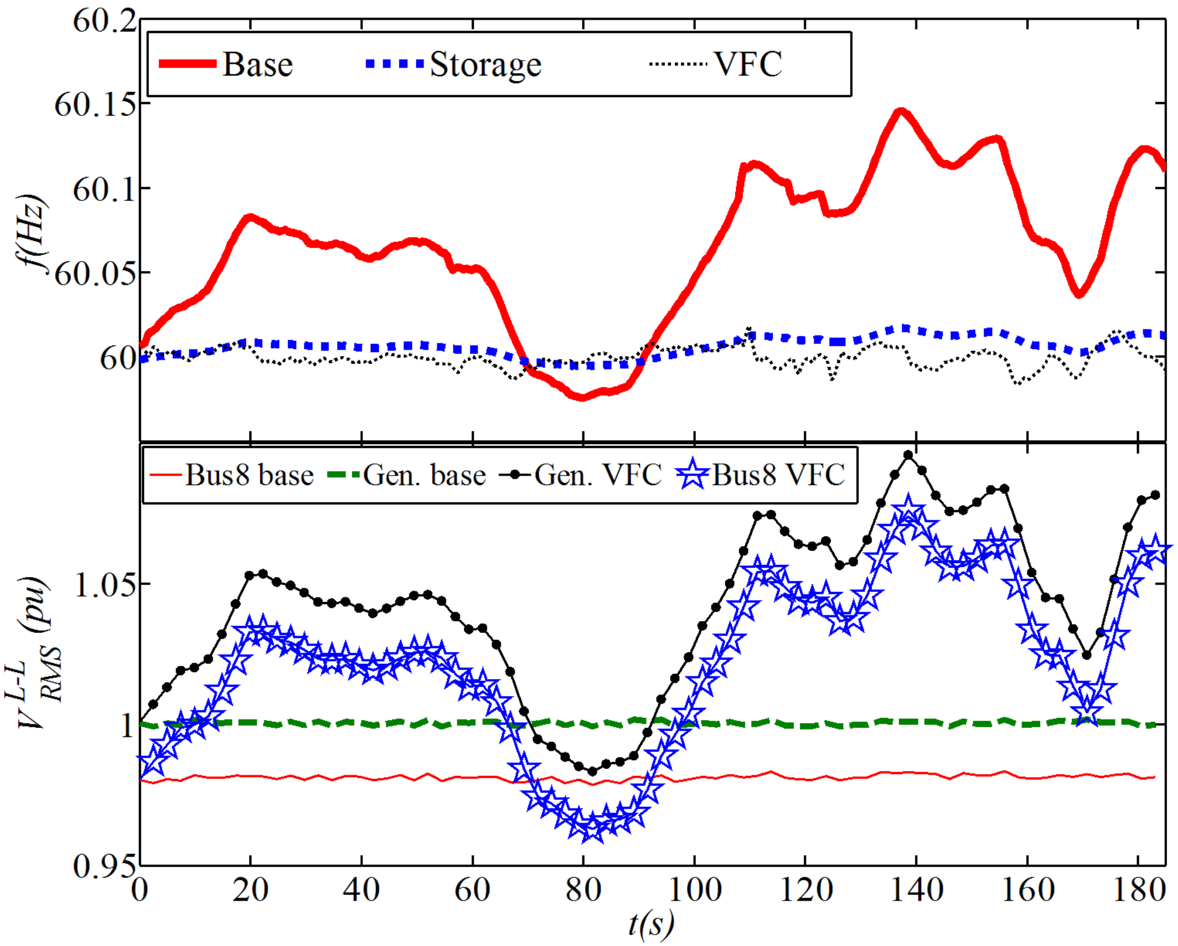
$$\xrightarrow[\Delta V=5\%]{V=V_0=1\text{ pu}} \Delta P_D = \left(\left(1+\Delta V\right)^{1.5} - 1\right)P_0 = 7.6\% P_0$$

- Hence, a controller similar to a PSS can be added to any microgrid voltage regulator:



Stability and control
VFC

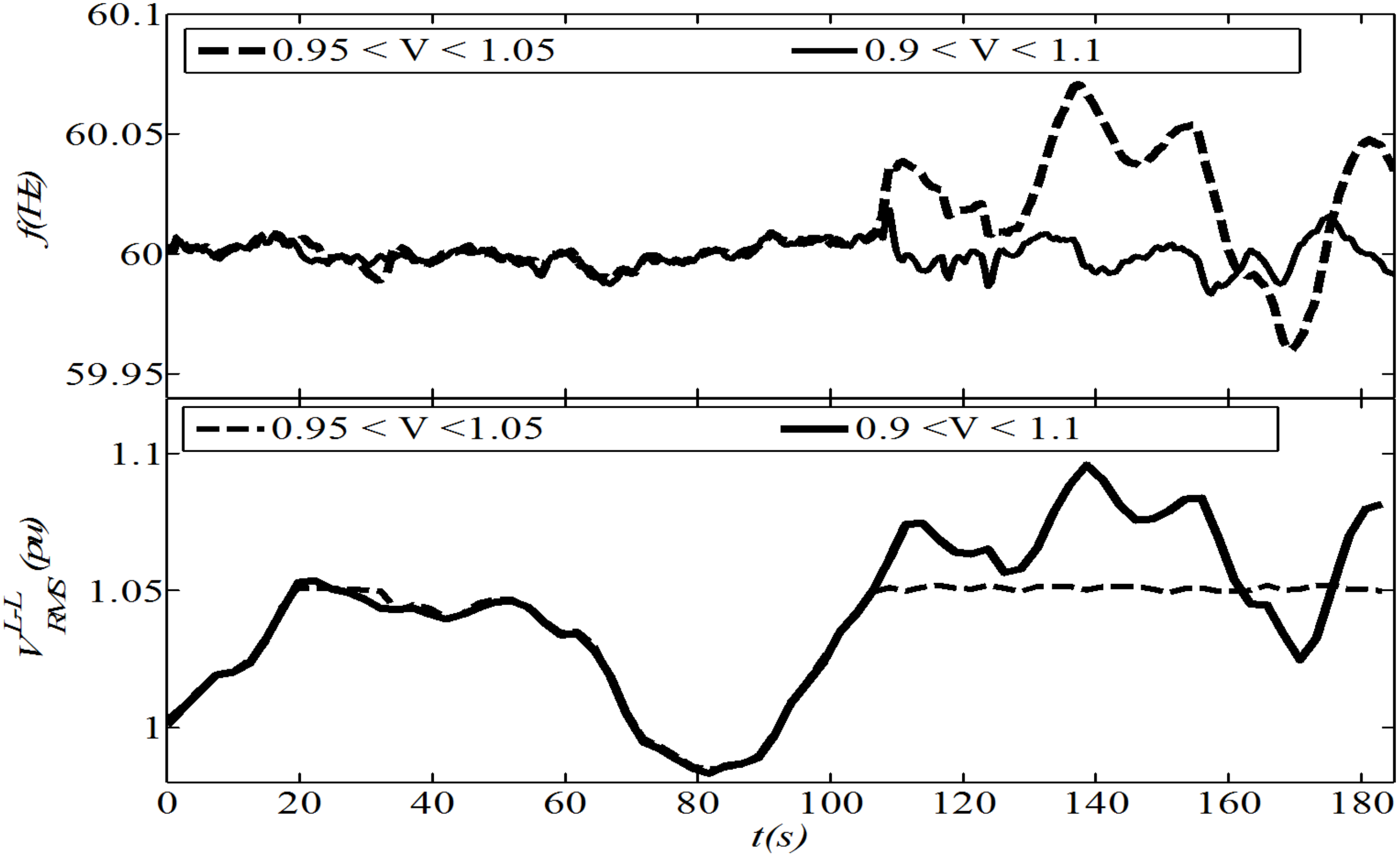
- Results:



Stability and control

VFC

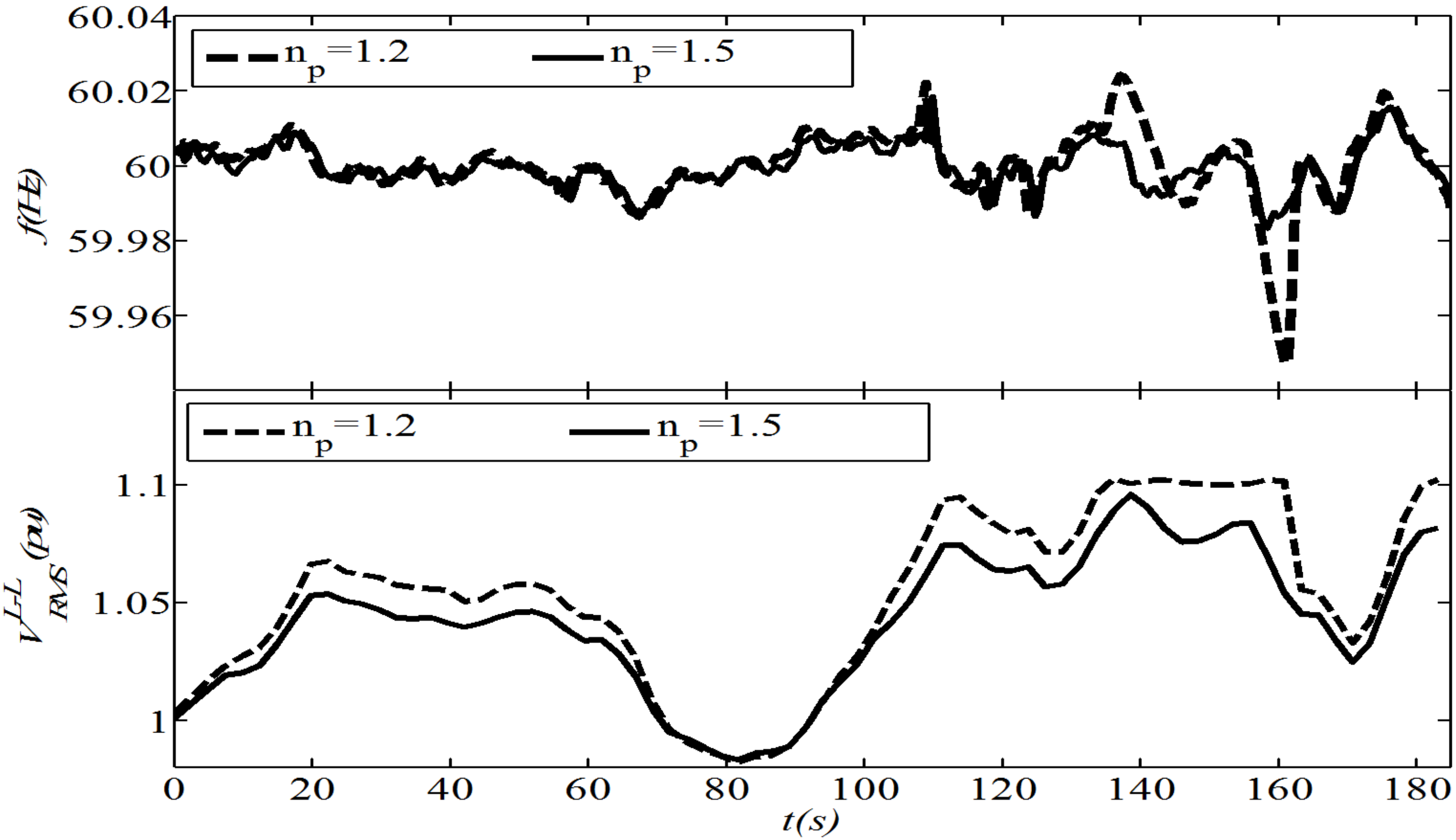
- Effect of regulator voltage limits:



Stability and control

VFC

- Effect of load composition:



V and F Stability and Control Conclusions

- Voltage profiles are fairly flat with proper voltage regulation; hence, voltages and feeders are not a major issue in microgrids.
- Load unbalance:
  - Loadability of the system decreased as unbalancing increases; eventually, critical poles cross the imaginary axes and the system becomes unstable.
  - The system is less transiently stable as unbalancing increased.
  - Classical phasor-models and tools are not appropriate to analyze and understand stability in microgrids.
  - Proposed UVS is simple and improves microgrid stability.

Stability and control

V and F Stability and Control Conclusions

- Frequency stability:
  - Not an issue with enough gen. set reserves.
  - With high penetration of variable renewables ESS is required.
- VFC:
  - It has been demonstrated in a real, large microgrid that load power voltage dependency can be used as reserves to control frequency.
  - Proposed VFC acts as an additional control to conventional frequency controllers, decreasing dependency on ESS and potentially yielding savings.

Outline

- Introduction
- Definitions
- Stability and control
- **Energy management systems**

Energy management systems
The Challenge

- An Energy Management System (EMS) is a set of protocols and computer applications designed to assist power system operators in the operation of the grid, including:
  - State estimation.
  - OPF.
  - Voltage control/reactive power optimization.
  - Security assessment.
  - Load forecasting.

Energy management systems
The Challenge

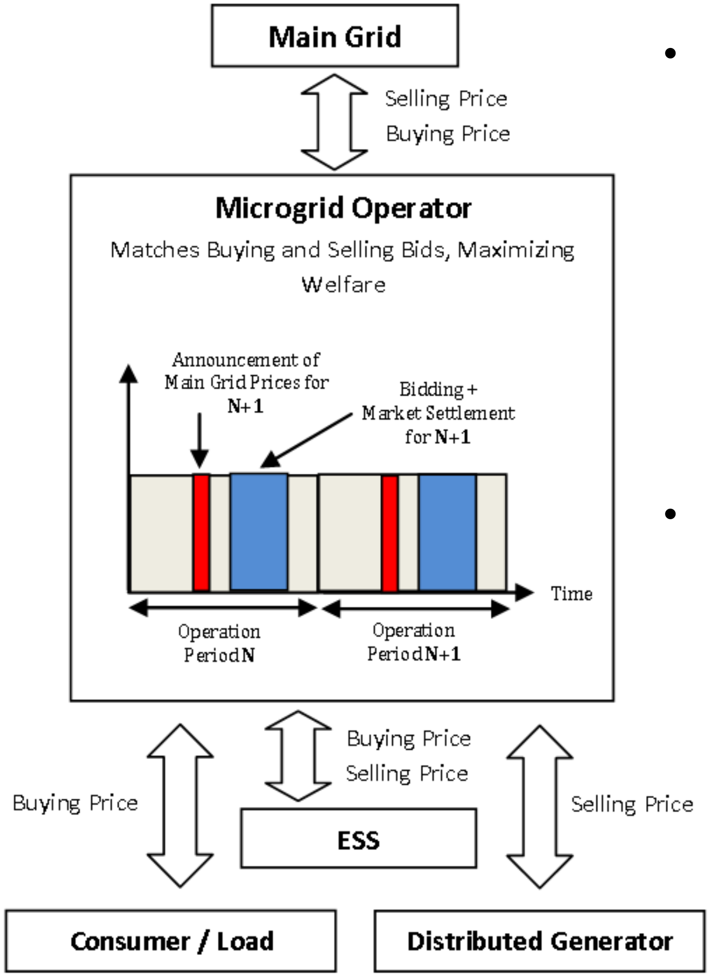
- In microgrids, all the EMS applications must be performed by an autonomous automated system.
- The operation of an EMS in a microgrid becomes more challenging due to the critical demand-supply balance, low inertia of the system, non-dispatchable renewable sources, and the presence of energy storage systems.

Energy management systems
The Challenge

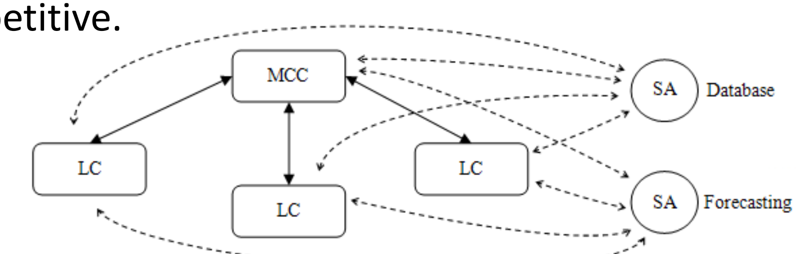
- The general EMS case:
  - Find the optimal or near optimal unit commitment of units.
  - Find the optimal or near optimal dispatch of units.
  - Find the optimal or near optimal voltage settings.
- Challenges for EMS in microgrids:
  - Intermittent and hard to predict generation.
  - System states are coupled in time due to Unit Commitment (UC) decisions and Energy Storage Systems (ESS).
  - Multiple objectives (e.g. total cost, emissions)
  - Multiple owners and sometimes conflicting objectives.

Energy management systems

Decentralized EMS

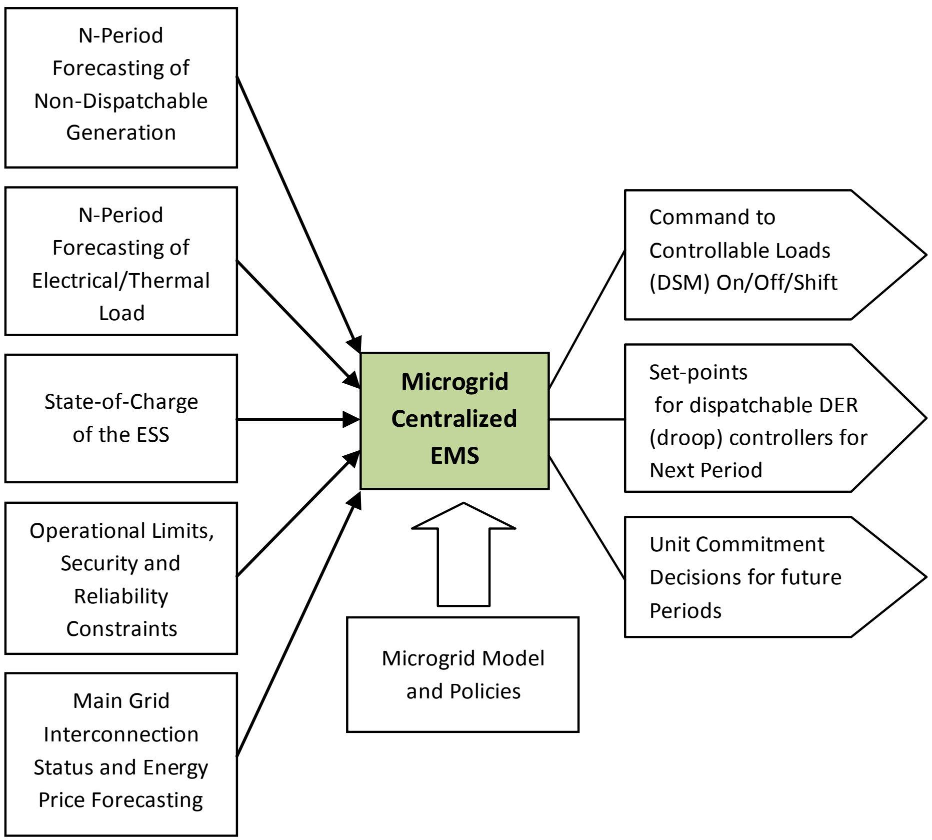


- Advantages:
  - Market-like environment, with direct incentive for investments.
  - More suitable for grid-connected mode with multiple owners.
  - Distributed decision-making, capturing local updated information and objectives.
  - Allows for “plug-in” approach.
- Disadvantages:
  - Not able to send appropriate signals for multi-stage operation planning with intermittent generation.
  - Has problems in oligopolic microgrids (stand-alone) and requires special rules to make intermittent sources competitive.



Energy management systems

Centralized EMS



- Advantages:
  - Allows the implementation of traditional optimization methods.
  - Able to handle multi-period optimization.
  - More suitable for stand-alone operation, when demand-supply balance within the microgrid is critical.
- Disadvantages:
  - Obligates the different actors to share information about operation costs and constraints.
  - Difficult to implement in a multiple-owner microgrid with different and conflicting objectives.
  - The EMS needs to be re-adjusted when more units are added.

Energy management systems

EMS Deterministic Model

- The EMS defines the optimal steady-state conditions of a microgrid while considering its security and reliability, and can be formulated as a multi-step optimization problem as follows:

$$
\begin{aligned}
& min \sum_{k_t=t}^{t+K} F\left(x_{k_t}, z_{k_t}, u_{k_t}, p_{k_t}\right) \\
& s.t. \quad z_{k_t+1} = w\left(x_{k_t}, z_{k_t}, u_{k_t}, p_{k_t}\right) && \forall k_t = t, \dots, t+K \\
& \qquad g_{k_t}\left(x_{k_t}, z_{k_t}, u_{k_t}, p_{k_t}\right) = 0 && \forall k_t = t, \dots, t+K \\
& \qquad h_{k_t}\left(x_{k_t}, z_{k_t}, u_{k_t}, p_{k_t}\right) \leq 0 && \forall k_t = t, \dots, t+K \\
& \qquad \left\| u_{k_t+1} - u_{k_t} \right\| \leq \Delta u_{k_t}^{max} && \forall k_t = t, \dots, t+K
\end{aligned}
$$

Outputs:

- Unit commitment
- Dispatch of units
- Voltage settings

z_{kt} : Vector of discrete time-dependent variables, typically state of charge of storage systems.

p_{kt} : Vector of parameters representing the best available estimation at step $k = t$ of system demand, intermittent generation, fuel prices, etc., for all the time-steps in the multi-stage horizon.

u_{kt} : Vector representing the control variables.

x_{kt} : Represents the time-independent variables, such as voltages and phase angles.

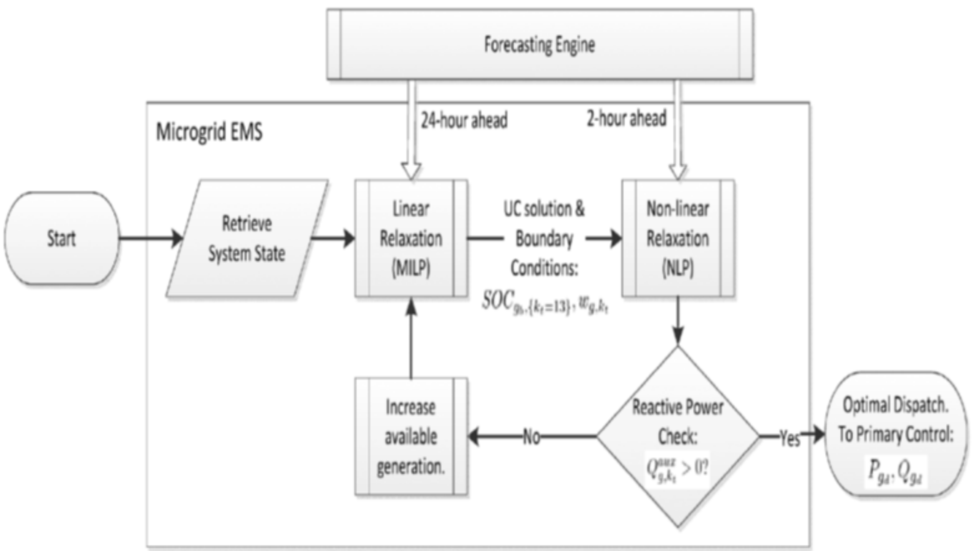
Energy management systems

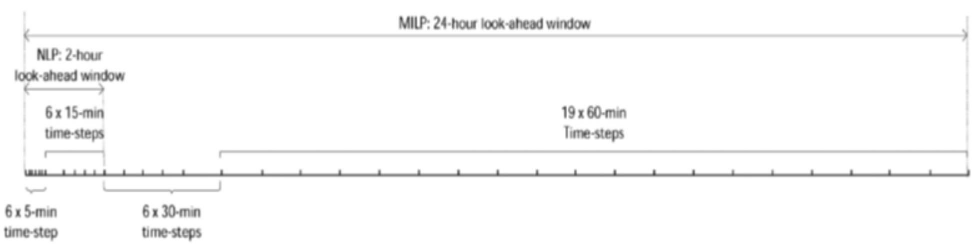
EMS Deterministic Model

- Model Predictive Control (MPC) approach:
  - An optimization problem is formulated and solved at each discrete time-step.
  - At each time-step, the solution to the optimal control problem is solved over a certain pre-defined horizon using the current state of the system as the initial state.
  - The optimization calculates a control sequence for the whole horizon, but only the control action for the next time step is implemented.
  - The process is repeated at the next time-step.

Energy management systems

EMS Deterministic Model I

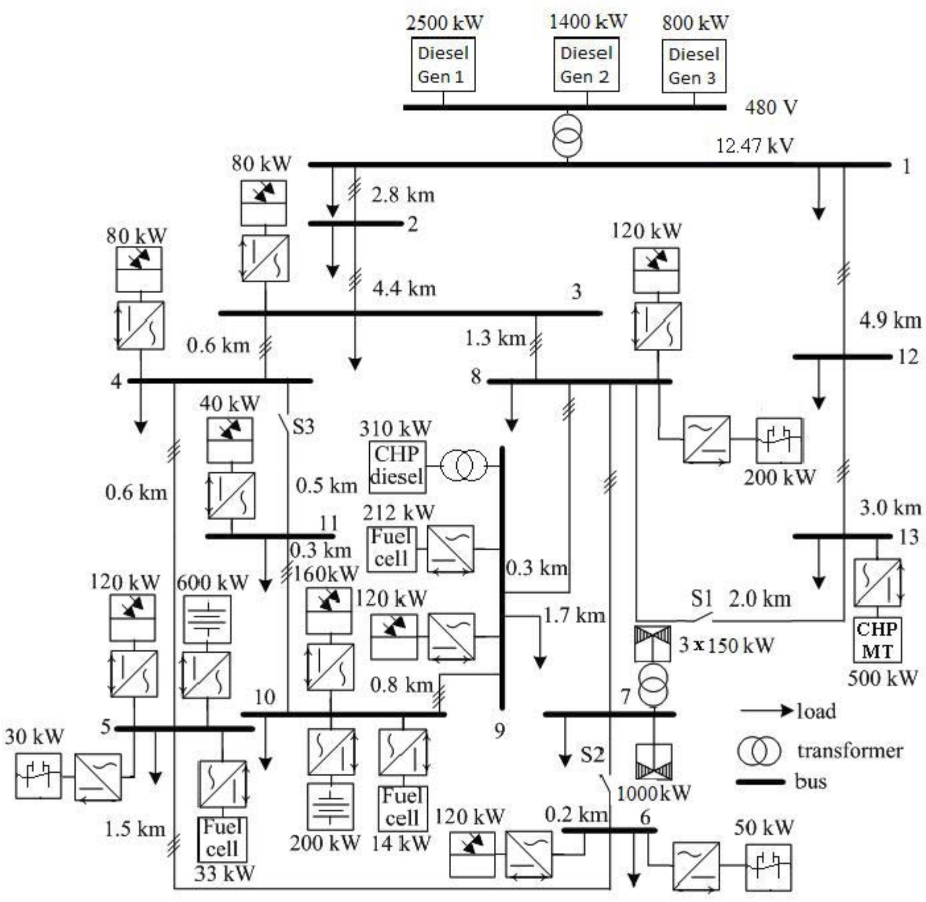


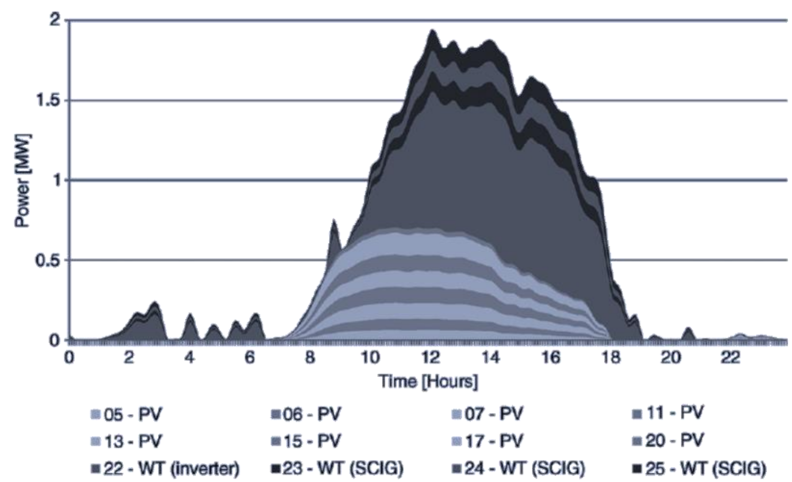


- D. Olivares, C. A. Cañizares, and M. Kazerani, "A Centralized Energy Management System for Isolated Microgrids," *IEEE Transactions on Smart Grid*, vol. 6, no. 4, July 2014, pp. 1864-1875.
- Decoupled approach:
  - UC and Economic Load Dispatch (ELD) performed with different update rates.
  - Two different resolutions and horizons of forecast.
  - Multi-stage ELD to optimize ESS operation.
  - Delivers UC decisions and operating points to DERs (power output of DG, output/input of ESS, shiftable/shedable loads commands, etc.).
  - Detailed 3-phase model to represent unbalanced conditions typical of microgrids (distribution networks).

Energy management systems

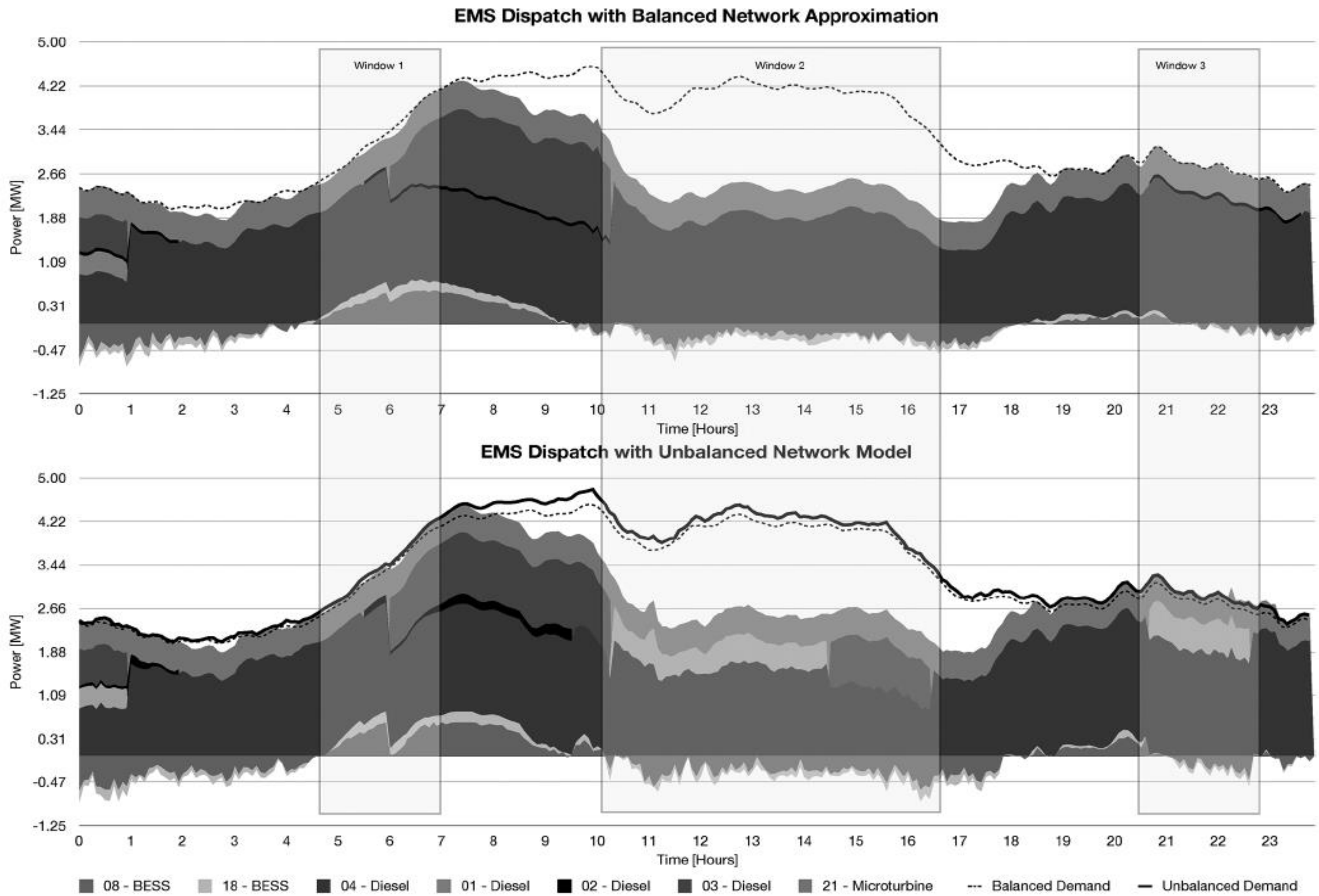
EMS I Example





Energy management systems

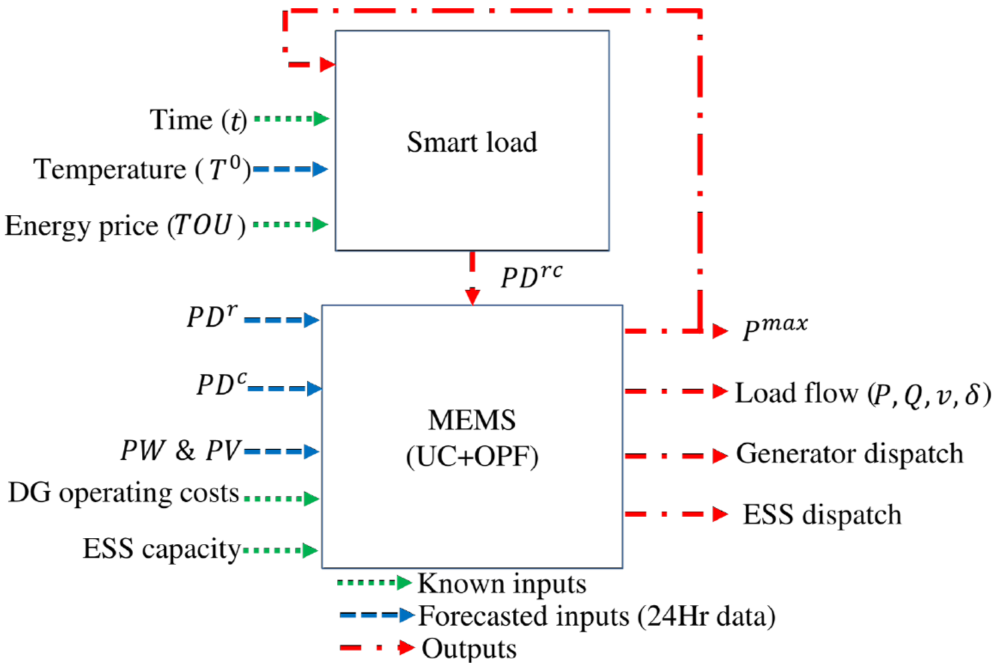
EMS I Example



Energy management systems

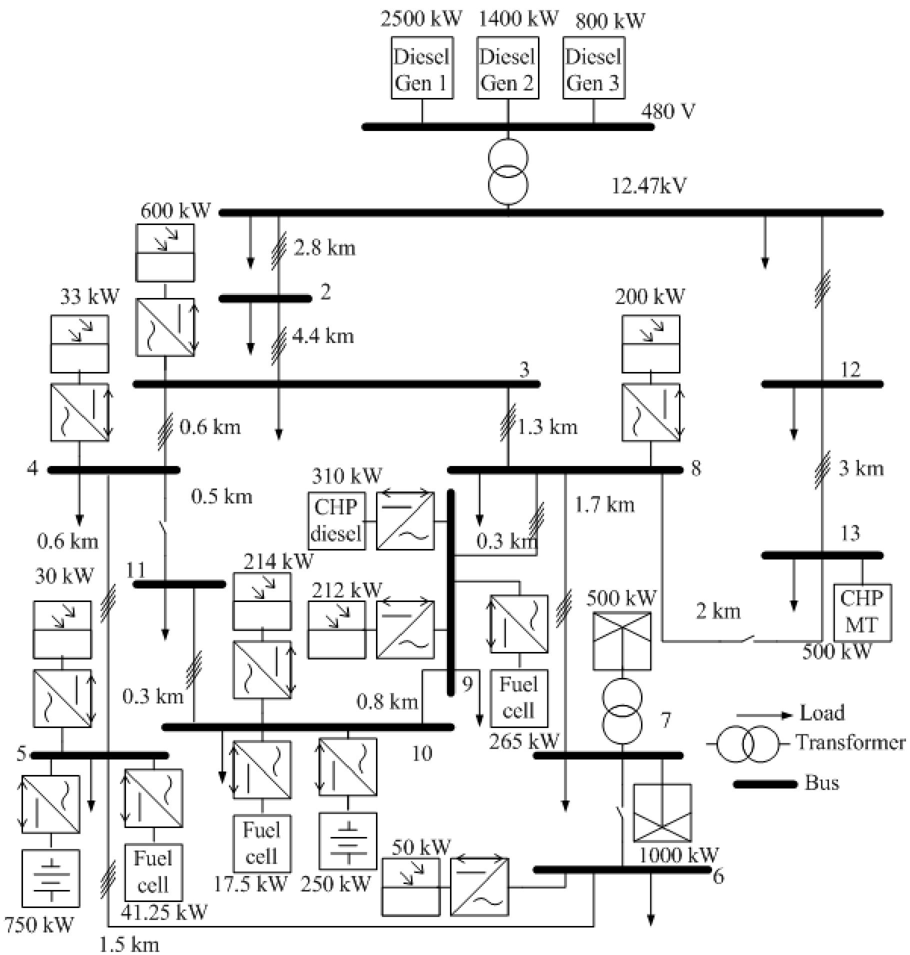
EMS Deterministic Model II

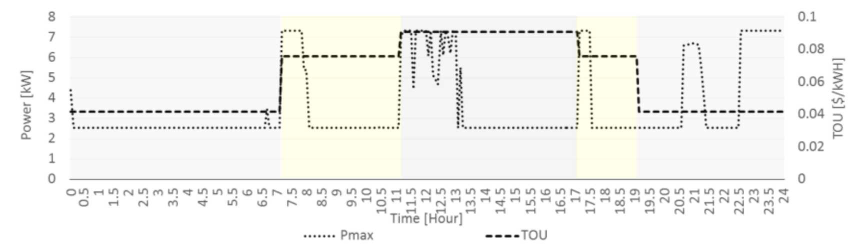
- B. V. Solanki, A. Raghurajan, K. Bhattacharya, and C. A. Cañizares, "Including Smart Loads for Optimal Demand Response in Integrated Energy Management Systems for Isolated Microgrids," *IEEE Transactions on Smart Grid*, accepted November 2015, 10 pages.
- Microgrid EMS (MEMS) considers:
  - Residential controllable loads.
  - Unit Commitment (UC) for Distributed Energy Resources (DERs) and power flow constraints simultaneously.
- A Neural Network (NN) based Residential Controllable Lod Porfile Estimator (RCLPE) is used to determine smart load models.
- MPC is used to account for uncertainties associated with renewables and electricity demand.



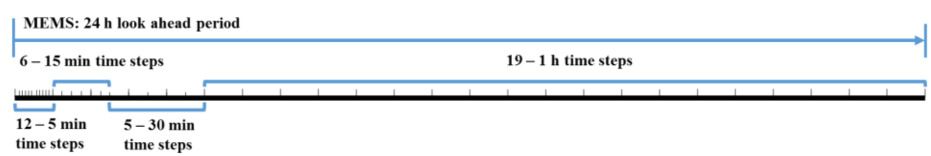
Energy management systems

EMS II Example



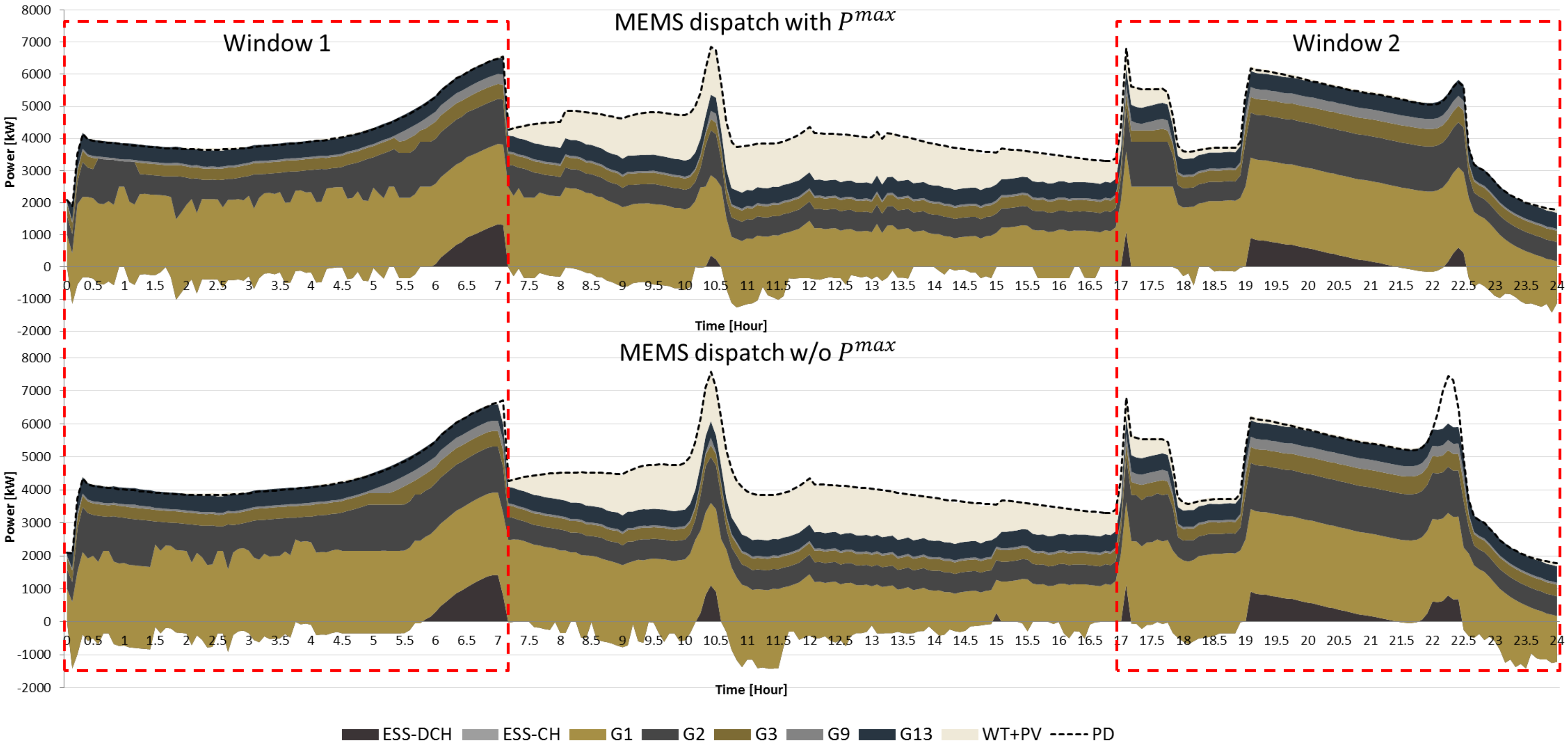


DR control [%]	Objective function [$]	Energy served by ESS [kWh]	Energy curtailed [kWh]	Load factor	Peak demand [kW]
0	83,781	3,037	528	0.580	7,575
20	62,447	2,870	351	0.589	7,431
40	42,464	2,808	185	0.6	7,287
60	25,099	2,760	41	0.611	7,141
100	19,941	2,416	0	0.631	6,851



Energy management systems

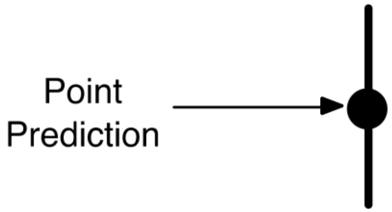
EMS II Example

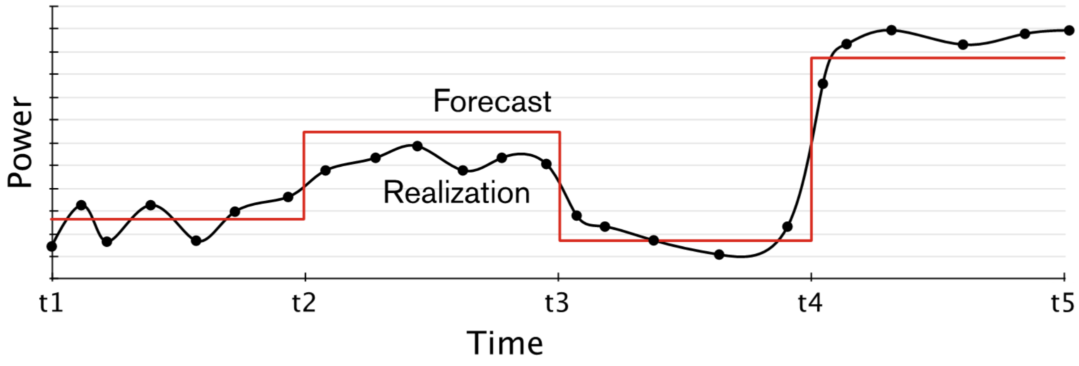


Energy management systems

EMS With Uncertainties

- Account directly in the EMS for forecast uncertainties (e.g. wind and solar generation, load), which can have a significant effect on isolated microgrids:
  1. Wait-and-see (deterministic with MPC/RCH models):
     - Close tracking of the problem with small time steps, solving the dispatch problem using the most current information, and including an explicit reserve requirement.
     - Assumes that point forecasts are accurate and the system natural reserve can handle the mismatches, otherwise shed load.

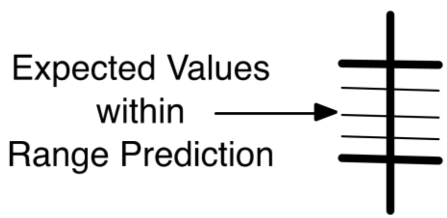


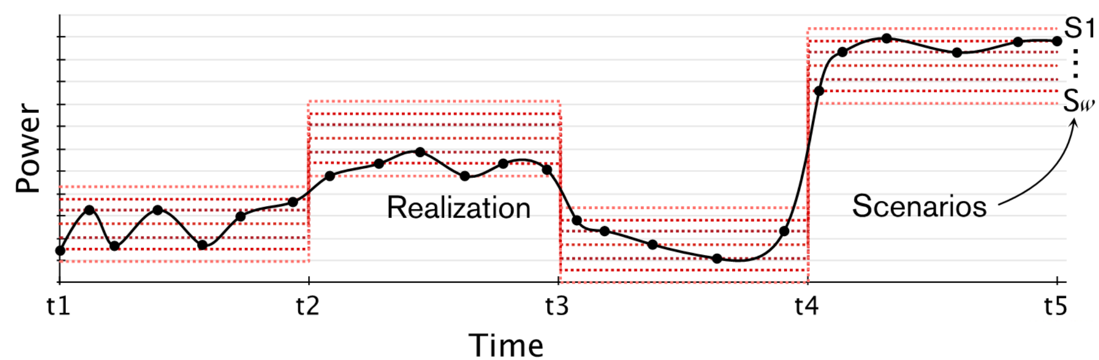


Energy management systems

EMS With Uncertainties

2. Stochastic optimization:
   - Minimize the expected cost over a discrete representation of the uncertainty, leading to large-scale problems.
   - Accounts directly for the stochastic characteristic of wind power, improving the ability of the system to perform corrective actions without load shedding.
   - First stage variables provide probabilistic guarantee on the feasibility of all second stage expected outcomes.

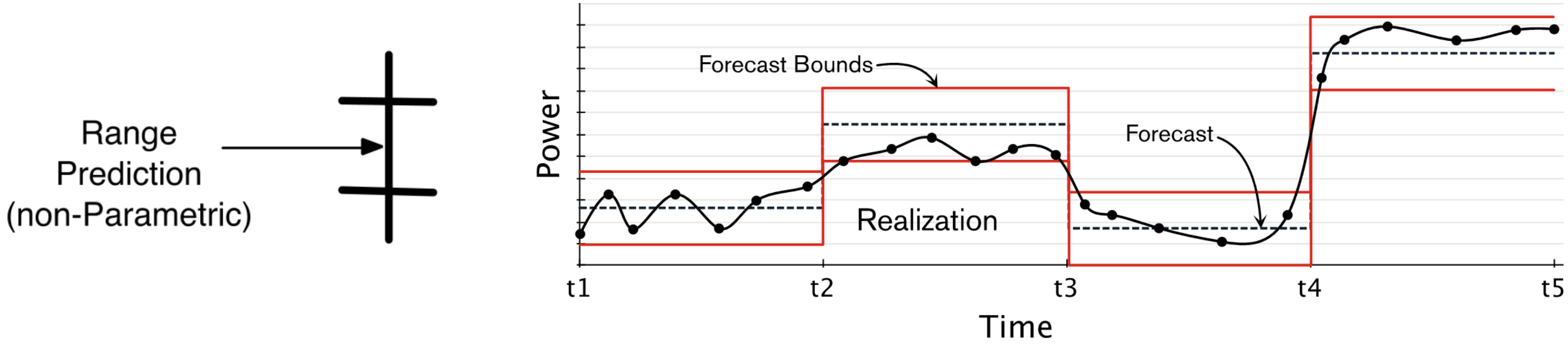




Energy management systems

EMS With Uncertainties

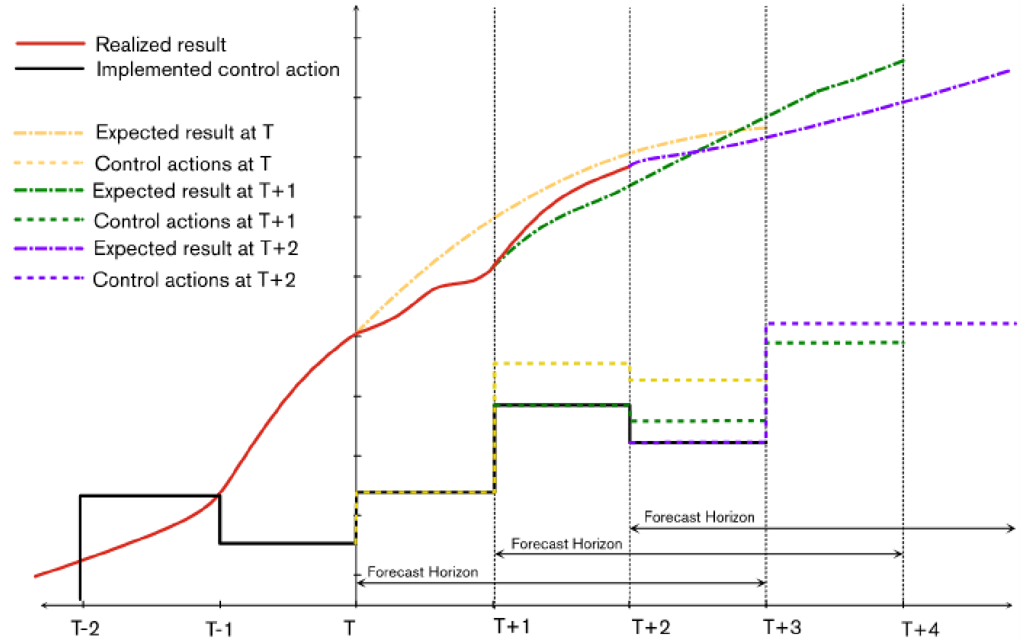
3. Intervals (robust and AA-based optimization):
   - Does not require any probabilistic modeling.
   - Determines a solution that guaranties feasibility for any realization within the bounds of the uncertainty set.
   - Bounds can be given or calculated based on the historical forecast error.
   - Uncertainty sets are able to relate the risk preference of the operator with the choice of the uncertainty set, incorporating probabilistic information if available.



Energy management systems

Model Predictive Control (MPC) and Receding Horizon Control (RHC)

- An MPC plus RHC technique assumes that control set-points are determined using a finite-horizon mathematical problem.
- The optimization problem is solved for a sequence of control actions a over finite horizon, but only the control action for *t = t+1* is implemented.
- The mathematical program accounts for estimates of future system states and forecasted inputs.



$$\min_{\{z_t,\ldots,z_{t+n}\}} \sum_{t}^{t+n} J(z_t, y_t)$$

$$\text{s.t.} \quad H\left(z_t, y_t, \rho, \mathcal{F}^* | t\right) \leq 0 \qquad \forall t$$

Energy management systems

MPC and RHC

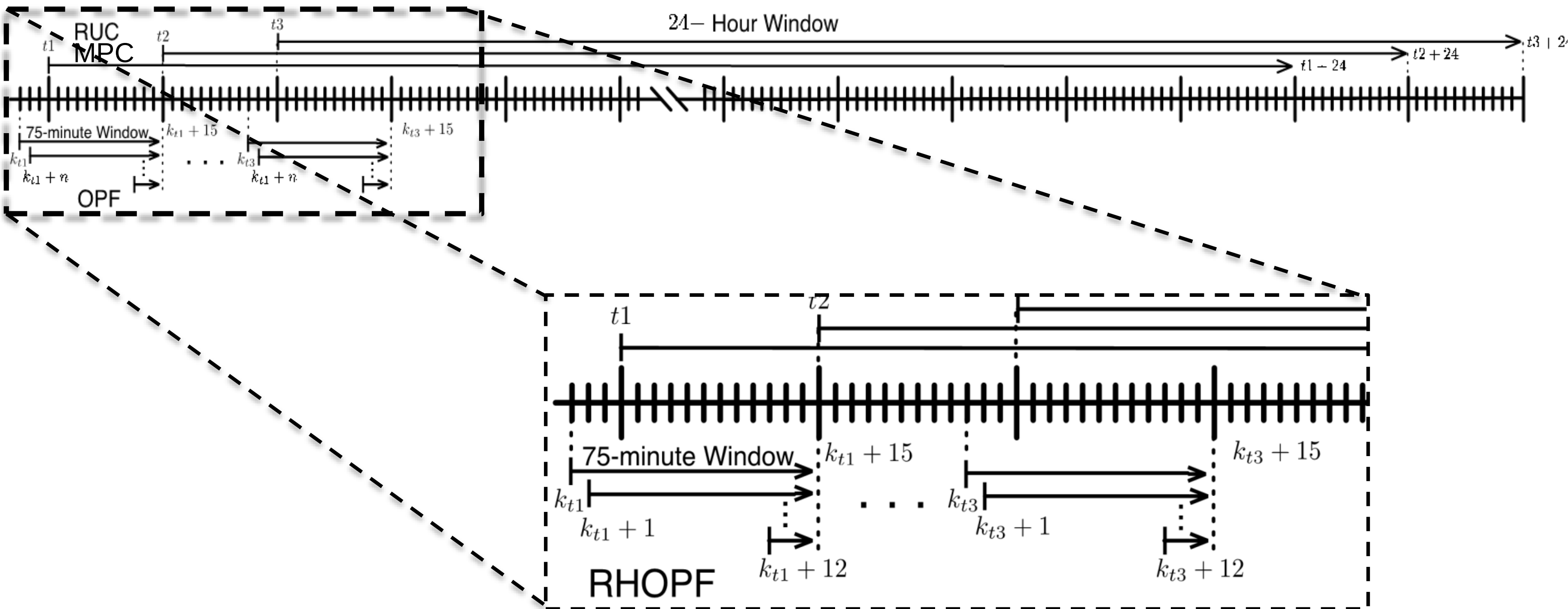
$$
\begin{aligned}
\min_{\substack{\{z_{1t},\dots,z_{1t+n},\\ z_{2t},\dots,z_{2t+n}\}}} \quad & \sum_{t}^{t+n} \left[J_1(z_{1t}, y_t) + J_2(z_{2t}, y_t)\right] & \\
\text{s.t.} \quad & H_1\left(z_{1t}, y_t, \rho\right) \leq 0 & \forall t \\
& H_2\left(z_{2t}, y_t, \rho, \mathcal{F}^* | t\right) \leq 0 & \forall t \\
& H_3\left(z_{1t}, z_{2t}, y_t, \rho, \mathcal{F}^* | t\right) \leq 0 & \forall t
\end{aligned}
$$

- A 2-stage MPC+RHC recourse model obtains a solution for the first-stage decision variables such that the second-stage variables can accommodate the uncertain outcomes.
- The dispatch task in the microgrid EMS integrates two decision processes:
  - First-Stage (MPC): Unit Commitment (UC) and the target state of charge for the ESS.
  - Second Stage (RCH): Three-Phase OPF.
- Uncertainty is mainly handled in the first stage or UC.

Energy management systems

MPC and RHC

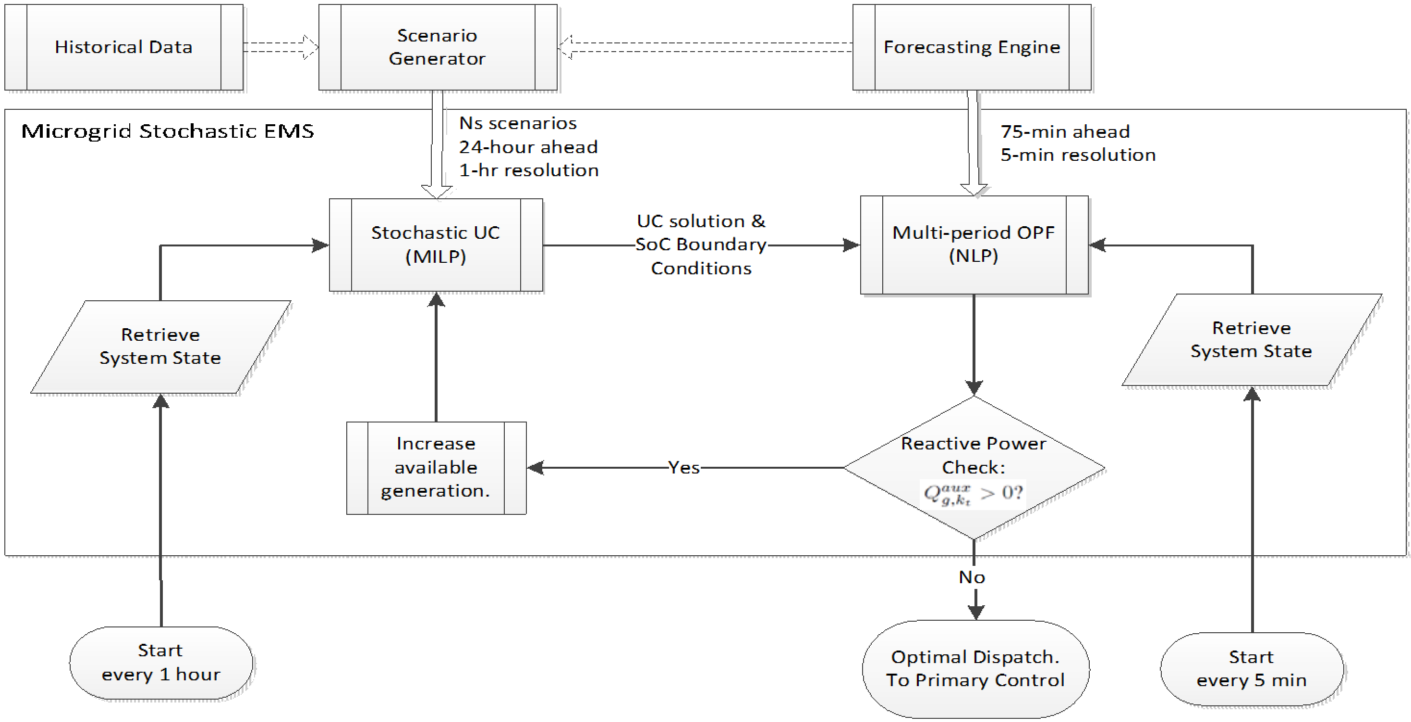
- The look-ahead windows used are:



Energy management systems

Stochastic UC (SUC)

- D. Olivares, J. D. Lara, C. A. Cañizares, and M. Kazerani, "Stochastic-Predictive Energy Management System for Isolated Microgrids," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, November 2015, pp. 2681- 2693:



Energy management systems

SUC

Cost Function

$$\left\{ \min \quad \sum_{t=1}^{T} \left[c^{\intercal} x_t + \sum_{\omega \in \Omega} \pi_\omega \cdot \left(d_p^{\intercal} \widehat{P}_t^{\omega} - d_c P_{curt,t}^{\omega} + d_s P_{shed,t}^{\omega} \right) \right] \right.$$

Minimum up-down, start-stop logic, ESS SOC at *t*=*t*+*1*

$$\left\{ \begin{array}{lll} \text{s.t.} & A_1 I_c x_t \leq 0 & \forall t \\ & x_{t+1} - A_2 x_t \leq a_1 & \forall t \end{array} \right.$$

Energy balance, ramping, ESS balance, max-min limits

$$\left\{ \begin{array}{ll} b_1 \widehat{P}_t^{\omega} + P_{shed,t}^{\omega} - P_{curt,t}^{\omega} \leq b_{2\omega,t} & \forall t \quad \forall \omega \\ \widehat{P}_{t+1}^{\omega} - B_1 \widehat{P}_t^{\omega} \leq b_3 & \forall t \quad \forall \omega \\ A_3 I_c x_t + P_{g,t}^{\omega} \leq 0 & \forall t \quad \forall \omega \\ I_{rw} \widehat{P}_t^{\omega} = \widetilde{P}_{g_{rw},t}^{\omega} & \forall t \quad \forall \omega \end{array} \right.$$

- The formulation is tested with 100 possible scenarios, generating 100 possible dispatch combinations.

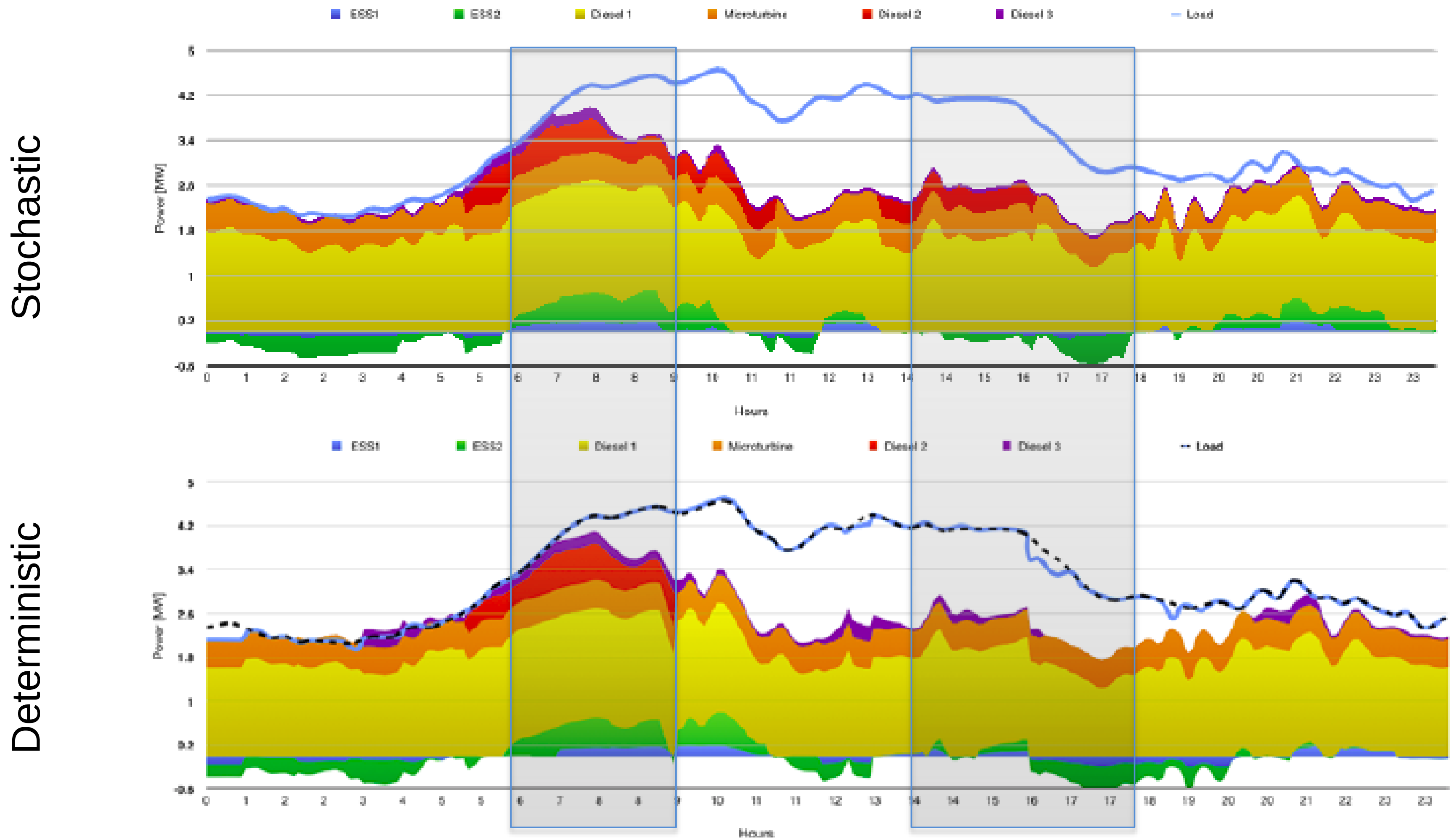
Energy management systems

SUC Example

- For the CIGRE microgrid test system, the following study cases allow to validate and compare the SUC approach against the MPC+RCH deterministic approach:
  – Available storage capacity (B250, B500).
  – Scenario generation approach (historic and statistic ensembles).
  – Length of the SUC look-ahead window (8-hour and 12 hour).

Energy management systems

SUC Example



Energy management systems

Robust UC (RUC)

- Proposed in Jose Lara's Sept. 2014 MASc thesis: "Robust Energy Management Systems for Isolated Microgrids Under Uncertainty."
- The UC problem is modified to include storage, and consider the SOC of batteries at *t = t+1* as first stage variables, thus using the ESS as hedging.
- The objective is to obtain the least-cost uncertainty-aware solution for the first-stage variables, given a bounded uncertainty set:

$$\min_{\substack{u_{g,t},v_{g,t}\\ w_{g,t},P_{g,t}}} \max_{\Delta P_{w,t}} \sum_{t} \sum_{g} \left[C_g^u u_{g,t} + C_g^v v_{g,t} + C_g^w w_{g,t} + \underbrace{C_g^P P_{g,t} + C_{sh} P_{sh,t} + C_c P_{c,t}}_{\text{Recourse}} \right]$$

$$\begin{aligned}
\text{s.t.} \quad & H_1(\rho, u_{g,t}, v_{g,t}, w_{g,t}, SOC_{s,t+1}) \leq 0 \\
& H_2(\rho, P^*_{\omega,t}, SOC_{s,t}, P_{g,t}, P_{sh,t}, P_{c,t}, \Delta P_{w,t}) \leq 0 \\
& H_3(\rho, P^*_{\omega,t}, u_{g,t}, v_{g,t}, w_{g,t}, SOC_{s,t}, P_{g,t}, P_{sh,t}, P_{c,t}, \Delta P_{w,t}) \leq 0 \\
& \Delta P_{w,t} \in \mathcal{U}
\end{aligned}$$

Energy management systems

RUC

- Master problem:

$$\min_{\substack{u_{g,t}^{k+1}, v_{g,t}^{k+1}, w_{g,t}^{k+1} \\ P_{g,t}^{k+1}}} \sum_t \sum_g \left[C_g^u u_{g,t}^{k+1} + C_g^v v_{g,t}^{k+1} + C_g^w w_{g,t}^{k+1}\right] + \theta^{k+1}$$

$$\text{s.t.} \sum_t \left[C_{sh} P_{sh,t}^{k+1} + C_c P_{c,t}^{k+1} + \sum_g C_g P_{g,t}^{k+1}\right] \leq \theta^{k+1} \qquad \forall k$$

$$SOC_{s,t+1}^{k+1} = SOC_s^{fix} \qquad \forall k$$

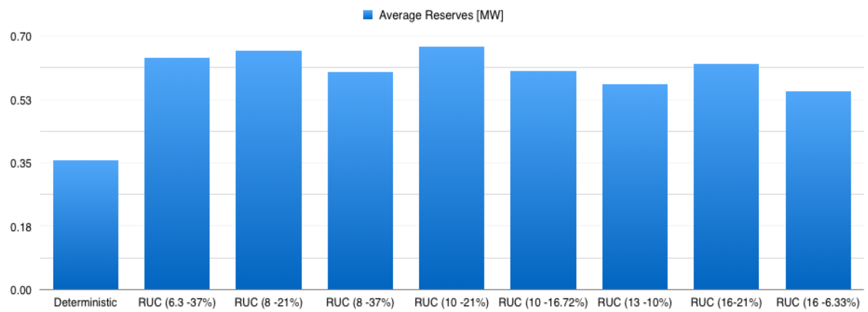
$$H_1(\rho, P_{\omega,t}^*, u_{g,t}^{k+1}, v_{g,t}^{k+1}, w_{g,t}^{k+1}, SOC_{s,t+1}^{k+1}) \leq 0$$

$$H_2(\rho, P_{\omega,t}^*, SOC_{s,t}^{k+1}, P_{g,t}^{k+1}, P_{sh,t}^{k+1}, P_{c,t}^{k+1}, \Delta P_{w,t}^{k+1}) \leq 0 \qquad \forall k$$

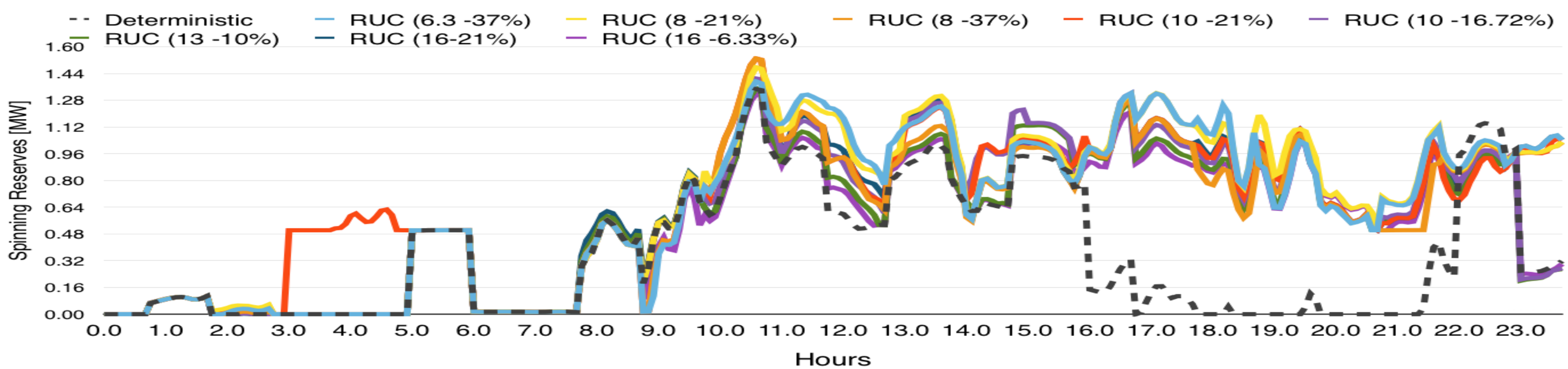
$$H_3(\rho, P_{\omega,t}^*, u_{g,t}^{k+1}, v_{g,t}^{k+1}, w_{g,t}^{k+1}, SOC_{s,t}^{k+1}, P_{g,t}^{k+1}, P_{sh,t}^{k+1}, P_{c,t}^{k+1}, \Delta P_{w,t}^{k+1}) \leq 0 \qquad \forall k$$

- Once the sub-problem yields a solution for the uncertainty vector, the result is employed to update the solution of the first-stage variables.
- New cuts are introduced at each iteration by duplicating H2 and H3.

Energy management systems
RUC Example



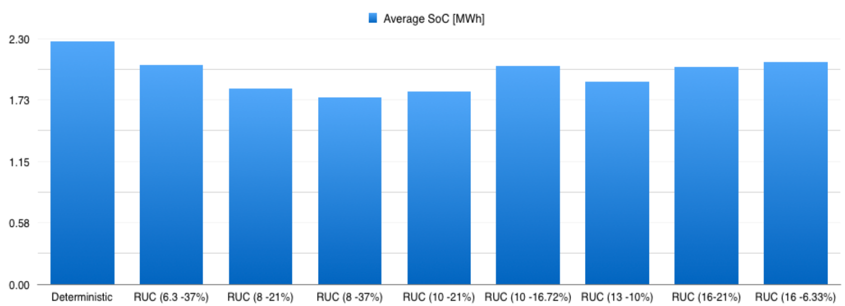
- The hedged approach is able to commit enough reserves to compensate for variations on the instantaneous wind power with respect to the forecast.
- More conservative policies yield increased levels of reserves.

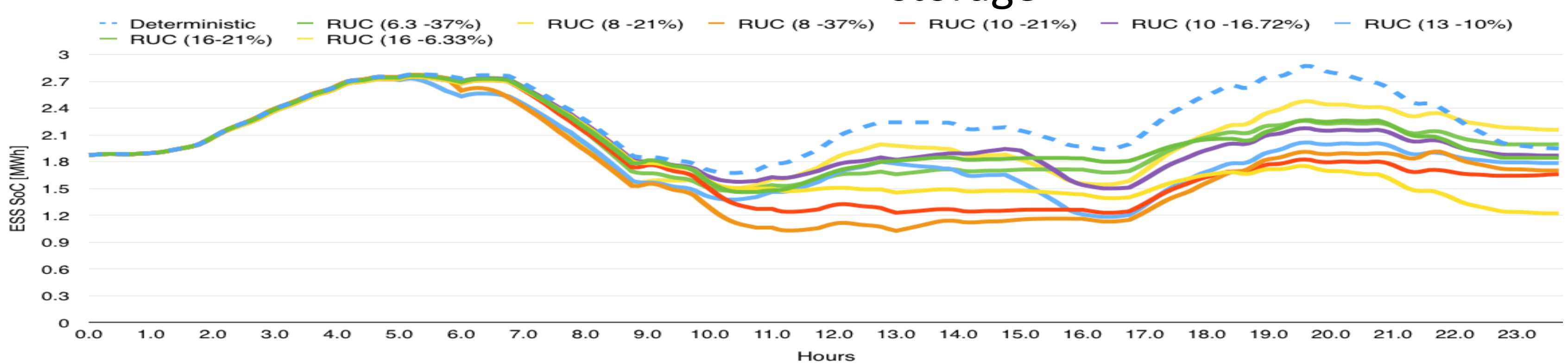


Energy management systems

RUC Example

- The deterministic case maintains an average SoC higher than the hedged UC.
- The robust formulation leads to a higher utilization of the ESS and a flatter profile of SoC levels, consistent with a more conservative management of the storage





Energy management systems

Affine Arithmetic (AA) EMS

- Enhanced interval model for self validated numerical computing, in which system variables are modeled as affine forms of some “primitive” variables:
  - It keeps track of correlations between output and input quantities.
  - Resolves the Interval Arithmetic (IA) dependency problem and results in narrower intervals; for example, for interval $[\underline{x}\,,\bar{x}]$:
    - IA: $\hat{x} - \hat{x} = [\,\underline{x} - \bar{x}\,, \bar{x} - \underline{x}\,]$
    - AA: $\tilde{x} - \tilde{x} = 0$
  - Significantly more efficient than IA.

Energy management systems

AA OPF

- M. Pirnia, C. A. Cañizares, K. Bhattacharya, and A. Vaccaro, "An Affine Arithmetic Approach for Microgrid Dispatch with Variable Generation and Load," *Proc. Power Systems Computation Conference*, August 2014, 7 pages:

$$\min \quad F(\tilde{P}^G) = \sum_{i \in Th} \alpha_i \tilde{P}_i^{G\,2} + \beta_i \tilde{P}_i^G + c_i$$

$$\begin{aligned}
\text{s.t.:}\quad & \Delta\tilde{P}_i\left(\tilde{e}_i, \tilde{f}_i, \tilde{I}_{r_i}, \tilde{I}_{im_i}, \tilde{P}_i^G, \tilde{P}_i^D\right) = 0 && \forall i \in N \\
& \Delta\tilde{Q}_i\left(\tilde{e}_i, \tilde{f}_i, \tilde{I}_{r_i}, \tilde{I}_{im_i}, \tilde{Q}_i^G, \tilde{Q}_i^D\right) = 0 && \forall i \in N \\
& |\tilde{V}_i|^2 = \tilde{e}_i^2 + \tilde{f}_i^2 && \forall i \in N \\
& P_i^{min} \leq \tilde{P}_i^G \leq P_i^{max} && \forall i \in NPG \\
& Q_i^{min} \leq \tilde{Q}_i^G \leq Q_i^{max} && \forall i \in NPG \\
& I_{ij}^{min} \leq \tilde{I}_{ij} \leq I_{ij}^{max} && \forall ij \in L \\
& V_i^{min} \leq |\tilde{V}_i| \leq V_i^{max} && \forall i \in N
\end{aligned}$$

Energy management systems

AA OPF

- Center values correspond to the deterministic case.
- Noise magnitudes and errors ε model deviations due to uncertainty.
- Noise errors can be adjusted.

$$\widetilde{e_i} = e_{i,0} + \sum_{j \epsilon N} e_{i,j}^{P} \ \varepsilon_{P_j} + \sum_{j \epsilon N} e_{i,j}^{Q} \ \varepsilon_{Q_j}$$

$$\widetilde{f_i} = f_{i,0} + \sum_{j \epsilon N} f_{i,j}^{P} \ \varepsilon_{P_j} + \sum_{j \epsilon N} f_{i,j}^{Q} \ \varepsilon_{Q_j}$$

$$e_{i,j}^{P} = \left.\frac{\partial e_i}{\partial P_j^D}\right|_0 \approx \frac{e_i^N - e_i^0}{\Delta P_j^D}$$

$$e_{i,j}^{Q} = \left.\frac{\partial e_i}{\partial Q_j^D}\right|_0 \approx \frac{e_i^N - e_i^0}{\Delta Q_j^D}$$

$$f_{i,j}^{P} = \left.\frac{\partial f_i}{\partial P_j^D}\right|_0 \approx \frac{f_i^N - f_i^0}{\Delta P_j^D}$$

$$f_{i,j}^{Q} = \left.\frac{\partial f_i}{\partial Q_j^D}\right|_0 \approx \frac{f_i^N - f_i^0}{\Delta Q_j^D}$$

Energy management systems

EMS With Uncertainties Comparison

- Various EMS models for isolated microgrids have been developed, based on decoupling the problem in sequential MILP UC and NLP OPF problems, with different horizons and update rates.
- UC:
  - MPC:
    - Easiest to implement.
    - Adequate performance.
    - Results on lowest reserves but highest possible load shifting/shedding due to forecasts errors.
  - Stochastic programming:
    - More complex to implement but manageable.
    - Adequate performance if not “too many” scenarios.
    - Requires p.d.f. assumptions and proper selection of scenarios.
    - Results in more reserves and little load shifting/shedding.

Energy management systems

EMS With Uncertainties Comparison

- Robust optimization:
  - Most complex to implement.
  - Adequate performance.
  - Does not require p.d.f. and user may define desired risk level through a budget of uncertainty Γ, which can be associated with intervals.
  - Reserves and load shifting/shedding depend on Γ value.
- AA:
  - More complex to implement.
  - Performance and accuracy are reasonable.
  - Does not require p.d.f. and user may define desired risk levels through intervals.
  - Reserves and load shifting/shedding depend on chosen intervals.

Energy management systems

EMS With Uncertainties Comparison

- OPF:
  - RHC:
    - Relatively easy to implement.
    - Good performance.
    - Requires occasional UC revisions, which depend on system stress conditions.
  - AA:
    - There are 3 possible implementation approaches, with different levels of complexity and accuracy.
    - Performance depends on implementation.
    - Need for UC revisions should be less, depending on intervals chosen.

Thank you!

Rodrigo Palma
rodpalma@cec.uchile.cl

http://www.researcherid.com/rid/A-1849-2012