Extension of Thermal Models to Assess Integrated Photovoltaics and Mobile Applications

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Motivation, Problem Statement, Approach

- Many analytical one-dimensional thermal models exist in Photovoltaic (PV) module assessment [1-4].
- These models are based on a system of layers and interfaces (Figure 1).
- Analytical equations describe heat transfer (via radiation, convection or direct heat transfer) between interfaces, heat sources and sinks.

$$0 = E_{in,n} - E_{out,n} + E_{source,n} - E_{sink,n}$$

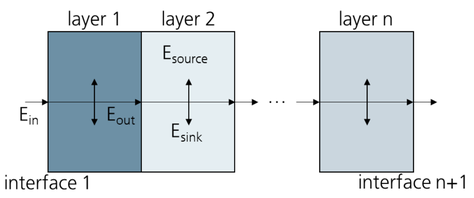

Fig 1: One-dimensional energy balance model

- Boundary conditions (i.e. ambient temperatures) are required to solve equations and to calculate layer temperatures.
- They change depending on the application type of the PV module (Figure 2).
- Boundary conditions can be easily added in existing models by implementing parameters for front and rear side environmental conditions separately.
- **Easily updated boundary conditions allow for extended application of one-dimensional thermal models for PV module assessment.**

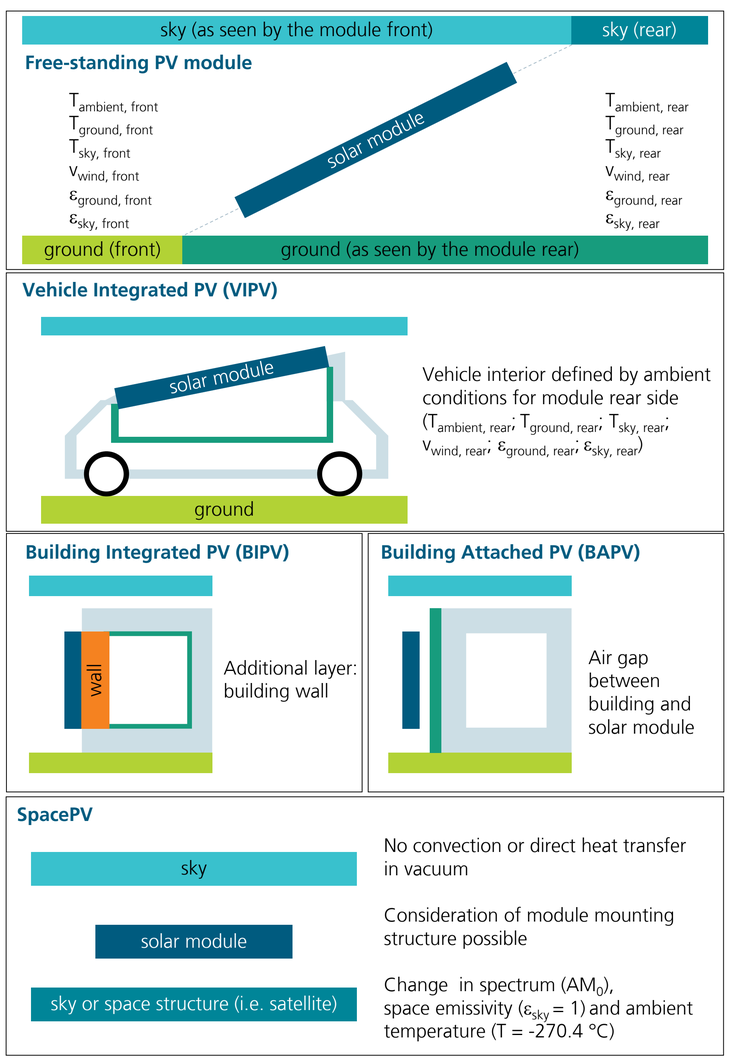

Fig 2: Application types of PV modules, different colors indicate differences in boundary conditions between module front and rear side

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Implementation and Application Types

- Changes in the boundary conditions (Table 1) are implemented into an existing thermal model [1].
- The thermal model is implemented into SmartCalc.Module [6] – a multi-physics analysis tool to calculate PV module power output.
- Impact of application scenarios are analyzed for a conventional 120× G12R half cell TOPCon glass-glass module.

Table 1: Boundary conditions for each of the application types

Application	Qualitative changes compared to free-standing	Scenario parameters
Free-standing		1000 W/m² AM1.5 perpendicular direct front irradiance, 0 W/m² rear irradiance 25 °C ambient and ground temperature (front and rear side) 45° module inclination v_{wind} = 1 m/s (front and rear side) ε_{ground} = 0.9 (front and rear side)
NMOT	– No changes for Nominal Module Operating Temperature	800 W/m², 20 °C, 1 m/s
VIPV	– Car air temperature inside ≠ ambient temperature outside – Car container wall temperature = car air temperature – No wind speed inside vehicle – Solar module replaces car roof (no added layer behind the module, roofing structure may be added as module layer)	$t_{ambient}$ = 25 °C, $t_{interior}$ = 20 °C $V_{wind, front}$ = 13.9 m/s (50 km/h), $v_{wind, interior}$ = 0 m/s No additional layer considered (module = car roof) 0° module inclination (horizontal module mounting)
BIPV	– Building air temperature ≠ ambient temperature – Building wall temperature = building air temperature – Wind speed inside the building = 0 m/s – Additional layer is added to the module (the wall), full contact of the module to the wall is assumed: heat exchange with the building interior	$t_{ambient}$ = 25 °C, $t_{interior}$ = 20 °C $v_{wind, outside}$ = 1 m/s, $v_{wind, interior}$ = 0 m/s 90° module inclination (vertical module mounting) KfW40 wall: U-value = 0.14 W/m²K: thermal conductivity = 0.07 W/mK, thickness = 0.48 m
BAPV	– Module rear sees no sky: building properties replace sky properties for rear side – Ground temperature and sky temperature rear are replaced by building temperature – Wind speed front ≠ wind speed rear	25 °C ambient, ground and building temperature 1 m/s wind on module front, 0 m/s on rear side 90° module inclination (vertical module mounting)
SpacePV	– No convection – Parameters of a mounting structure on module rear may replace space – Changes in ambient conditions apply compared to terrestrial applications (i.e. spectrum)	No mounting structure: space module is free floating E = 1367 W/m², AM_0, $T_{ambient}$ = -270.4 °C, ε = 1

Results

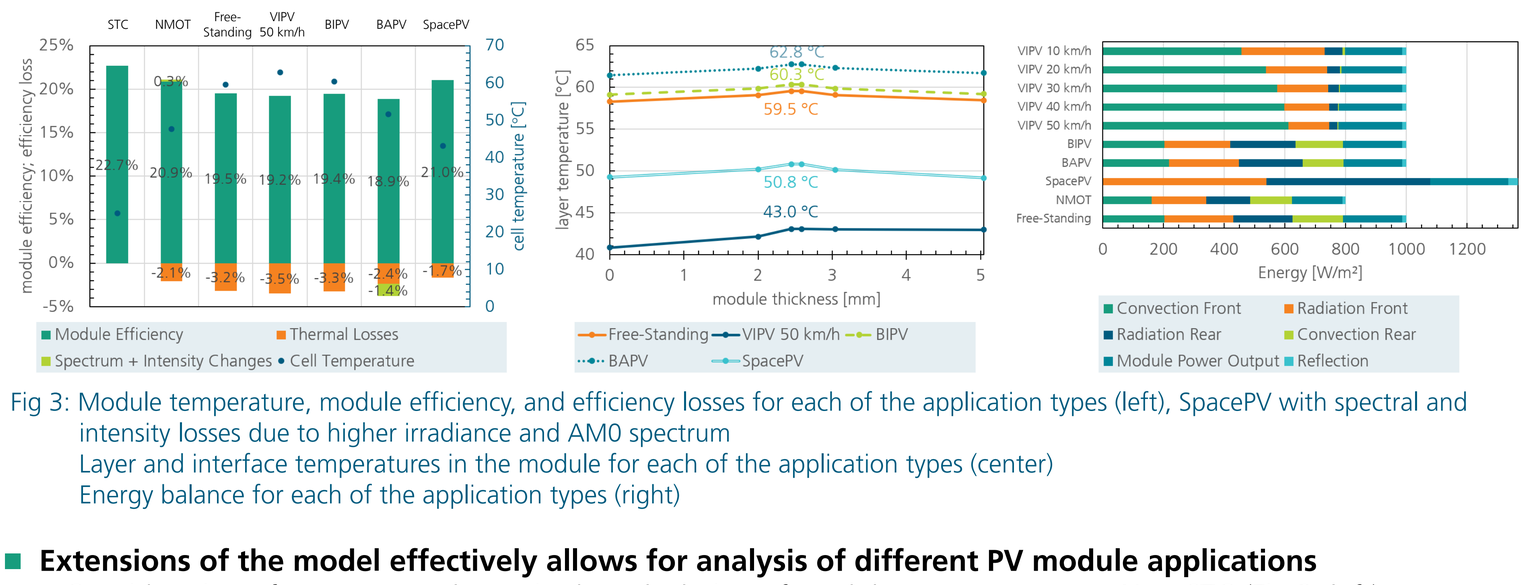

Fig 3: Module temperature, module efficiency, and efficiency losses for each of the application types (left), SpacePV with spectral and intensity losses due to higher irradiance and AM0 spectrum
Layer and interface temperatures in the module for each of the application types (center)
Energy balance for each of the application types (right)

- **Extensions of the model effectively allows for analysis of different PV module applications**
  - Consideration of temperature losses in the calculation of module power output at Non-STC (Fig 3, left)
  - Module power output and efficiency are significantly impacted by the application type.
- **Layer temperatures and cell temperature significantly impacted by application type** (Fig 3, center)
  - Highest temperatures for BAPV
  - Strong cooling effect of headwind for Vehicle Integrated PV
- **Energy dissipation mechanisms vary significantly between application types** (Fig 3, right)
  - Only radiative thermal dissipation in space applications
  - Significant heat flow to building interior for BIPV
  - Strong impact of vehicle speed on front convection and VIPV cell temperature

→ **Introduction of application types to one-dimensional energy equilibrium modelling extends flexibility of thermal analysis for PV modules**

References

1 Mittag et al., „Thermal Modelling of Photovoltaic Modules in Operation and Production", 36th EUPVSEC (4CO24), Marseille, 2019
2 Notton et al., „Modelling of a double-glass photovoltaic module using finite differences", Applied Thermal Engineering, 2005
3 Lu et al., "Energy analysis of silicon solar cell modules based on an optical model for arbitrary layers", Solar Energy, 2007
4 Gu Wenbo, et al., „Coupled electrical-thermal modelling of photovoltaic modules under dynamic conditions", Energy, 2019
5 Hanifi, H., et al., „Determination of electrical characteristics and temperature of PV modules by means of a coupled electrical-thermal model", 2020
6 SmartCalc.Module – available via www.cell-to-module.com

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