Performance Indices for Parallel Agriculture and PV Usage - Approaches to quantify land use efficiency in agrivoltaic systems

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Agenda

- Introduction of Agrivoltaics and Main Research Results
- LER as a Performance Index for Land Use Efficiency
- Other Possible Performance Indices

Examples of Integrated Photovoltaics

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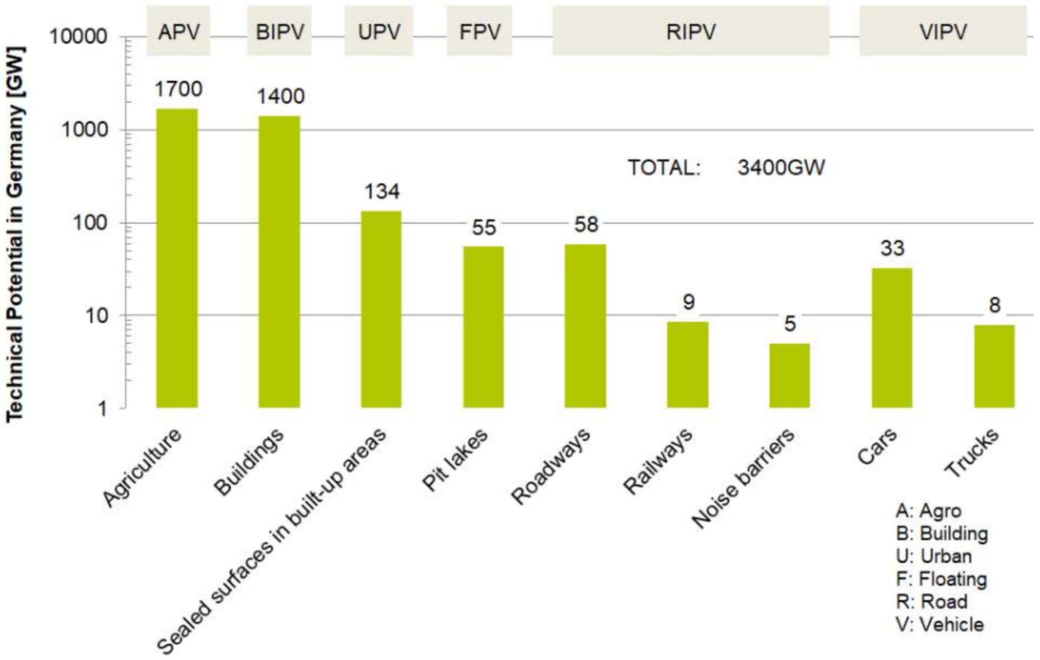
Challenges of the Energy Transition

- **Technical Land Potential:**
  Consideration of technical, infrastructural and ecological constraints



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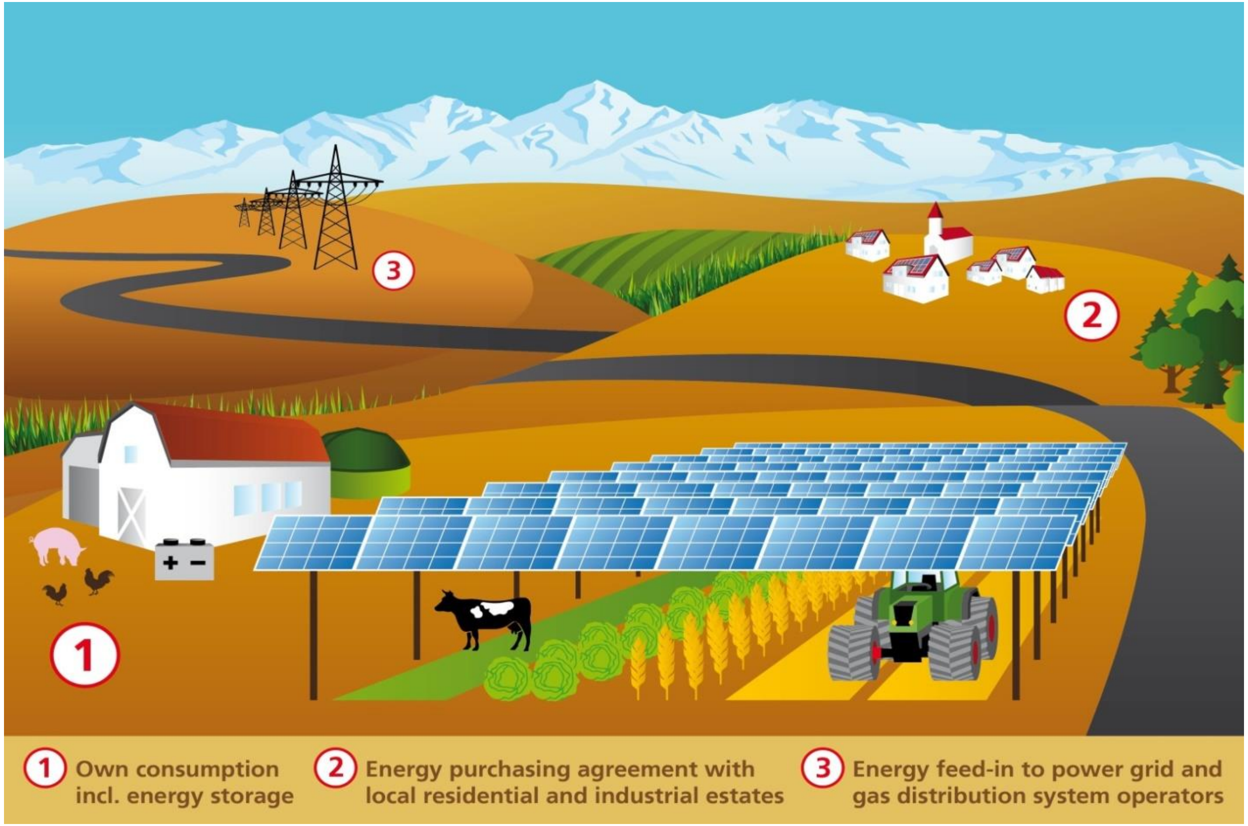
Agrivoltaics – From the Idea to the Implementation

- **The Concept**



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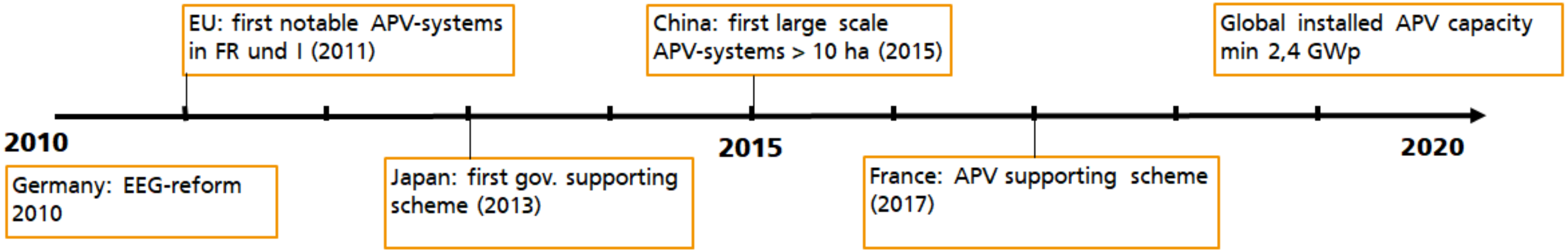
Agrivoltaics – From the Idea to the Implementation

- **Brief History**
- From 2000 EEG feed-in tariffs for Renewable Energies
- PV „revolution“
- First large scale ground-mounted PV plants (PV-GM)
- EEG-reform 2010: PV-GM only in exceptional cases on arable land
- The time has come for APV

Timeline of APV from 2010 until today



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Agrivoltaics – From the Idea to the Implementation

- **Proof of Concept – Worldwide**

- (A) **Germany,** University Weihenstephan, 30 kWp, 2013
- (B) **Italy**, R.E.M. Tech Energy, 3 x APV systems since 2011, 3.2 MWp, 1.3 MWp, 2.15 MWp
- (C) **France**, University of Montpellier, 50 kWp, 2010, 2017 – 2019: 45 MWp
- (D) **Japan**, Solar Sharing, Ministry of Agriculture, Forest and Fishery, Akira Nagashima

  1.054 Solar Sharing 2013 - 2018, 80 kWp/Projekt, 85 MWp
- (E) **Italy**, Corditec, Ahlers, 800 kWp, 2012
- (F) **Egypt**, SEKEM, Almaden, Kairo, 90 kWp, 2017
- (G) **USA**, University of Arizona, approx. 50 kWp, 2017
- (H) **Taiwan**, Green Source Technology, 400 kWp, 2016

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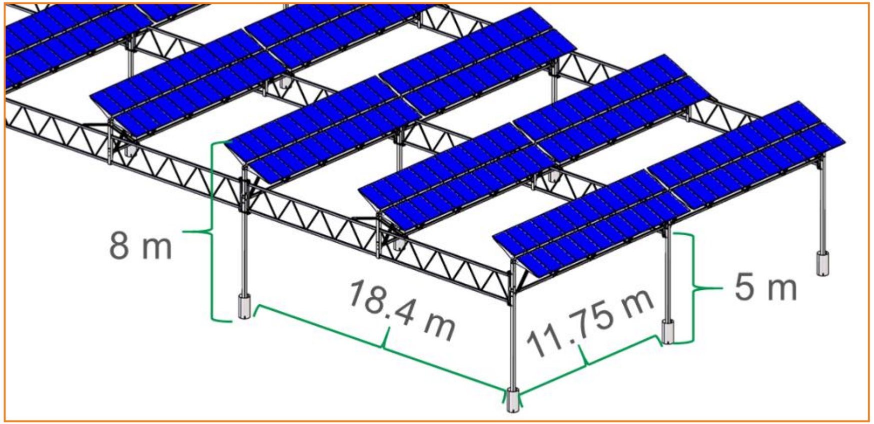
Research Results APV-RESOLA

- **Pilot Plant in Heggelbach: Facts and Figures I**
- Installed: 2016 in Heggelbach
- Region: Bodenseekreis
- Length: 136m
- Width: 25m
- Height: 8m
- Area: ~ 1/3 ha
- Vertical clearance: 5m
- Installed capacity: 194 kWp
- Crops: clover, celery, potatoes and winter wheat



Source: Hilber Solar

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Research Results APV-RESOLA

• Pilot Plant in Heggelbach: Facts and Figures II

- Light management
- Fixed-tilt towards southwest
- Bifacial glas/glas PV-modules
- Yield monitoring
- Passageway for agricultural machinery
- Rain water distribution
- Spinnanker fundaments
- Ram protection
- No fence
- Cross Compliance: high environmental sustainability


Source: BayWa r.e


Source: BayWa r.e


Source: Spinnanker

Research Results APV-RESOLA

- **Community: Citizen Workshop and Local Survey**
- Consensus in PV expansion:
  - Priority on available roof surfaces and industrial areas
  - Preferences for APV compared to PV-GM
- Learning from experiences with biogas plants
  - „Uncontrolled APV growth“ must be avoided
- Optimal integration in the landscape
  - Bringing together production and consumption
  - Concentration of APV-systems should be limited
  - Size of APV-systems should be limited

Source: Deutschlandfunk

Source: de.fotolia.com

Source: de.fotolia.com

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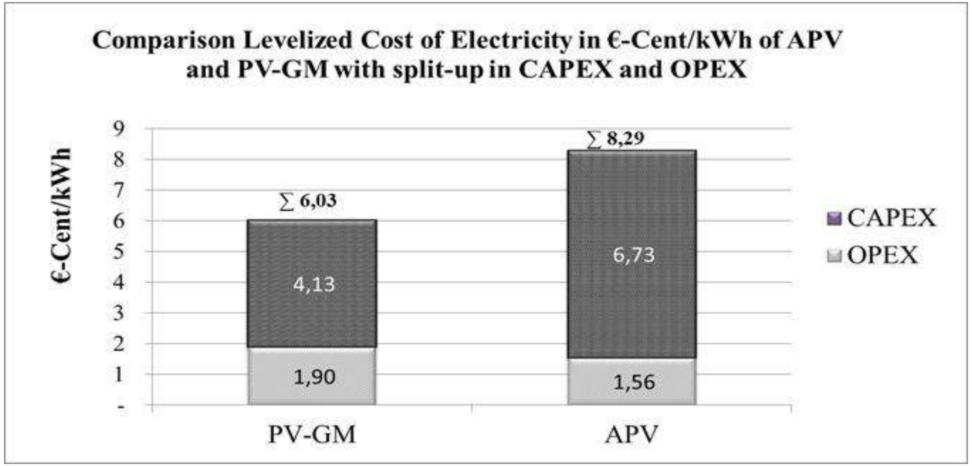
Research Results APV-RESOLA

• Economy: PV-Power Generation Cost



Source: Fraunhofer ISE

Assumptions:

- Annual electricity yield:
  - PV-FFA: 1209 kWh/kWp
  - APV: 1284 kWh/kWp
- Area: 2 ha
  - PV-FFA: 1.38 MWp
  - APV: 1.04 MWp
- Agricultural costs and earnings excluded

- APV-OPEX < than PV-GM due to synergy effects
- APV-LCOE > approx. 1/3 higher than PV-GM
- Already today competitive with roof-mounted PV < 10 kWp
- Yield reduction and additional expenses balanced by land rent contract (€1.440 €/a)

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- **LER as a Performance Index for Land Use Efficiency**
- Other Possible Performance Indices

Land Equivalent Ratio

- **The Concept**

Land Equivalent Ratio (LER): the sum of the respective yield ratios of dual land use to mono land use

$$LER = \frac{Yield_{agri}(dual)}{Yield_{agri}(mono)} + \frac{Yield_{elec}(dual)}{Yield_{elec}(mono)}$$

(Mead & Willey,1979)

- Adopted from agroforestry
- Crop yields measured in mono and dual systems
- One possible interpretation: A 1.3 LER would mean that a 10 ha agrivoltaic system would produce as much crops and electricity as 13 ha of mono productions
- LER > 1 indicates increased productivity of dual land use
- But: in many publications theoretical considerations based on agriculture experiments without taking land losses into account

Land Equivalent Ratio

- **The Concept**

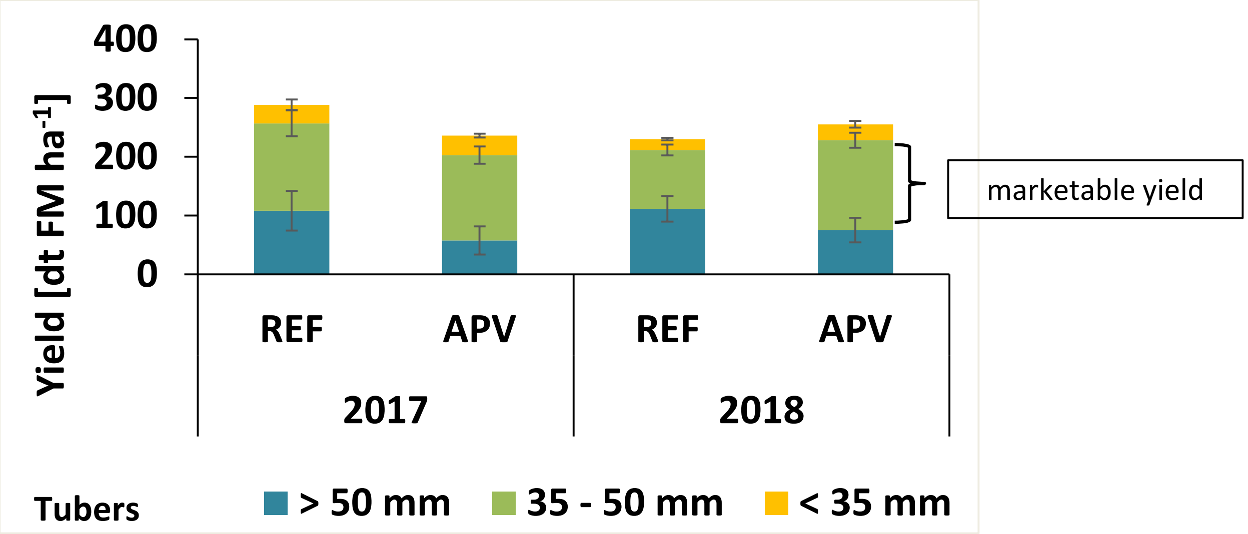
Additional consideration of land losses (LL)

$$LER = \frac{Yield_{agri}(dual)}{Yield_{agri}(mono)} + \frac{Yield_{elec}(dual)}{Yield_{elec}(mono)} - \mathrm{LL}$$

- LL occur if part of the land cannot be cultivated due to the mounting structure
- Crop yields measured under the agrivoltaic system and on a reference plots
- When larger land machines are employed, LL are usually much larger than the built-up area itself
- Case Heggelbach: LL approx. 8.3%, covered area < 1%

Land Equivalent Ratio

- **Agriculture: Example Yield Potatoes**



Source: Universität Hohenheim

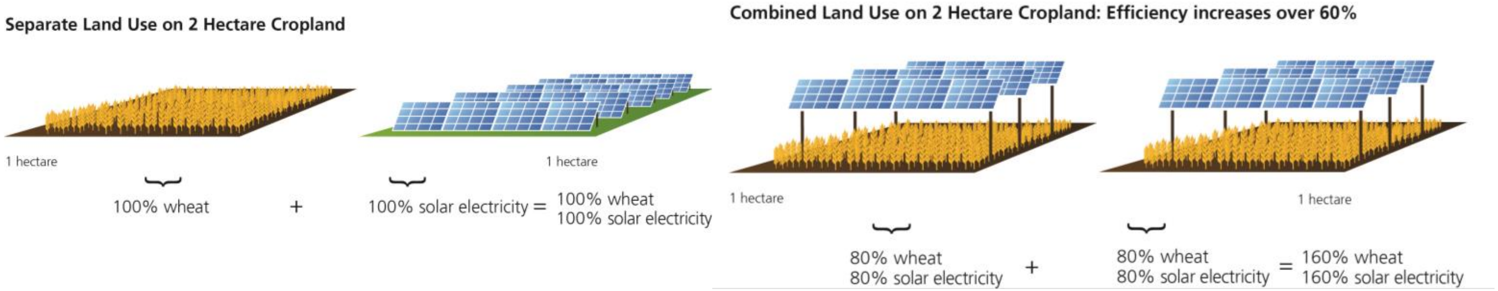
Source: Universität Hohenheim

Source: Hofgemeinschaft Heggelbach

- 2017: Yield under agrivoltaic reduced by 18 %
- 2018: Yield under agrivoltaic increased by 11 %
- Higher share of tubers with diameter 35 - 50 mm under agrivoltaic in both harvests

Land Equivalent Ratio

- **APV-RESOLA LER I: Rounded Figures from Wheat Yield 2017 and Expected Average**



- Crop: wheat
  - Approx. 80% of wheat and 80% of electricity
  - LL approx. 10%
  - LER approx. 1.5
  - Rise of land use efficiency of 50 %
- No particularly shadow-tolerant or even shade-loving plants were selected

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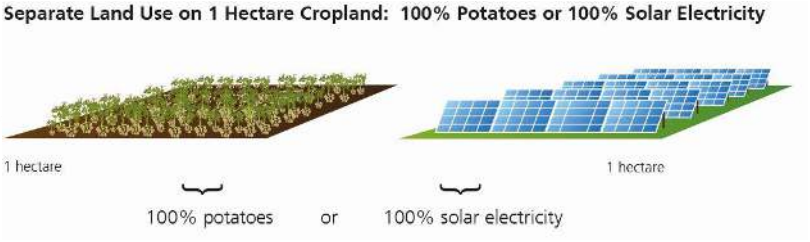
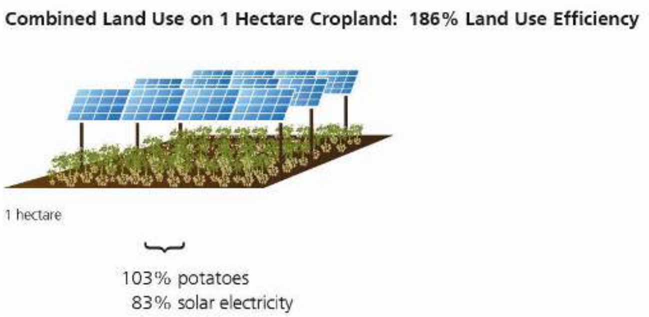
Land Equivalent Ratio

• APV-RESOLA LER II: Potatoe Yield 2018





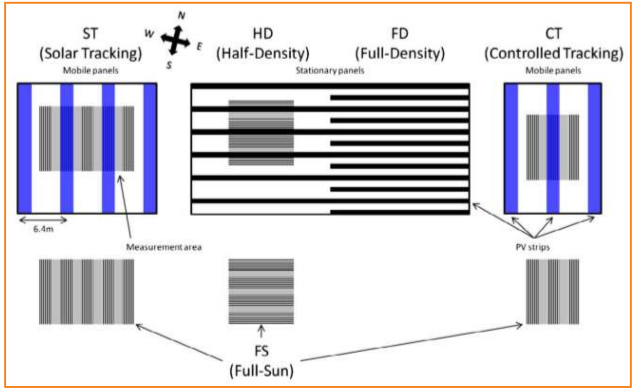
- Crop: potatoes
- $LER\ 2018 = \frac{255{,}26\,\frac{dt}{ha}\,(dual)}{230{,}02\,\frac{dt}{ha}\,(mono)} + \frac{249.857\,\frac{kWh}{a}(dual)}{301.032\,\frac{kWh}{a}(mono)} - 0.083\ = 1.86$
- Extension of potential PV area without land use conflicts
- Improvement of land use efficiency between 60 – 90 % possible in Germany
- Large potential in regions with land scarcity and in arid / semi-arid climate zones

Land Equivalent Ratio

• Other LER Research Results in Agrivoltaics

- Dupraz et al., 2011
  - Modelling of light transmission and agricultural yields for agrivoltaic systems with varying module densities
  - Food crop: durum wheat
  - Results: LER between 1.35 and 1.73
- Valle et al., 2017
  - Performances of agrivoltaic systems by comparing fixed and dynamic systems with two different orientations
  - Food crop: lettuce
  - Results: LER between 1.10 and 1.50
  - Tracked systems lead to higher LERs

Source: Dupraz et al., 2011



Source: Valle et. al, 2017

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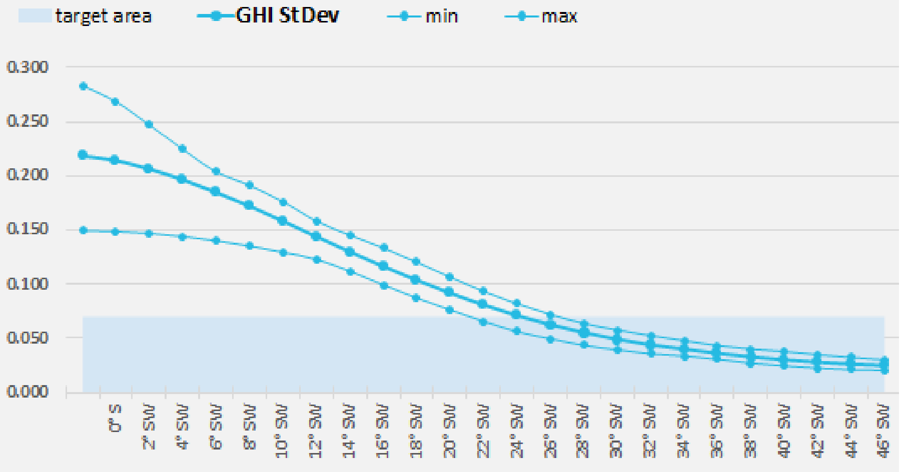
Other Performance Indices

- **Light Homogeneity I**

Standard deviation compared to an unshaded field for different orientations one meter over ground

- Feasibility Study conducted by Fraunhofer ISE for Paras, Maharashtra, India, 2018
- Modelled with Fraunhofer ISE tool ASSIST
- $s^2 = \frac{1}{n-1} \sum_{n-1}^{n} (x_i - \overline{x})^2$
- Targeted light homogeneity area reached from between 26° SW and 28° SW



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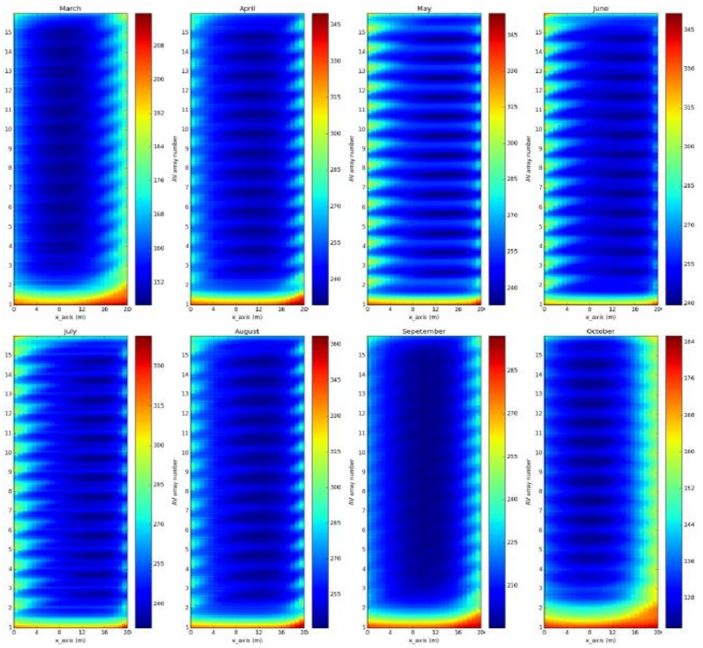
Other Performance Indices

• Light Homogeneity II

Simulation of radiation distribution under agrivoltaic system

- Preliminary to APV-RESOLA project
- Model based on the APV's specific configuration settings and the local irradiation conditions in Heggelbach, southern Germany
- Deviations of 30° from 0°S result in quite homogeneous radiation distribution
- Local conditions (e.g., orientation of field borders, direction of travel of machinery, irrigation structures etc.) might require greater deviations from 0°S



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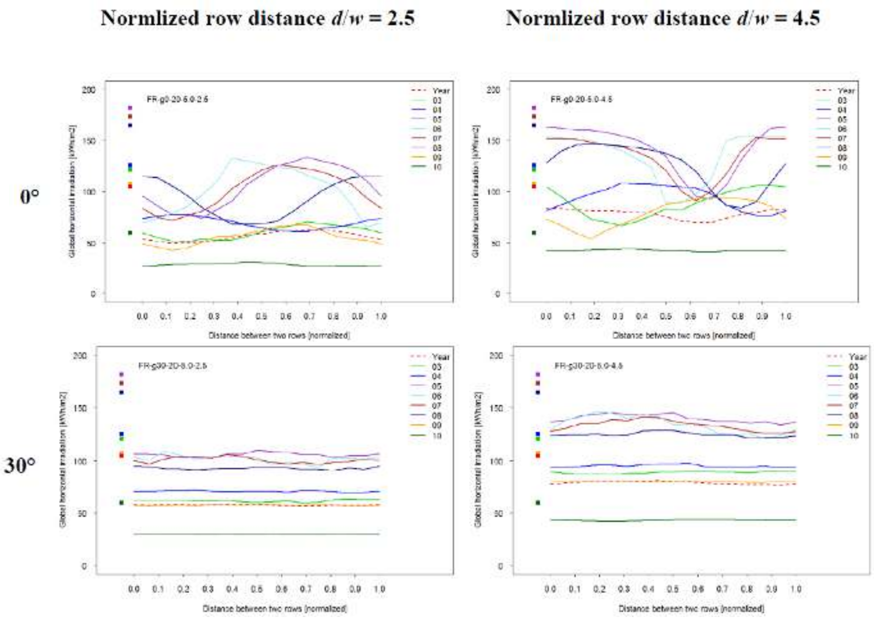
Other Performance Indices

- **Light Homogeneity III**

Monthly sums of irradiation (y-axis) under simulated agrivoltaic systems between two module rows (x-axis)

- Shown are the months March to October and yearly averages
- Small squares (left side) indicate unshaded irradiation values



Other Performance Indices

- **Further Measures**
  - Maximum sunlight reduction
  - Solar Massachusetts Renewable Energy Target Program
    - During growing season, max. sunlight reduction: < 50%
  - Vertical and width clearing
    - Enable cultivation with machinery
  - Soil compaction
    - Avoidance of system installation during humid weather
  - Type of foundation
    - Reversible or permanently installed


Source: BayWa r.e


Source: BayWa r.e


Source: Next2Sun GmbH

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Thank you very much for your attention!

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