DETAILED MODELING OF COMPLEX BIPV SYSTEMS

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PVPDMC 2016
Freiburg, October 25th

Fraunhofer Institute for Solar Energy Systems ISE
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AGENDA

- Which challenges occur for building integrated photovoltaics?

- Simulation of irradiance, cell temperature, electrical cell behaviour, module interconnection and inverter behaviour

- Example project in Zürich (Art Nouveau building from 1908)
BIPV – a short definition

- **BIPV = Building-Integrated Photovoltaics**
  - Components of the building skin, that additionally generate electrical power output

- Requirements and possible issues
  - Fulfilling of building norms, statics, durability (higher demands than for standard PV), appearance from outside and inside, thermal insulation, watertightness, electrical efficiency…
Challenges for BIPV systems regarding electrical system design

- Planning and construction process much more complex
- Different orientations of modules
- Partial shading
- Different module sizes
- Complex module interconnections
- Complex inverter requirements
- ...

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Simulation-based approach for complex BIPV systems

For each time step:

1. Irradiance
Simulation-based approach for complex BIPV systems

For each time step:

1. Irradiance

2. Cell temperature
Simulation-based approach for complex BIPV systems

For each time step:

1. Irradiance
2. Cell temperature
3. Cell IV curves
Simulation-based approach for complex BIPV systems

For each time step:

1. Irradiance
2. Cell temperature
3. Cell IV curves
4. System IV curves (DC output)
Simulation-based approach for complex BIPV systems

For each time step:

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4. System IV curves (DC output)
5. Inverter (AC output)
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Topic I: Irradiance Calculation
Open Source Ray-Tracing Program RADIANCE

- Calculation of the sky radiance distribution based on horizontally measured irradiance values according to Perez model\(^1\)
- Backward ray-tracing of scene with the geometry of the building and its surroundings with corresponding optical properties of materials including:
  - Partial shading
  - Multiple reflections from ground or other surfaces

Output
Irradiance values for each PV cell involved and each time step of the defined time range (e.g. 5-min steps and one year)

Topic I: Irradiance Calculation

Sky

The diffuse radiation from the sky is important for:

- Calculation of the irradiance on tilted surfaces
- Analysis of partial shading

The model of Perez (1993) allows the calculation of the sky radiance distribution and is implemented in the ray-tracing program RADIANCE (gendaylit).
Topic I:  Irradiance Calculation

**Needed:** Irradiance level in the PV module that can be compared to STC irradiance

**Step 1:** Irradiance in front of the PV Module

\[ E = \int_{\Omega} L \cos(\theta_M) \, d\Omega \]

\[ \rightarrow E \text{ doesn’t include the higher reflectance of the PV module at large incidence angles!} \]

**Step 2:** Calculation of an “effective” irradiance

\[ E_{eff} = \int_{\Omega} L \cdot K(\theta_M) \cdot \cos(\theta_M) \, d\Omega \approx E_{dir} \cdot K(\theta_{dir}) + E_{diff} \cdot K(\bar{\theta} = 60^\circ) \]
Simulation-based approach for complex BIPV systems

For each time step:

1. Irradiance
2. Cell temperature
3. Cell IV curves
4. System IV curves (DC output)
5. Inverter (AC output)
Topic IV: Electrical simulation of the DC circuit

Simple Example: Standard Module

Interconnection:

→ PV cells, resistances, diodes

→ parallel, series, cross-connected

the electrical circuit of a standard 60-cell PV module
Topic IV: Electrical simulation of the DC circuit

Simple Example: Standard Module

Interconnection:

→ PV cells, resistances, diodes
→ parallel, series, cross-connected

1. Calculation of the IV curves

*IV curve of the standard 60-cell PV module at different (homogeneous) irradiance levels on one shaded PV cell at 1000 W/m² irradiance on all other PV cells.*

*Blue: 1000 W/m², green: 800 W/m², …, yellow: 0 W/m²*
Topic IV: Electrical simulation of the DC circuit
Simple Example: Standard Module

Interconnection:
→ PV cells, resistances, diodes
→ parallel, series, cross-connected

2. Calculation of the operation points

Operation points of the shaded PV cell in a standard 60-cell PV module at different (homogeneous) irradiance levels on the shaded PV cell and 1000 W/m² irradiance on all other PV cells, vs. the applied PV module voltage.

Blue: 1000 W/m², green: 800 W/m², ..., yellow: 0 W/m²
Outcomes so far

- In almost all cases, BIPV systems have to deal with inhomogeneous irradiation. The impact of shading and multiple reflections (ground, other buildings) is not negligible and can be calculated.

- Inhomogeneous irradiation leads to module/system IV curves and cell operation points that vary strongly in time and are difficult to predict. They have to be simulated.

- The temperature situation has to be investigated in advance. Especially for thermally insulated facades, peak temperatures can be higher than expected.

- The inverter has to be chosen with care. Voltage or power restrictions can lead to serious losses or damage.
Example Project in Zürich

Renovation of an urban building. Goal: “Plus Energy Building”
Example Project in Zürich

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Example Project in Zürich

Data in brief:

- 100% power supply (grid connection)
- Nominal system power: 27.94 kWp
- 198 PV modules with 112 different sizes
- 19 different module expositions
- **Goal: 14000 kWh per year**
Example Project in Zürich

- Calculation of time-dependent irradiance (1)
- Calculation of time-dependent module temperature (2)
- Calculation of cell IV characteristics for all irradiance and temperature levels (3)
- Calculation of system IV curve based on the electrical interconnections of cells and modules including bypass diodes (DC output) (4)
- Calculation of inverter output (AC output) (5)
Example Project in Zürich

- **Calculation of time-dependent irradiance** (1)

- **Calculation of time-dependent module temperature** (2)

- **Calculation of cell IV characteristics for all irradiance and temperature levels** (3)

- **Calculation of system IV curve based on the electrical interconnections of cells and modules including bypass diodes (DC output)** (4)

- **Calculation of inverter output (AC output)** (5)
Example Project in Zürich

Irradiance simulation

Calculation of irradiance for every PV cell (time steps: 10 min)
Example Project in Zürich
Calculation of DC-output

Example of subsystem: One PV Module
Example Project in Zürich
Various challenges to electrical system design

- Which modules can be interconnected in series to strings?

- Which strings can be interconnected in parallel?

- Inverter restrictions (MPP tracking range, voltage range) very important for systems with frequent partial shading

Result: 14 sub-systems with minimized mismatch losses of 6.2 %
Calculated yield: **512.78 kWh / kWp; 14328 kWh**
Example Project in Zürich

Status

- System built and converting energy since March 2016
- Goal: 14000 kWh/year
- Predicted complete year (based on data from Test Reference Year): 14328 kWh (100%)
- Predicted April to September (based on data from Test Reference Year): 10502 kWh (73%)
- Measured April to September 2016: 9780 kWh (68%, means 93% of prediction) (preliminary data)
Example Project in Zürich

Status

% of predicted yield April-September

Sub system nr.
Summary and Outlook

Detailed simulation approach for (BI)PV systems allows for an accurate calculation and optimization with regard to:

- Irradiance conditions including shading
- Electrical design (cell and module interconnection)
- Inverter behavior
- Fail-safe design

For an exemplary project in Zürich, a 27.9 kWp BIPV system with 198 modules, 112 different module sizes and 14 inverters has been electrically designed and simulated.

- Predicted yield annual: 14328 kWh/year
- Yield after construction April - September 2016: 9780 kWh (93% of prediction for April - September)
Thanks to all project partners and colleagues!

Gallus Cadonau (Bauherr)

FENT Solare Architektur

Ertex solar

Solarinvert

Fraunhofer ISE
Thank you for your attention!

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Simulation based approach for complex BIPV systems

For each time step:

1. **Irradiance**
   - Raytracing based on
     - 3D geometry
     - Meteorological data (diffuse and direct irradiation)

2. **Cell temperature**
   - Calculation based on
     - Module layer structure
     - Irradiance

3. **Cell IV-curves**
   - Calculation based on
     - Datasheet specifications
     - Two diode model

4. **System IV-curves (DC-output)**
   - Calculation based on
     - Electrical interconnection including diodes, resistances etc.

5. **Inverter (AC-output)**
   - Calculation based on
     - Inverter specifications
# Example Project in Zürich – detailed result of optimization

<table>
<thead>
<tr>
<th>Sub system</th>
<th>Inverter input ports</th>
<th>No. of PV cells</th>
<th>No. of module orientations</th>
<th>Nominal power [Wp]</th>
<th>Calculated DC-output per kWp and year (without inverter)</th>
<th>Calculated mismatch losses</th>
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<td>A</td>
<td>6</td>
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</tbody>
</table>
Topic I: Irradiance Calculation

Angular Correction

\[ E_{eff} = \int_{\Omega} L \cdot K(\theta_M) \cdot \cos(\theta_M) \, d\Omega \approx E_{dir} \cdot K(\theta_{dir}) + E_{diff} \cdot K(\bar{\theta} = 60^\circ) \]

Examples of different \( K(\theta_M) \) curves (Martin, 2001\(^1\)):

\( E_{eff} \) can be directly compared to the irradiance level at STC.