

# MODELING AND OPTIMIZATION OF A MICRO-GRID: HUATACONDO, ISOLATED VILLAGE IN NORTHERN CHILE

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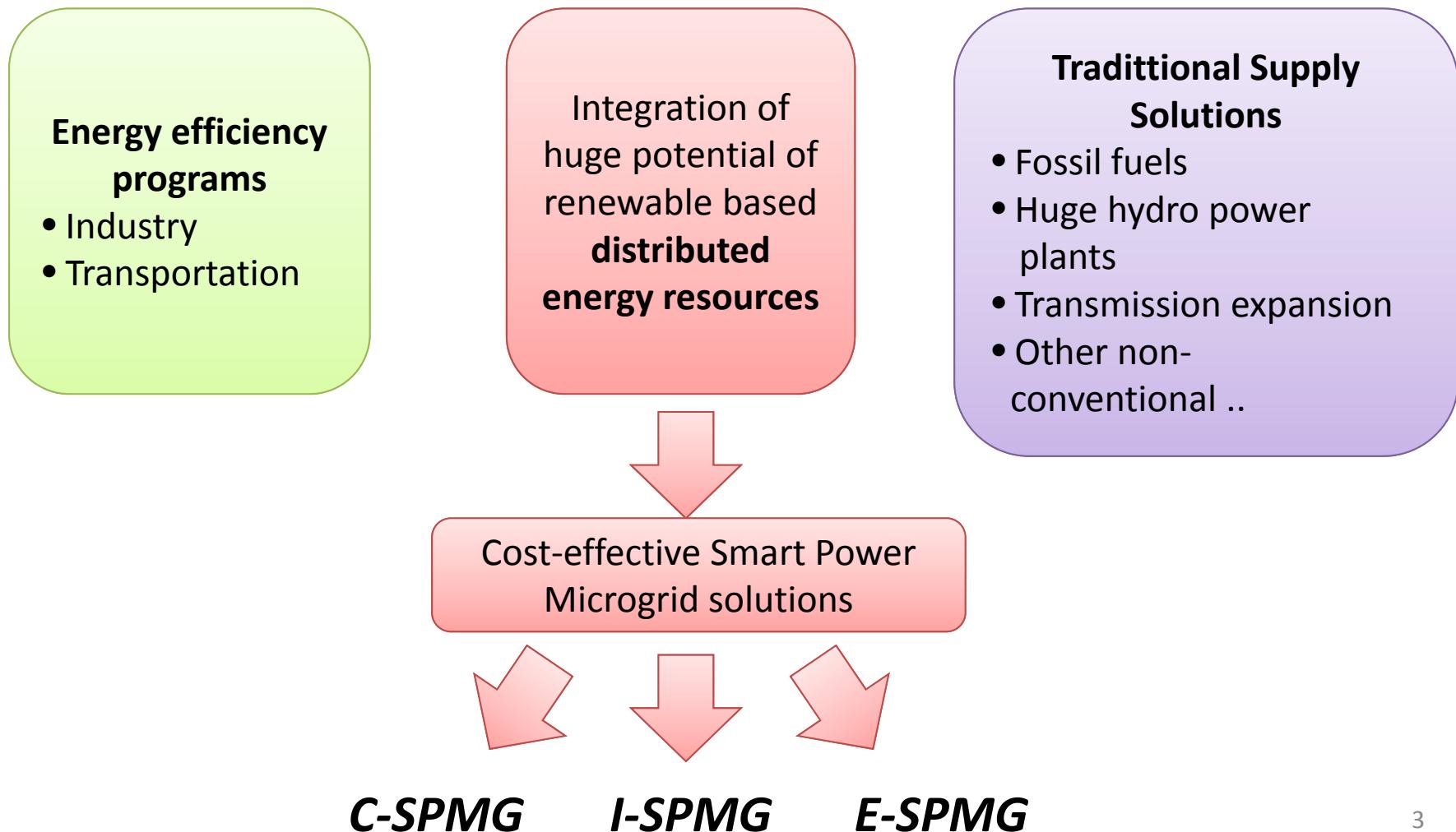
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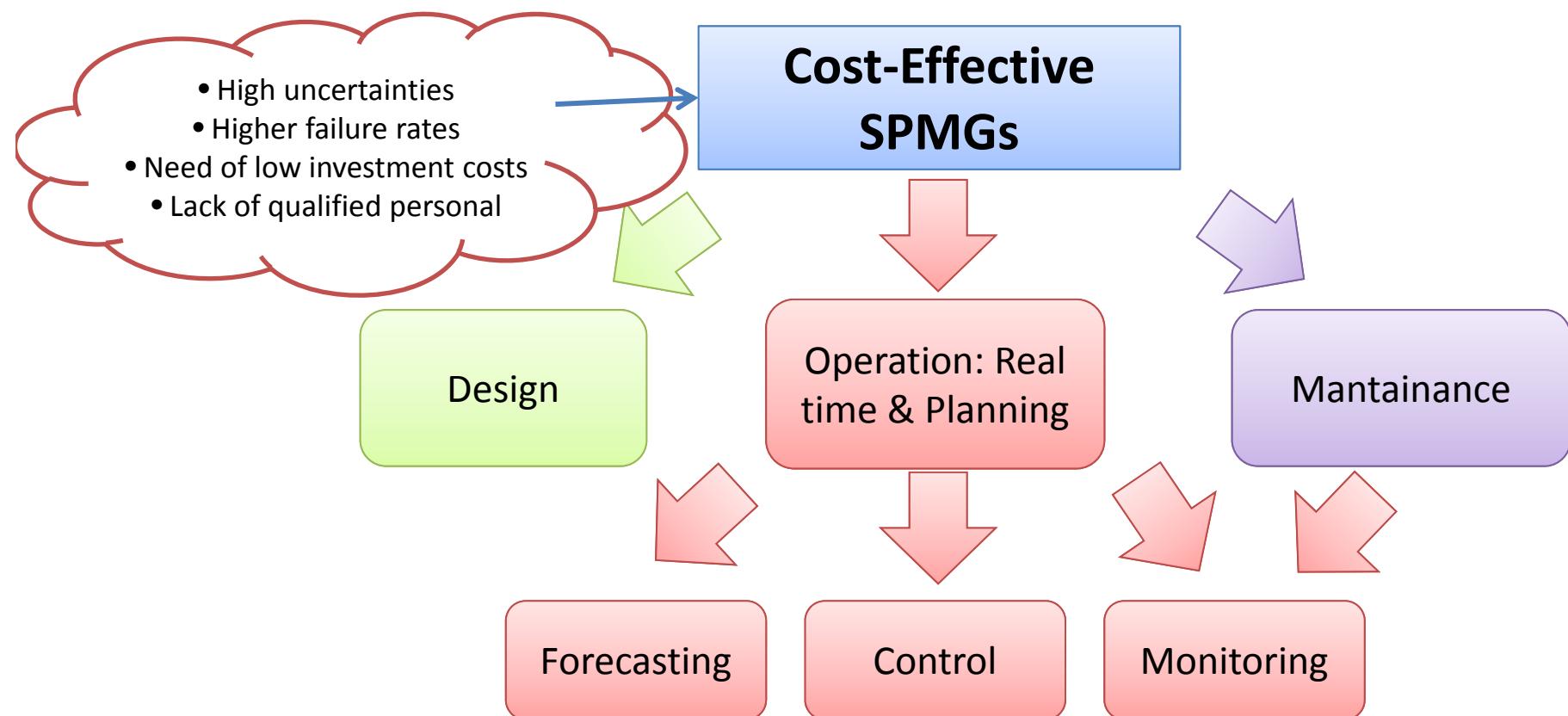
# Chilean Energy Supply Challenge



# Chilean Energy Supply Challenge

- Coordinated integration of distributed renewable resources to the interconnected power grid (C-SPMG).
- Electrification of remote villages with abundant local renewable energy resources, through SPMGs operating in island mode (**I-SPMG**).
- Development of critical infrastructure power systems (emergency systems) for locations prone to face natural disasters such as earthquakes, tsunamis, storms, floods, etc (**E-SPMG**).

# Challenges for Micro-grids



# Current Projects

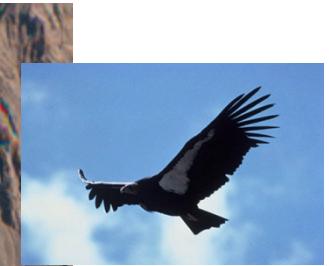
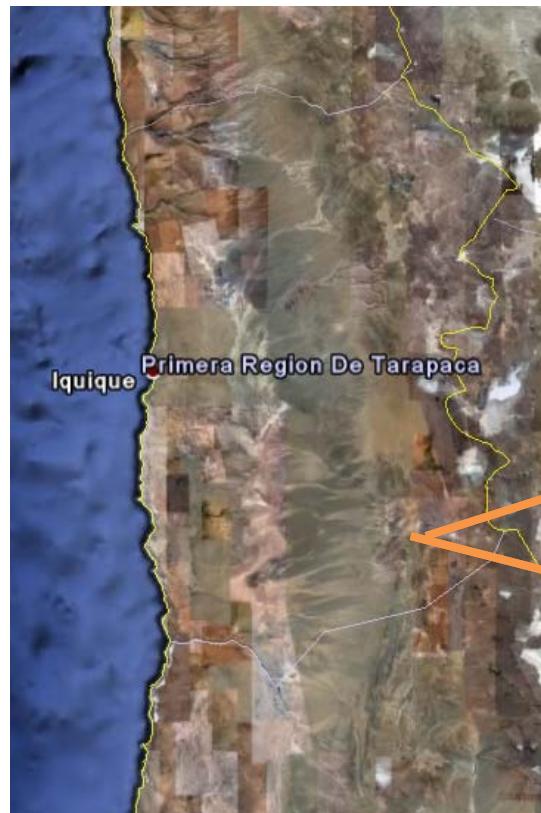
- **Huatacondo I-SMG**
  - 10 hours of energy supply by a diesel generator, 100 people.
  
- **Parca I-SMG**
  - 25 people
  - BHP
  
- **Ollagüe I-SMG**
  - 17 hours of energy supply by a diesel generator, 131 people.
  
- **Juan Fernández E-SMG**



# Smart Micro-grid Vision for Chile



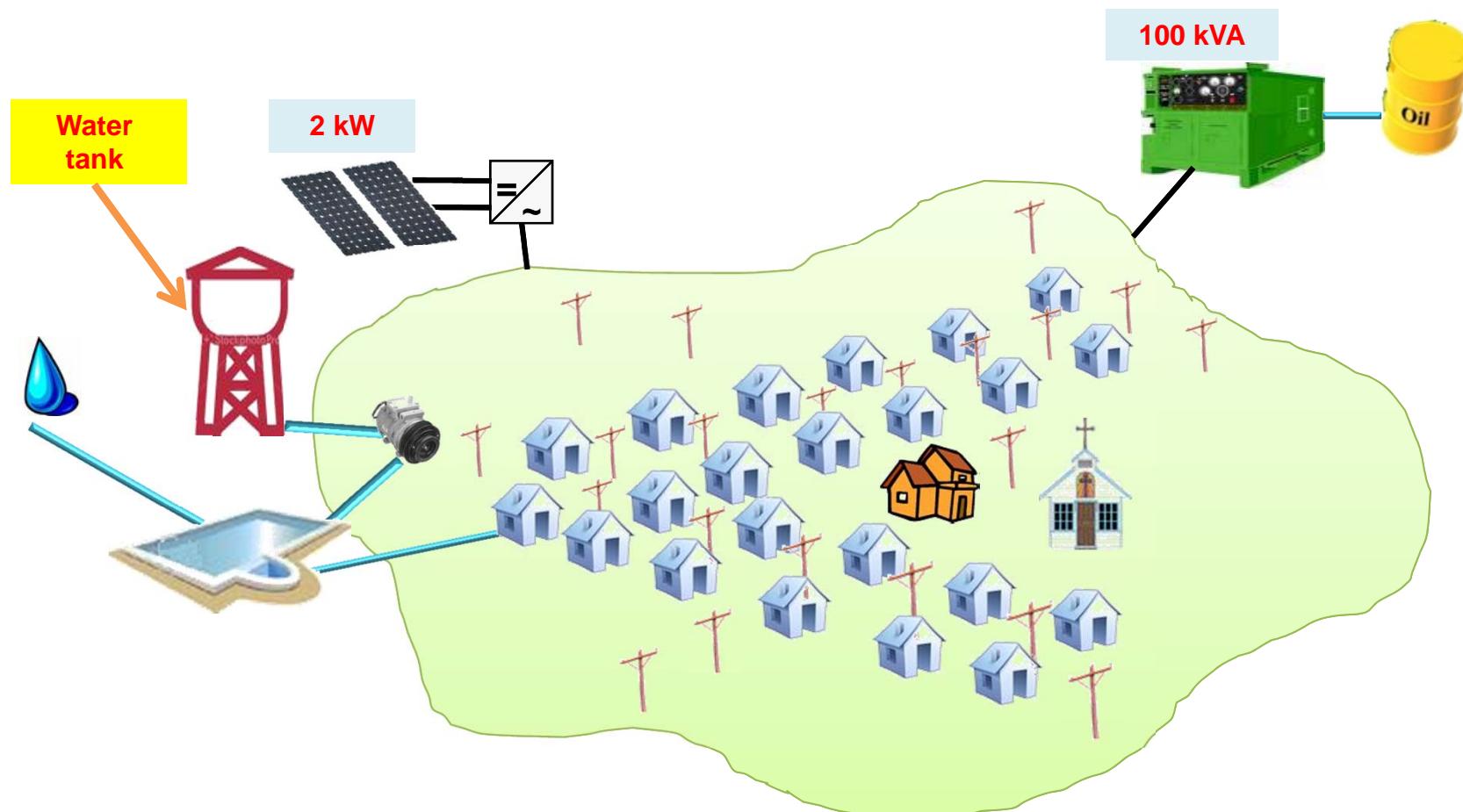
# Huatacondo, Isolated Village in Northern Chile



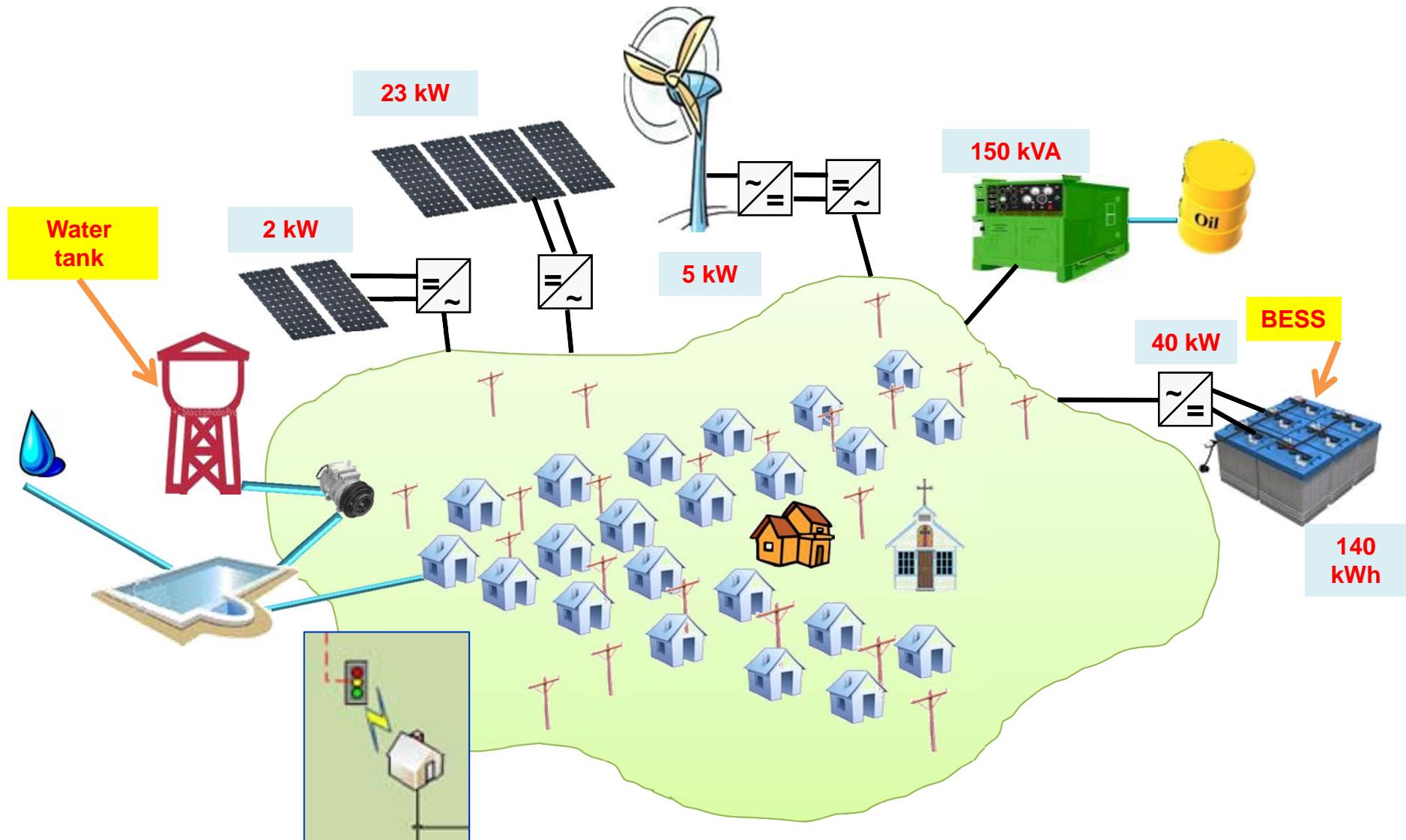
## Huatacondo

- Isolated rural town
- 100 people (500)
- Electricity 10 h/day – Diesel generator

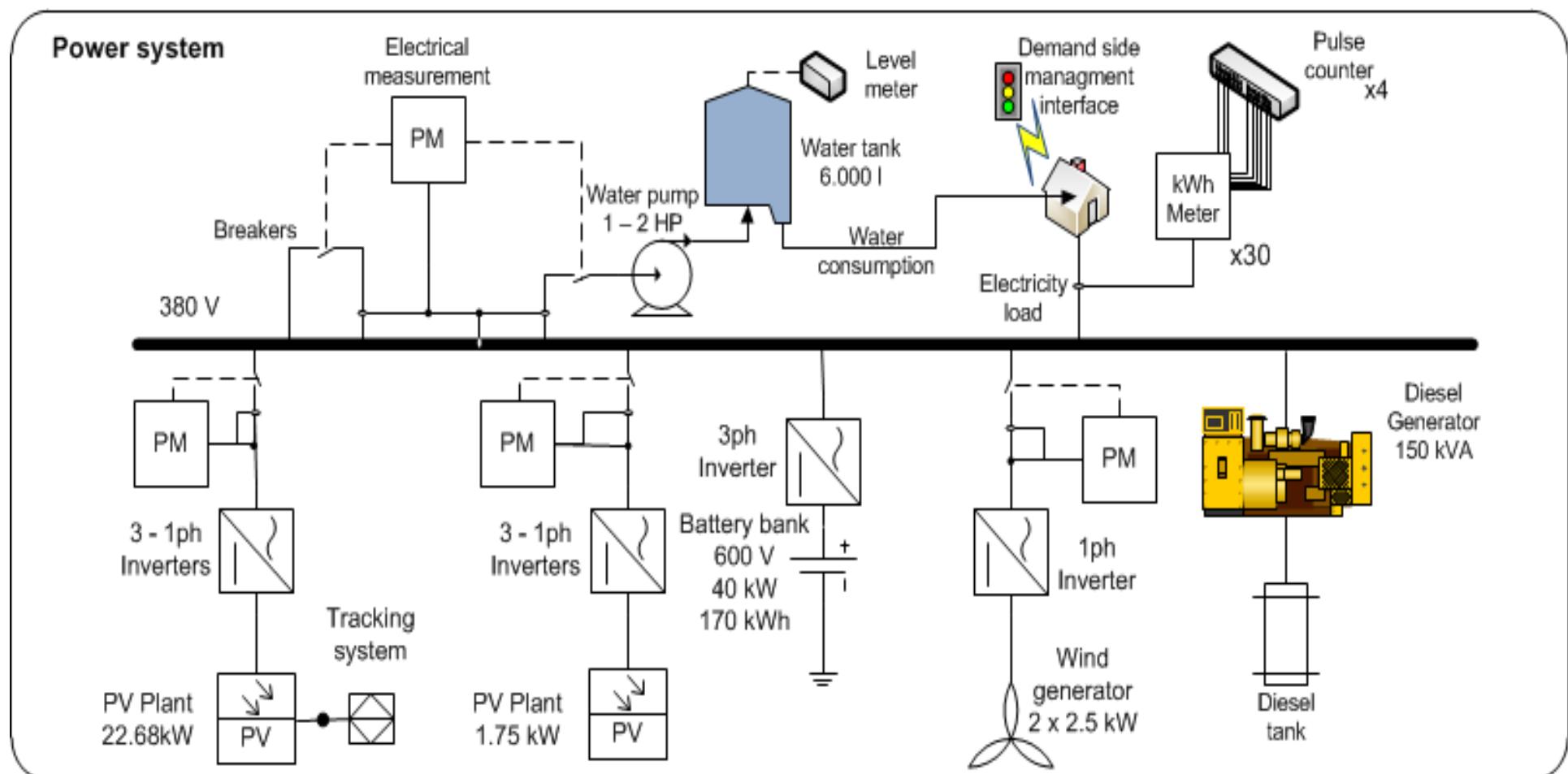
# Huatacondo, Isolated Village in Northern Chile



# Huatacondo, Isolated Village in Northern Chile



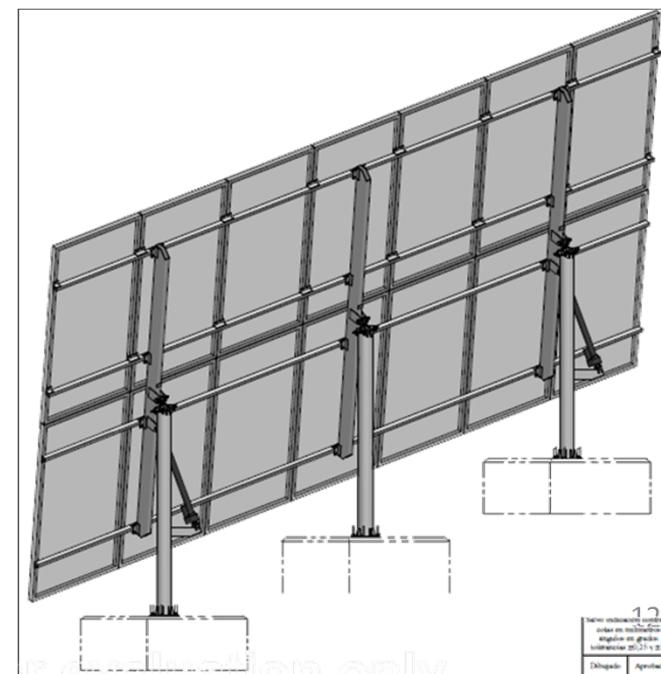
# Huatacondo, Isolated Village in Northern Chile



# Huatacondo, Isolated Village in Northern Chile



Technical  
Developments







# Research Developments

- At design level for micro-grids:
  - Load Profile Generator for a Renewable Based Micro-grid Using Self Organizing Maps
- At operational level for micro-grids:
  - A Energy Management System Based on the Rolling Horizon Strategy for an Isolated Micro-grid.

# Load Profile Generator for a Renewable Based Micro-grid Using Self Organizing Maps\*

\*Llanos, J., Sáez, D., Palma-Behnke, R., Núñez, A., Jiménez-Estevez, G. "Load Profile Generator and Load Forecasting for a Renewable Based Microgrid Using Self Organizing Maps and Neural Networks", IEEE World Congress on Computational Intelligence IEEE WCCI 2012 June 10-15, Brisbane, Australia.

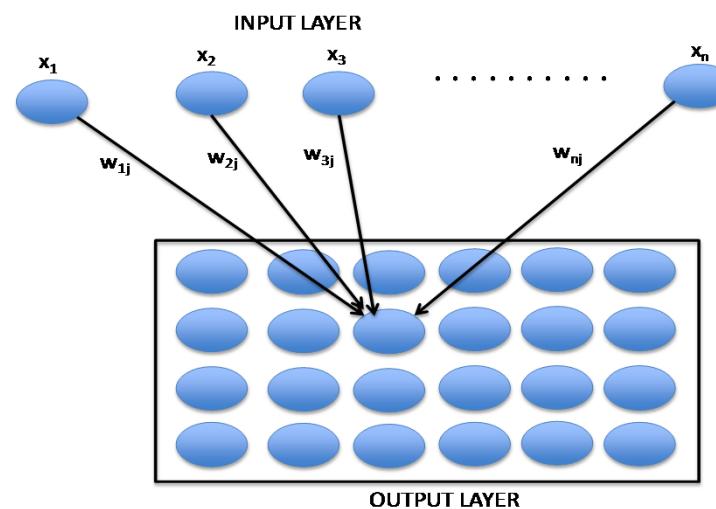
# Load Profile for Micro-grids

- In isolated small communities, the energy supply is difficult to predict because it is not always available, is limited according to some schedules and is highly dependent on the consumption behavior of each community member.
- Most of the research in the literature on the generation of electricity demand profiles is based on real-time measurements.
- In this proposal, we include only socio-economic aspects and some variables related to the consumption behavior of the community, and without considering any measurement of the electricity demand.



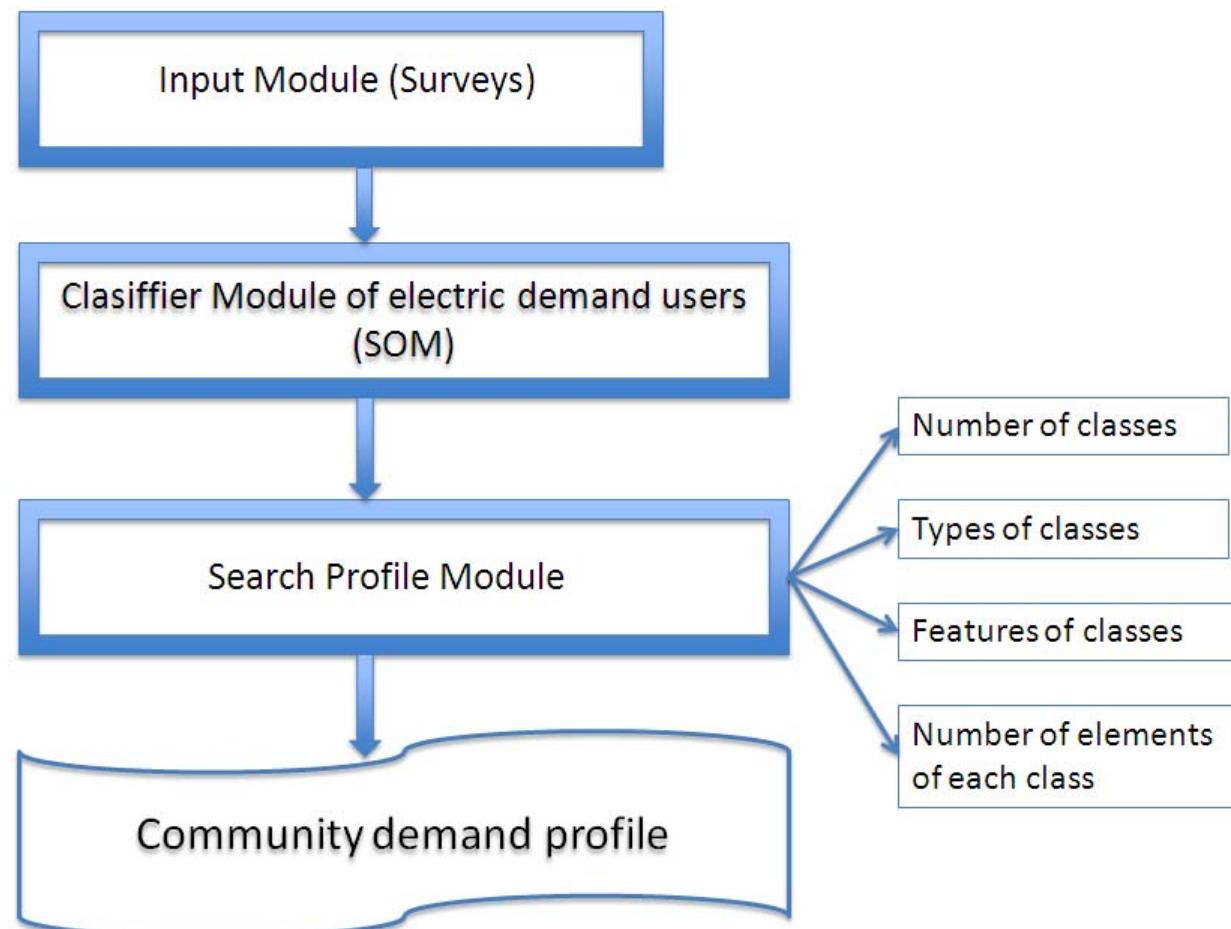
# Load Profile Generation based on SOM

- The proposed method includes a household classifier based on a Self Organizing Map (SOM) that provides load patterns by the use of the socio-economic characteristics of the community obtained in a survey.
- A SOM permits to classify patterns in an unsupervised way, by extracting classification criteria from the data.



# Load Profile Generation based on SOM

- SOM procedure for generating the electricity demand profiles.



# Load Profile Generation based on SOM

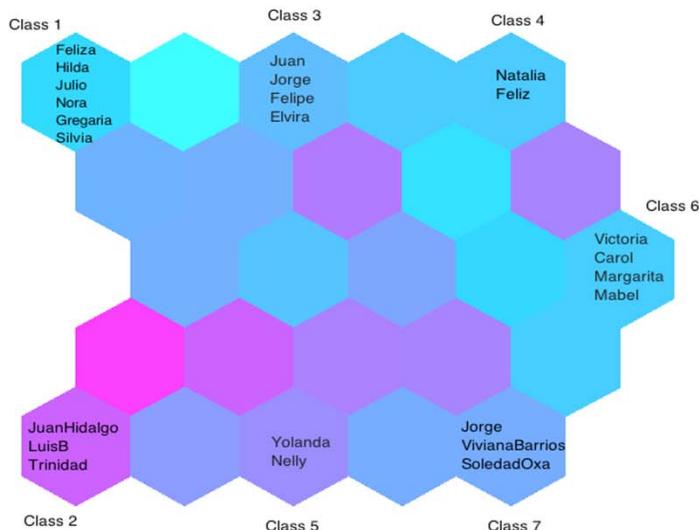
- **Input module.** Relevant information is obtained from the community through well-structured surveys.
  - Statistical data from various sources (population and housing censuses, websites, etc.)
  - The individual surveys (number of persons living in the house, ages and occupations, incomes, number and type of electrical appliances, and hours of use of each appliance).
- **Classifier module.** Different kinds of houses are obtained in the community in an unsupervised way, considering some criteria known a priori such as the number of family members, occupation of each of them, income, number of electrical appliances, and so on.
  - number of families in each class using an automated classifier by a SOM.

# Load Profile Generation based on SOM

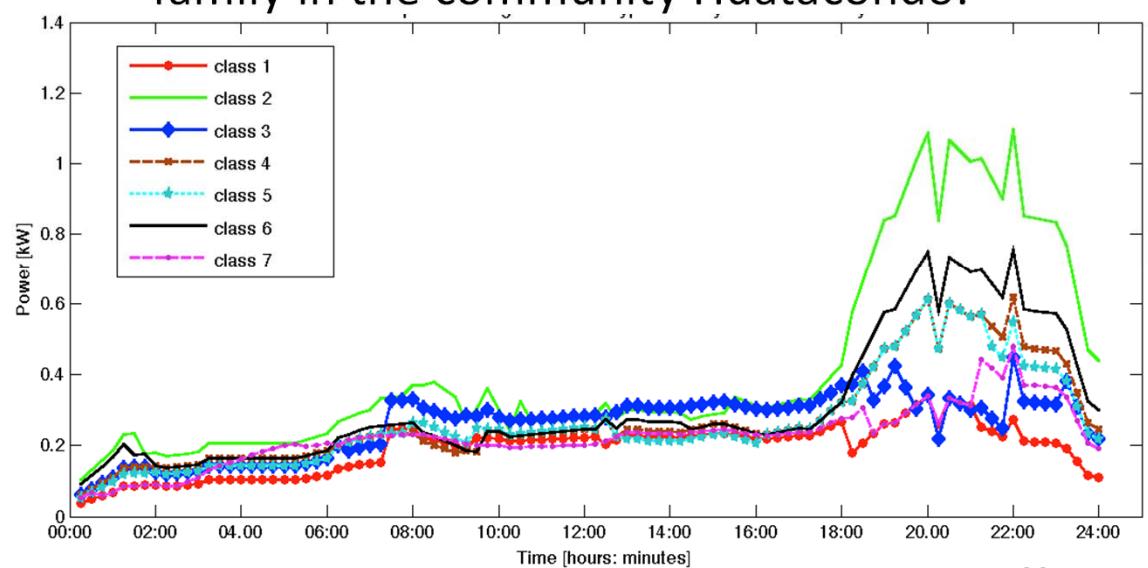
- **Search profile module.** It searches for the class with very similar characteristics in the database.
  - a metering system is installed at some houses and by using a survey, the characteristics of each house is obtained assigning a type of house.
  - The groups of the database are: elderly couple, elderly person alone, elderly person and adult, adult alone, adult couple, couple with a child, etc.
- **Community demand profile.** The total residential demand is obtained by summing the product of the number of elements in each class by the profile assigned to the class.

# Load Profile Generation based on SOM

- Real-data based results  
Classification Huatacondo house types

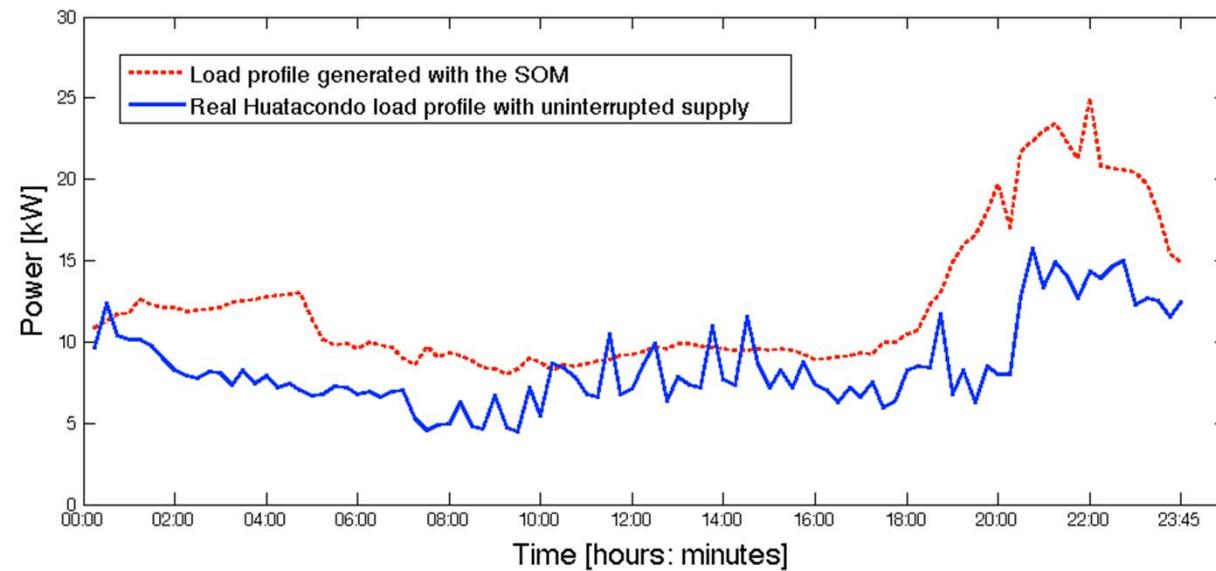


Electricity demand profiles of each type of family in the community Huatacondo.



# Load Profile Generation based on SOM

- Real-data based Results



- The errors of each class and the high stochasticity features of the microgrid have an effect in the prediction of the total consumption; however, the trends are very similar and useful as it generates a diary electricity demand profile of a community without measures of the electricity consumption<sup>23</sup>

## Remarks

- A method based on SOM for generating diary load profiles in isolated communities is presented.
- This load profile generator can be used to design the unit size of distributed generators of micro-grid projects.
- The proposed load profile generator was tested using real data from the village called Huatacondo, obtaining a demand profile rather similar to the real one.

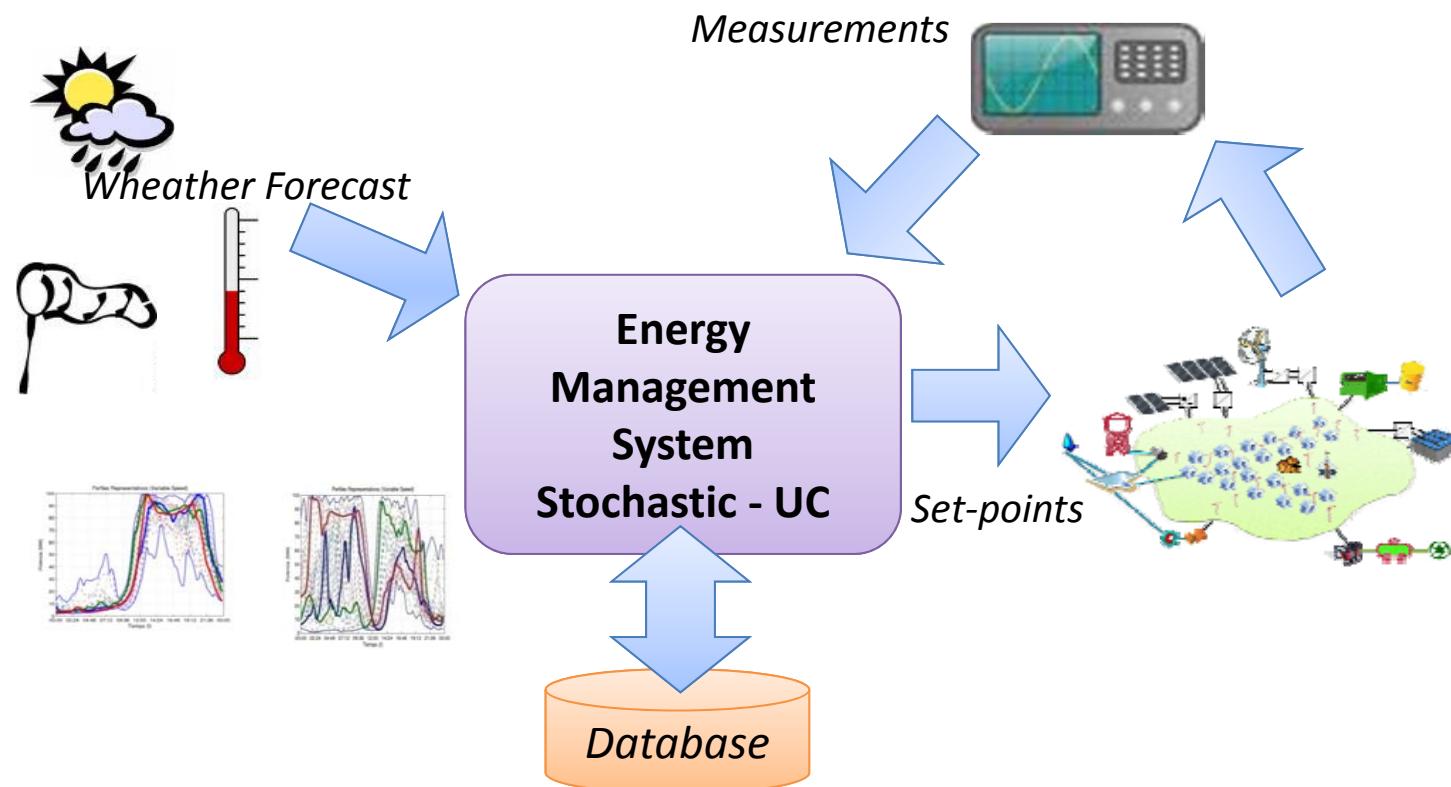
# A Energy Management System Based on the Rolling Horizon Strategy for an Isolated Micro-grid\*

\*Palma-Behnke R., Benavides C., Aranda E., Llanos J., Sáez D. "Energy Management System for a Renewable based Microgrid with a Demand Side Management Mechanism", IEEE Symposium Series on Computational Intelligence - SSCI 2011 April 11-15, 2011 - Paris, France.

Palma-Behnke, R., Benavides, C., Lanas, C., Severino, B., Reyes, L., Llanos, J., Sáez, D. "A Microgrid Energy Management System Based on the Rolling Horizon Strategy". IEEE Transactions on Smart Grid (under review).

# EMS – Rolling Horizon

- The EMS provides online set points for each generation unit and signals for consumers (a demand-side management mechanism)

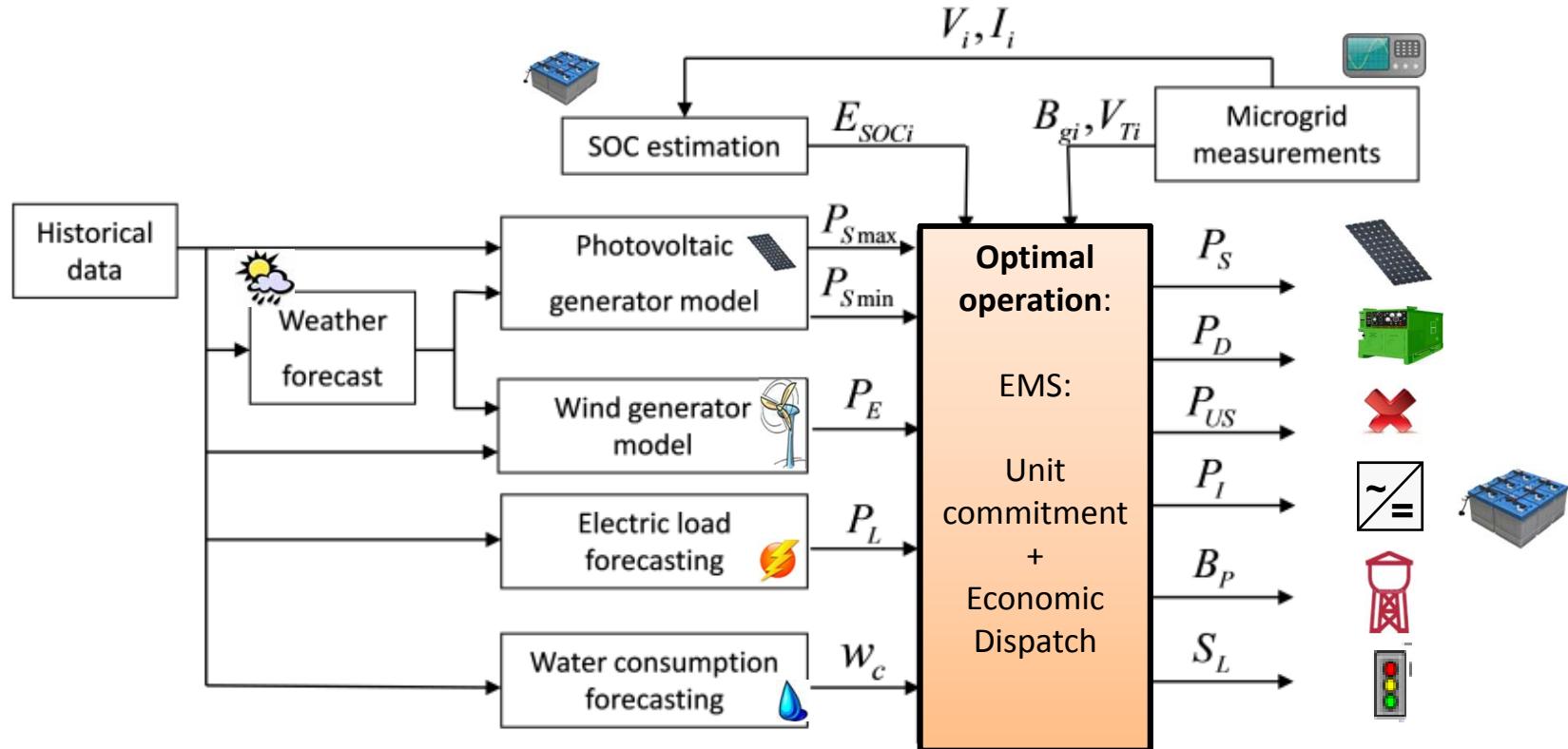


# EMS – Rolling Horizon

- **Objective function:** EMS minimizes the **operational costs** while supplying the water and load demands, considering a two days ahead prediction of the weather conditions (192, 15 min steps).
- **Unit modeling:** The generation units (conventional and renewable) can be represented as **Mixed integer linear models**.
- **Constraints:** The **power balance** in the microgrid must be satisfied and physical limits.



# EMS – Rolling Horizon



## Inputs

maximum and minimum available solar power ( $P_{S\max}, P_{S\min}$ ), wind power ( $P_E$ ), load profile ( $P_L$ ), water consumption ( $w_c$ ), initial conditions for the battery charge ( $E_{SOC_i}$ ), battery bank voltage ( $V_i$ ) and current ( $I_i$ ), water tank level ( $V_{Ti}$ ) and diesel on/off state ( $B_{gi}$ ).

## Outputs

power references for the diesel ( $P_D$ ) generator, the ESS inverter power ( $P_I$ ), the binary signals for the water supply system ( $B_P$ ), the desired solar power ( $P_S$ ) and the signals for loads ( $S_L$ ).

# EMS – Rolling Horizon

- Objective function

$$J = \delta_t \sum_{t=1}^T C(t) + \sum_{t=1}^T C_s(t) + C_{US} \delta_t \sum_{t=1}^T P_{US}(t) + C_{Tf} \sum_{t=1}^T V_{Tf}(t) + C_H(T)$$

|                                      |                                  |                                                      |                                                          |                                           |
|--------------------------------------|----------------------------------|------------------------------------------------------|----------------------------------------------------------|-------------------------------------------|
| <i>Diesel<br/>variable<br/>costs</i> | <i>Start-up<br/>diesel costs</i> | <i>Penalization of<br/>the unsupplied<br/>energy</i> | <i>Penalization of<br/>the unserved<br/>water supply</i> | <i>BESS<br/>lifetime<br/>penalization</i> |
|--------------------------------------|----------------------------------|------------------------------------------------------|----------------------------------------------------------|-------------------------------------------|

# Constraints

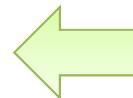
- Power balance for the micro-grid

$$P_D(t) + P_I(t) + P_{US}(t) = P_L(t) + B_P(t)\bar{P}_P - P_S(t) - P_E(t)$$

|        |          |          |      |      |       |      |
|--------|----------|----------|------|------|-------|------|
| Diesel | Inverter | Unserved | Load | Pump | Solar | Wind |
| Gen.   | Gen.     | energy   |      | load | Gen.  | Gen. |

- Solar power

$$P_{Smin}(t) \leq P_S(t) \leq P_{Smax}(t)$$



$$P_S(t, \alpha) = \eta_S A_S R_S(t, \alpha)$$

$$\hat{R}_s(t+1) = R_{CS}(t+1) \times \frac{1}{n} \sum_{i=0}^{n-1} k^*(t-i)$$

The solar power is controlled by the east-to-west inclination angle of the panels ( $\alpha$ ).

# Modeling of Conventional Units

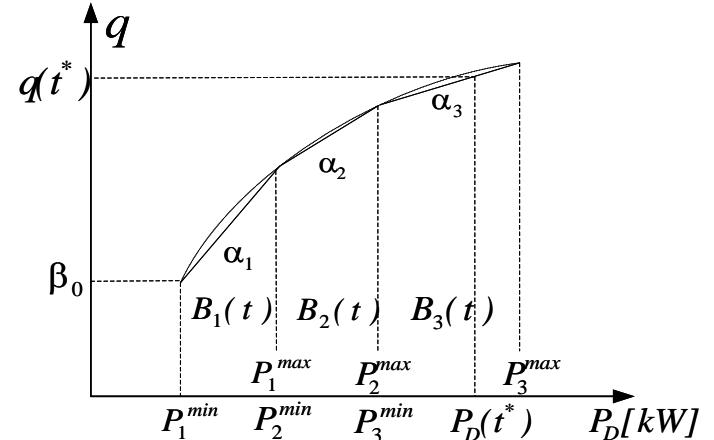
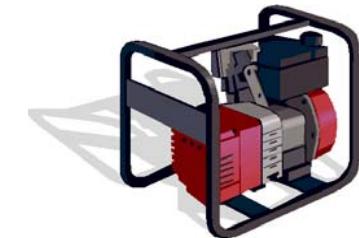
- Diesel generator:

- Operational costs. A non-convex cost function is approximated by piecewise linear segments:

$$q(t) = \sum_{v=1}^{n_v} (\alpha_v P_v(t) + \beta_v B_v(t))$$

$$P_D(t) = \sum_{v=1}^{n_v} P_v(t)$$

$$P_v^{\min} B_v(t) \leq P_v(t) \leq P_v^{\max} B_v(t), \quad v = 1, \dots, n_v$$



- Start-up costs

$$C_s(t) \geq C_D(B_g(t) - B_{g0}) = 1$$

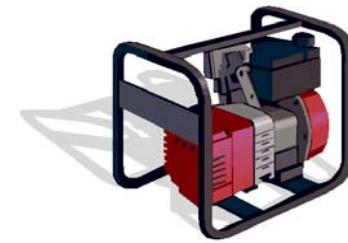
$$C_s(t) \geq C_D(B_g(t) - B_g(t-1))^t > 1$$

$$C_s(t) \geq 0$$

$$B_g(t) = \sum_{v=1}^{n_v} B_v(t) \leq 1$$

# Modeling of Conventional Units

- **Diesel generator:**
  - Fuel tank modelling:



$$V_D(t) = V_D(t-1) - \left( \sum_{v=1}^{n_v} \alpha_v P_v(t) + \beta_v B_v(t) \right)$$

$$V_{Dmin} \leq V_D(t) \leq V_{Dmax}$$

$$V_D(T) \geq V_D^T \quad \text{End of the horizon condition}$$

# Modeling of the BESS

- ***Battery bank:***

- *Energy model*

$$E(t) = E(t-1) - \delta_t P_B(t)$$

- *Inverter model*

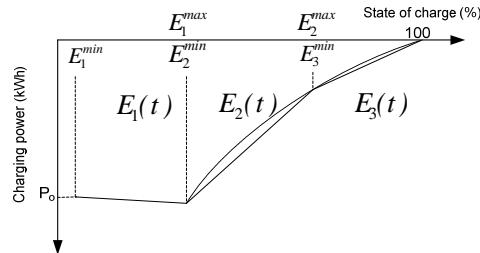


$$P_I(t) = \begin{cases} \eta_{Id} P_B(t) - P_{I0} & P_B(t) \geq 0 \\ \frac{P_B(t)}{\eta_{Ic}} - P_{I0} & P_B(t) < 0 \end{cases}$$

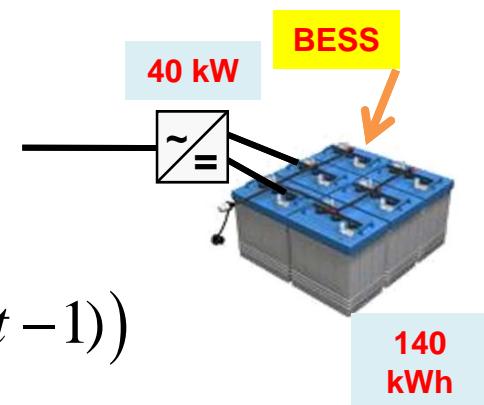
battery injects power to the hybrid grid

battery charging mode

$P_B$  is the battery current power  
 $P_{I0}$  is the own consumption of the inverter



$$P_{Bmin}(E(t-1)) \leq P_B(t) \leq P_{Bmax}(E(t-1))$$



# Modeling of the BESS

- Battery bank lifetime reduction cost:

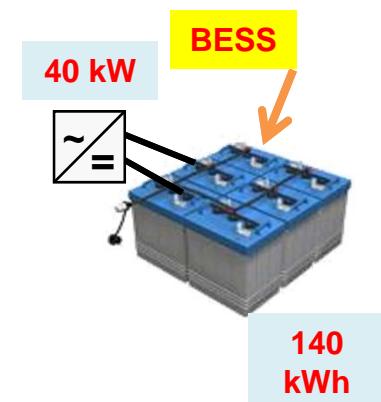
$$C_H(T) = [SoH(T) - SoH(1)] \cdot C_I$$



$$SoH(t) = SoH(t-1) - [\eta_T(t-1) + \eta_{wz}(t-1)] \cdot \delta_t$$

*coefficient  
associated with  
the battery  
temperature*

*working zone  
coefficient*



# Water Supply Management

- Water tank volume:

$$V_T(t) = V_T(t-1) + \delta_t w_f(t) - \delta_t w_c(t)$$

water inflow      water consumption      unserved water consumption

$$w_f(t) = \kappa_T \eta_P P_p(t) = \kappa_T \eta_P \overline{P}_P B_p(t)$$

$P_p$  is the pump water  
 $B_p$  represents the on-off of the pump



# Demand Side Management

- It was supposed that online signals can be sent to the consumers in order to modify their temporal consumption pattern, leaving daily energy constant.
- Load:  $P_L(t) = S_L(t)\tilde{P}_L(t)$

$$S_{Lmin}(t) \leq S_L(t) \leq S_{Lmax}(t)$$



$$\sum_{t=T_1}^{T_2} P_L(t) \geq \sum_{t=T_1}^{T_2} \tilde{P}_L(t)$$

$S_L$  is the shifting factor of the electric demand

$P_L$  is the expected load and  $\tilde{P}_L(t)$  is the electric load



## Results for EMS

- To validate the proposed EMS-based UC-RH, a one-day-ahead UC was also implemented.
- Prediction horizon of 48 hours considering a sampling time of 15 minutes ( $T=192$  ahead steps).
- EMS optimization problem is solved using a Branch & Cut algorithm (CPLEX version 10.2).

# Results for EMS

- Prediction errors for the wind power, solar power and electric load.

|                    | <b>1-hour ahead</b> | <b>24-hour ahead</b> | <b>48-hour ahead</b> |
|--------------------|---------------------|----------------------|----------------------|
| Wind power         |                     |                      |                      |
| RMSE [kW]<br>(std) | 0.42<br>(0.25)      | 1.24<br>(1.08)       | 1.48<br>(1.24)       |
| Solar power        |                     |                      |                      |
| RMSE [kW]<br>(std) | 1.26<br>(0.55)      | 1.37<br>(1.27)       | 1.43<br>(1.35)       |
| Electric load      |                     |                      |                      |
| RMSE [kW]<br>(std) | 1.36<br>(0.79)      | 2.25<br>(1.38)       | 2.68<br>(1.683)      |

GFS-WRF model for wind speed.

Wind power: wind turbine profile (manufacturer)

Predicted irradiance, is average of the past indices.

Neural network modeling using empirical data

# Results for EMS

| SUMMER SEASON (PV/DIESEL/ESS) |                    | Control Strategy |                 |
|-------------------------------|--------------------|------------------|-----------------|
|                               |                    | UC               | UC-RH           |
| Cost [CLP\$]<br>(std)         | Start-up Diesel    | 2006             | 1173            |
|                               | Operational Diesel | 19997            | 18192           |
|                               | Total Diesel       | 22063<br>(1641)  | 18309<br>(1036) |
|                               | Energy deficit     | -1613            | -1559           |
|                               | Unserved Energy    | 0                | 0               |
|                               | Total              | 20450<br>(1855)  | 16750<br>(861)  |
| WINTER SEASON (PV/DIESEL/ESS) |                    |                  |                 |
| Cost [CLP\$]<br>(std)         | Start-up Diesel    | 4891             | 1488            |
|                               | Operational Diesel | 26836            | 24546           |
|                               | Total Diesel       | 31727<br>(3465)  | 26034<br>(1581) |
|                               | Energy deficit     | 2355             | -1018           |
|                               | Unserved Energy    | 1500             | 240             |
|                               | Total              | 34082<br>(3592)  | 25016<br>(1671) |

The UC-RH reduces the expected total cost (18% for summer and 27% for winter) because of the lower start-up and operational diesel costs.

## Results for EMS

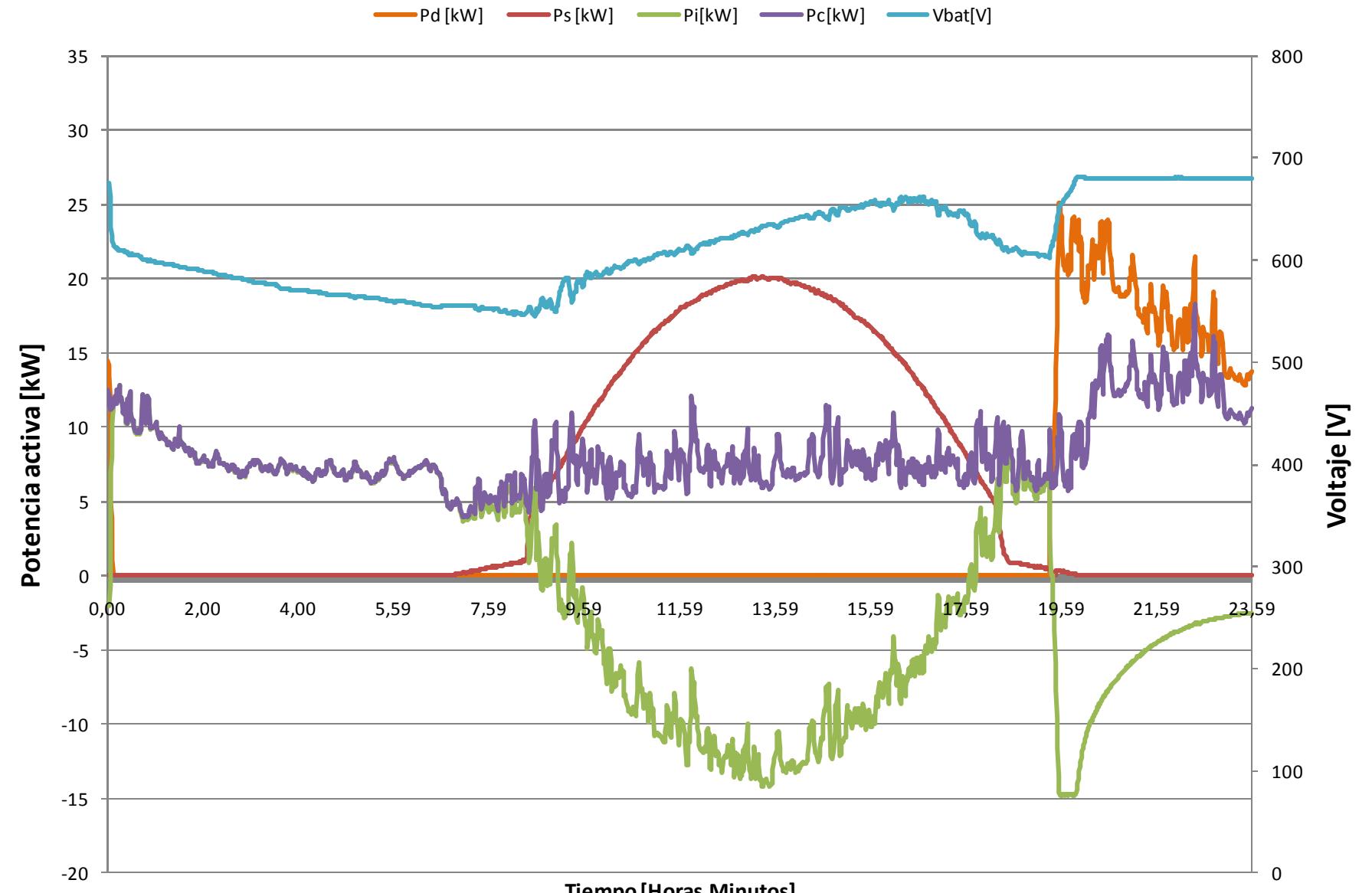
- The results of the proposed EMS using DSM for the microgrid (PV/Diesel/ESS)

|              |                 | $S_{Lmin}(t) / S_{Lmax}(t)$ |           |         |           |
|--------------|-----------------|-----------------------------|-----------|---------|-----------|
|              |                 | 1.0/1.0                     | 0.95/1.05 | 0.9/1.1 | 0.85/1.15 |
| Cost [CLP\$] | Start-up        | 1000                        | 1000      | 1000    | 1000      |
|              | Operational     | 14424                       | 12264     | 11487   | 10564     |
|              | Total Diesel    | 15424                       | 13264     | 12487   | 11564     |
|              | Unserved energy | 0                           | 0         | 0       | 0         |
|              | Total           | 15424                       | 13264     | 12487   | 11564     |

- The total cost decreases as the demand shifting coefficients are made more flexible.
- The system load is shifted to periods when the solar energy is available. In addition, the diesel operation is optimized, increasing its efficiency.

# Operation: Huatocondo

January 15<sup>th</sup>, 2011



## Remarks

- The rolling horizon presents the advantage of dealing with updated data from the forecast variables.
- The operational costs of the microgrid using the UC-RH are reduced for certain profiles of demand and irradiance in comparison with the UC.
- The benefits of DSM are achieved by means of shifting the behavior of consumers to periods in which there are more renewable resources available.
- The EMS allows efficient management of the water supply by optimizing the water pump activation as a flexible load, especially for periods with energy surplus.

## Conclusions

- A smart micro-grid concept and associated challenges were presented for the Chilean context.
- A method based on SOM for generating diary load profiles in isolated communities is presented, and it can be used to design the unit size of distributed generators of micro-grid projects.
- An energy management system based on rolling horizon for a renewable based microgrid is proposed, showing the economic benefits. It also includes an efficient management of the water supply and a demand side management.

## Future Research

- Development of an stochastic optimization approach.
- Optimal control strategies inside each 15-min step.
- Multi-agents and fault detection algorithms for smart grid operation modes.
- Network integration of the micro-grids and optimization of a micro-grid group.

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