Predictive management of energy resources in a microgrid: a simulation case study

1 PROMES-CNRS Laboratory, Perpignan, France

2 University of Perpignan Via Domitia, Perpignan, France

Aurélie Chabaud
Julien Eynard
Stéphane Grieu
Summary

1. Context and objectives

2. Energy resources management
   - Evaluation criteria
   - Impact on the grid
   - Overview of the strategy

3. Microgrid modeling
   - Single-storey house
   - Energy production and storage systems

4. Design and impact on the grid

5. Conclusion and outlook
Context of the study

- Environmental issues and concerns are growing
- Fossil fuels are running out
- Decentralized energy production is developing
  - Intermittency in renewables
  - Production impacts on the grid operation and stability
Objectives

Develop a predictive strategy for managing energy resources in houses equipped with production (PV solar panels/windmills) and storage systems (batteries)

- Promote energy self-consumption
- Minimize the impact of energy production on the grid
- Manage electricity storage
- Control energy consumption/Load shifting
Energy criteria

- **Renewable energy use:** \( J_{EnR} = \frac{\%EnR_c \times \%SC}{100} \)

- **Energy self-consumption:** \( \%SC = 100 \times \frac{EnR_c}{EnR_p} \)

- **Renewable energy coverage rate:** \( \%EnR_c = 100 \times \frac{EnR_c}{EnR_p + E_{EDF}} \)

  - \( EnR_c \) is the amount of renewable energy consumed (kWh)
  - \( EnR_p \) is the amount of renewable energy produced (kWh)
  - \( E_{EDF} \) is the amount of energy extracted from the grid (kWh)
  - \( \%EnR_c \) is the ratio of the renewable energy produced and consumed in situ to the total energy consumed (%)
  - \( \%SC \) is the ratio of the renewable energy consumed in situ to the renewable energy produced (%)
Economic cost & dynamic pricing

- Economic cost: \( J_{\text{cost}} = \sum_k E_{\text{inj}}(k) \cdot P_{\text{En}}(k) - E_{\text{EDF}}(k) \cdot P_{\text{En}}(k) \)

- Dynamic pricing: \( P_{\text{En}}(k) = \sum_i a_{ij} \times L^i_g(k) \times 10^{-3} \times T^j_{\text{out}}(k) \)

- \( E_{\text{inj}} \) is the amount of energy injected to the grid (kWh)
- \( P_{\text{En}} \) is the energy price (€.kWh\(^{-1}\))
- \( E_{\text{EDF}} \) is the amount of energy extracted from the electricity grid (kWh)
- \( a_{ij} \) are the polynomial coefficients, \( \forall i, j \in [1, 5] \)
- \( L_g \) is the electricity grid load (kW)
- \( T_{\text{out}} \) is the outdoor temperature (°C)
Status of the grid and grid threshold

Energy demand

<table>
<thead>
<tr>
<th>Periods</th>
<th>May, 1 to October, 31</th>
<th>November, 1 to April, 30</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak periods</strong></td>
<td>10:00 a.m. – 5:00 p.m.</td>
<td>7:00 a.m. - 1:30 p.m.</td>
</tr>
<tr>
<td>5:30 p.m. - 8:30 p.m.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:00 a.m. - 2:00 a.m.</td>
<td></td>
<td>6:00 a.m. - 7:00 a.m.</td>
</tr>
<tr>
<td><strong>Part-peak periods</strong></td>
<td>7:00 a.m. - 10:00 a.m.</td>
<td>1:30 p.m. - 2:30 p.m.</td>
</tr>
<tr>
<td>5:00 p.m. - 11:00 p.m.</td>
<td>4:00 p.m. - 5:30 p.m.</td>
<td>8:30 p.m. - 11:00 p.m.</td>
</tr>
<tr>
<td><strong>Off-peak periods</strong></td>
<td>2:00 a.m. - 7:00 a.m.</td>
<td>2:00 a.m. - 6:00 a.m.</td>
</tr>
<tr>
<td>11:00 p.m. - 12:00 a.m.</td>
<td>11:00 p.m. - 12:00 a.m.</td>
<td></td>
</tr>
</tbody>
</table>

Grid threshold: 30% or 70%

Status of the grid:
- Load > grid threshold : $J_{\text{grid}} = 1$
- Load < grid threshold : $J_{\text{grid}} = 0$
Impact on the grid

- **Injection impact:** \( I_{\text{inj}} = \frac{1}{1000} \times \sum_k E_{\text{inj}}(k) \times \Delta E_{\text{thres}}(k) \)

- **Extraction impact:** \( I_{\text{ext}} = -\frac{1}{1000} \times \sum_k E_{\text{EDF}}(k) \times \Delta E_{\text{thres}}(k) \)

- **Overall impact:** \( I_{\text{over}} = I_{\text{inj}} + I_{\text{ext}} \)

- \( E_{\text{inj}} \) is the amount of energy injected to the grid (kWh)

- \( E_{\text{EDF}} \) is the amount of energy extracted from the electricity grid (kWh)

- \( \Delta E_{\text{thres}} \) is the normalized deviation between the threshold and the status of the grid (-)
Non-predictive strategy (reference)

- Overproduction (1/3)

\[
\Delta(k) = EnR_p(k) - \frac{E_{1o}(k)}{\mu_{inv}}
\]

\[
E_{bat_{max}} - E_{bat}(k - 1) < \Delta(k)
\]

- Energy storage

\[
E_{bat}(k) < E_{bat_{min}}
\]

- Injection to the grid

Energy storage

Injection to the grid
Non-predictive strategy (reference)

- **Balance (2/3)**
  
  \[ \Delta(k) = 0 \]

  - No interaction with the grid and the batteries
  - No
  - \( E_{bat}(k) < E_{bat_{min}} \)
  - Yes
  - Extraction from the grid
  - Energy storage

- **Underproduction (3/3)**
  
  \[ \Delta(k) < 0 \]

  - Energy release
  - No
  - \( E_{bat}(k-1) - E_{bat_{min}} < \Delta(k) \)
  - Yes
  - Energy release
  - Extraction from the grid
Predictive strategy

- Overproduction (1/3)

\[ \Delta(k) > 0 \]

- \( \text{grid}(k) = P \)

- \( E_{EDP}(k) = 0 \)

- \( E_{bat}(k) < E_{bat_{min}} \)

- Injection to the grid

- Energy storage

- Extraction from the grid

- Energy storage

\[ E_{bat_{max}} - E_{bat}(k - 1) < \Delta(k) \]
Predictive strategy

- Balance (2/3)

\[
\Delta(k) = 0
\]

\[
\text{grid}(k) = P
\]

\[
E_{E,D,P}(k) = 0
\]

\[
E_{bat}(k) < E_{bat_{min}}
\]

- Extraction from the grid Energy storage
- No interaction with the grid and the batteries
Predictive strategy

- Underproduction (3/3)

\[ \Delta(k) < 0 \]

\[ E_{res}(k) = P \]

\[ E_{EDFp}(k) = 0 \]

\[ E_{bat}(k-1) - E_{bat_{min}} < \Delta(k) \]

- Extraction from the grid
- Energy storage

\[ E_{des}(k) < \Delta(k) \]

- Energy release
- Extraction from the grid

- Energy release
Prediction horizon

① Off-peak period:

- \( h = D_{HP} + D_I + D_P \)
- Threshold is 30%
Prediction horizon

② Part-peak period:

- Followed by a peak period
  - \( h = D_I + D_P \)
  - Threshold is 70%

- Followed by an off-peak period
  - \( h = D_I \)
  - Threshold is 30%
Prediction horizon

③ Peak period:

- Followed by a part-peak period
  - \( h = D_P \)
  - Threshold is 70%

- Followed by a new peak period
  - \( h = D_P + D_I + D_{Pp} \)
  - Threshold is 70%
Prediction data

- **Housing load:**
  \[ L_{h}^{j+1}(k + i) = L_{h}^{j}(k + i) + \beta_{h} \times (T_{out}^{j+1}(k) - T_{out}^{j}(k)) \]

- **Electrical grid load:**
  \[ L_{g}^{j+1}(k + i) = L_{g}^{j}(k + i) + \beta_{g} \times (T_{out}^{j+1}(k) - T_{out}^{j}(k)) \]

- **Symbols:**
  - \( L_{h}^{j+1} \): Housing load prediction (kWh)
  - \( L_{h}^{j} \): Housing load of previous day (kWh)
  - \( L_{g}^{j+1} \): Grid load prediction (kWh)
  - \( L_{g}^{j} \): Grid load of previous day (kWh)
  - \( T_{out} \): Outside temperature (°C)
  - \( j \): Index day of the year
  - \( i \): Time index for predicting with \( i = k : k + h \)
  - \( k \): Time index
  - \( \beta \): Parameter to optimize (\( \beta_{h} = 0,1 \) et \( \beta_{g} = 0,001 \))
Prediction data

- PV production:
  \[ EnR_{PV}^{j+1}(k+i) = EnR_{PV}^{j}(k+i) + \beta_{PV} \times (I_{r}^{j+1}(k) - I_{r}^{j}(k)) \]

- Vertical-axis windmill production:
  \[ EnR_{wind}^{j+1}(k+i) = EnR_{wind}^{j}(k+i) + \beta_{wind} \times (V_{wind}^{j+1}(k) - V_{wind}^{j}(k)) \]

- \( EnR_{PV}^{j+1} \) : PV production prediction (kWh)
- \( EnR_{PV}^{j} \) : PV production of previous day (kWh)
- \( EnR_{wind}^{j+1} \) : Windmill production prediction (kWh)
- \( EnR_{wind}^{j} \) : Windmill production of previous day (kWh)
- \( I_{r} \) : Solar irradiation (kWh.m\(^{-2}\))
- \( V_{wind} \) : Wind speed (m.s\(^{-1}\))
- \( j \) : Index day of the year
- \( i \) : Time index for predicting with \( i = k : k + h \)
- \( k \) : Time index
- \( \beta \) : Parameter to optimize (\( \beta_{PV} = 0.001 \) et \( \beta_{wind} = 1.1 \))
TRNSYS thermal model of an individual house

Case study: 150 m² single-storey house located in Perpignan (south of France), facing south and inhabited by four persons (two adults and two children)
TRNSYS thermal model of an individual house

Characteristics of the materials used in the considered single-storey house:

<table>
<thead>
<tr>
<th>Element</th>
<th>Material</th>
<th>Thickness [m]</th>
<th>U [W.m⁻².K⁻¹]</th>
<th>Uₚ[RT2005] [W.m⁻².K⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>BA13</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rockwool</td>
<td>0.06</td>
<td>0.602</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Cinderblock</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface coating</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal wall</td>
<td>BA13</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glass wool</td>
<td>0.04</td>
<td>0.845</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>BA13</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tiles</td>
<td>0.022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>Mortar</td>
<td>0.05</td>
<td>0.415</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Heavy concrete</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Expanded polystyrene</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td>BA13</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glass wool</td>
<td>0.1</td>
<td>0.196</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Air knife</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Terracotta</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garage ceiling</td>
<td>BA13</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Terracotta</td>
<td>0.2</td>
<td>2.37</td>
<td>0.34</td>
</tr>
<tr>
<td>Window</td>
<td>Double glazed</td>
<td>0.2</td>
<td>1.43</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Modeling of lifestyle and habits

Conventional occupation scenario set by RT 2005

<table>
<thead>
<tr>
<th>Week occupancy</th>
<th>Weekend occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0h-10h ; 18h-24h</td>
<td>0h-24h</td>
</tr>
</tbody>
</table>

Conventional French RT 2005 temperature set-points

<table>
<thead>
<tr>
<th>Set point</th>
<th>Occupancy periods</th>
<th>Non occupancy periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>19°C</td>
<td>16°C</td>
</tr>
<tr>
<td>Air conditioning</td>
<td>28°C</td>
<td>30°C</td>
</tr>
</tbody>
</table>
Production and storage systems modeling (energy mix)

Photovoltaic array
TRNSYS model 194

- Based on the calculation method presented by DeSoto\(^1\) and defined with various semi-empirical equations
- Determines the current and power of a photovoltaic array at a specific voltage

Production and storage systems modeling (energy mix)

Vertical-axis windmill
TRNSYS model 90

- Based on the work of Quilan\(^1\)
- Calculates the power output of energy conversion systems based on a power versus wind speed characteristics

Description of the functioning of the batteries:

- **Charging mode:**
  \[
  E_{bat}(t) = (1 - \tau) \cdot E_{bat}(t - 1) + \left( E_{EnR}(t) - \frac{E_{ch}(t)}{\eta_{inv}} \right) \cdot \eta_{bat}
  \]

- **Discharging mode:**
  \[
  E_{bat}(t) = (1 - \tau) \cdot E_{bat}(t - 1) + \left( \frac{E_{ch}(t)}{\eta_{inv}} - E_{EnR}(t) \right)
  \]

**Constraints:**
\[
E_{bat,min} = (1 - DOD) \times E_{bat,max} \quad \text{and} \quad E_{bat,max} = C_n
\]

- \( \eta_{inv} \): Inverter performance
- \( \eta_{bat} \): Charge performance
- \( E_{bat} \): Energy stored (kWh)
- \( E_{ch} \): Energy required (kWh)
- \( E_{EnR} \): Energy produced by the local production systems (kWh)
- \( \tau \): Hourly self-discharge rate
- \( DOD \): Depth Of Discharge
- \( C_n \): Nominal capacity (kWh)
Design of energy production and storage systems (predictive)

With PV panels and batteries

With PV panels, a vertical-axis windmill and batteries
Design of energy production and storage systems (predictive)

With PV panels and batteries

<table>
<thead>
<tr>
<th>System / Criterion</th>
<th>Predictive</th>
<th>No predictive without storage</th>
<th>No predictive with storage 70% threshold</th>
<th>No predictive with storage 30% threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels (kWp)</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Batteries (kWh)</td>
<td>130</td>
<td>-</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>$EnR_c$ (kWh)</td>
<td>8011</td>
<td>5632</td>
<td>7988</td>
<td>5736</td>
</tr>
<tr>
<td>$EnR_{inj}$ (kWh)</td>
<td>3404</td>
<td>6201</td>
<td>3428</td>
<td>6079</td>
</tr>
<tr>
<td>$E_{EDF}$ (kWh)</td>
<td>21367</td>
<td>23743</td>
<td>21383</td>
<td>23647</td>
</tr>
<tr>
<td>$E_{st}$ (kWh)</td>
<td>17882</td>
<td>6</td>
<td>2362</td>
<td>111</td>
</tr>
<tr>
<td>$%_{SC}$ (%)</td>
<td>67.70</td>
<td>47.60</td>
<td>67.50</td>
<td>48.47</td>
</tr>
<tr>
<td>$%_{EnR_c}$ (%)</td>
<td>27.27</td>
<td>19.17</td>
<td>27.19</td>
<td>19.53</td>
</tr>
<tr>
<td>$J_{EnR}$ (%)</td>
<td>18.46</td>
<td>9.13</td>
<td>18.36</td>
<td>9.46</td>
</tr>
<tr>
<td>$J_{cost}$ (€)</td>
<td>-1035.34</td>
<td>-1011.08</td>
<td>-1034.89</td>
<td>-1013</td>
</tr>
</tbody>
</table>
Design of energy production and storage systems (predictive)

With PV panels and batteries

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<tr>
<td>Batteries (kWh)</td>
<td>130</td>
<td>-</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>$I_{inj}$</td>
<td>1316</td>
<td>778</td>
<td>1318</td>
<td>859</td>
</tr>
<tr>
<td>$I_{sout}$</td>
<td>12800</td>
<td>5233</td>
<td>6390</td>
<td>6790</td>
</tr>
<tr>
<td>$I_g$</td>
<td>14116</td>
<td>6011</td>
<td>7709</td>
<td>7649</td>
</tr>
<tr>
<td>Threshold 70%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_{inj}$</td>
<td>2509</td>
<td>3518</td>
<td>2524</td>
<td>3580</td>
</tr>
<tr>
<td>$I_{sout}$</td>
<td>4636</td>
<td>-3119</td>
<td>-1415</td>
<td>-2172</td>
</tr>
<tr>
<td>$I_g$</td>
<td>7145</td>
<td>399</td>
<td>1108</td>
<td>1407</td>
</tr>
<tr>
<td>Threshold 30%</td>
<td></td>
<td></td>
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</table>
Design of energy production and storage systems (predictive)

With PV panels, a vertical-axis windmill and batteries

<table>
<thead>
<tr>
<th>System / Criterion</th>
<th>Predictive</th>
<th>No predictive without storage</th>
<th>No predictive with storage 70% threshold</th>
<th>No predictive with storage 30% threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels (kWp)</td>
<td>7.6</td>
<td>7.6</td>
<td>7.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Vertical axis windmill (kWp)</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Batteries (kWh)</td>
<td>200</td>
<td>-</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>$EnR_c$ (kWh)</td>
<td>16388</td>
<td>12057</td>
<td>16382</td>
<td>13244</td>
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<tr>
<td>$EnR_{inj}$ (kWh)</td>
<td>8589</td>
<td>13681</td>
<td>8590</td>
<td>12284</td>
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<tr>
<td>$E_{EDF}$ (kWh)</td>
<td>13001</td>
<td>17318</td>
<td>12998</td>
<td>16141</td>
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<tr>
<td>$E_{st}$ (kWh)</td>
<td>14423</td>
<td>-</td>
<td>4330</td>
<td>1195</td>
</tr>
<tr>
<td>%$_{SC}$ (%)</td>
<td>63.67</td>
<td>46.85</td>
<td>63.65</td>
<td>51.46</td>
</tr>
<tr>
<td>%$_{EnR_c}$ (%)</td>
<td>55.79</td>
<td>41.05</td>
<td>55.77</td>
<td>45.09</td>
</tr>
<tr>
<td>$J_{EnR}$ (%)</td>
<td>35.52</td>
<td>19.23</td>
<td>35.50</td>
<td>23.20</td>
</tr>
<tr>
<td>$J_{cost}$ (€)</td>
<td>-220.98</td>
<td>-209.59</td>
<td>-254.03</td>
<td>-222.27</td>
</tr>
</tbody>
</table>
Design of energy production and storage systems (predictive)

With PV panels, a vertical-axis windmill and batteries

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<tr>
<td>Batteries (kWh)</td>
<td>200</td>
<td>-</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Threshold</th>
<th>$I_{inj}$</th>
<th>$I_{sout}$</th>
<th>$I_g$</th>
<th>$I_{inj}$</th>
<th>$I_{sout}$</th>
<th>$I_g$</th>
<th>$I_{inj}$</th>
<th>$I_{sout}$</th>
<th>$I_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>4550</td>
<td>-145</td>
<td>1327</td>
<td>1001</td>
<td>4368</td>
<td>5369</td>
<td>4561</td>
<td>-1219</td>
<td>-1734</td>
</tr>
<tr>
<td>30%</td>
<td>2713</td>
<td>4762</td>
<td>3525</td>
<td>4368</td>
<td>5369</td>
<td>5369</td>
<td>4561</td>
<td>-1219</td>
<td>-1734</td>
</tr>
</tbody>
</table>
Several configurations promoting energy self-consumption are highlighted

Impact of local production on the grid is minimized

Better match between decentralized production, energy needs and injection to the grid