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

- Vehicle-Integrated PV
- Building-Integrated PV
- Agrivoltaics
- Urban Photovoltaics
- Road-Integrated PV
- Floating PV
• **Technical Land Potential:**
  Consideration of technical, infrastructural and ecological constraints
Agrivoltaics – From the Idea to the Implementation

• The Concept

1. Own consumption incl. energy storage
2. Energy purchasing agreement with local residential and industrial estates
3. Energy feed-in to power grid and gas distribution system operators
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

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**Timeline of APV from 2010 until today**

- **2010**
  - Germany: EEG-reform 2010

- **2011**
  - EU: first notable APV-systems in FR und I

- **2015**
  - China: first large scale APV-systems > 10 ha
  - Japan: first gov. supporting scheme (2013)

- **2020**
  - France: APV supporting scheme (2017)
  - Global installed APV capacity min 2.4 GWp
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
• **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
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
Research Results APV-RESOLA

- **Economy: PV-Power Generation Cost**

  - **Economy:** PV-Power Generation Cost
  - **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)

**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

Source: Fraunhofer ISE
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Land Equivalent Ratio

• The Concept

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

\[ LER = \frac{\text{Yield}_{\text{agri}}(\text{dual})}{\text{Yield}_{\text{agri}}(\text{mono})} + \frac{\text{Yield}_{\text{elec}}(\text{dual})}{\text{Yield}_{\text{elec}}(\text{mono})} \] (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)

\[ LER = \frac{\text{Yield}_{\text{agri}}(\text{dual})}{\text{Yield}_{\text{agri}}(\text{mono})} + \frac{\text{Yield}_{\text{elec}}(\text{dual})}{\text{Yield}_{\text{elec}}(\text{mono})} - LL \]

• 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

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<th>APV 2017</th>
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Source: Universität Hohenheim

- 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

Separate Land Use on 2 Hectare Cropland

Combined Land Use on 2 Hectare Cropland: Efficiency increases over 60%

• 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
Land Equivalent Ratio

• APV-RESOLA LER II: Potatoe Yield 2018

\[
LER\ 2018 = \frac{255.26 \text{ kWh}(\text{dual})}{230.02 \text{ kWh}(\text{mono})} + \frac{249.857 \text{ kWh}(\text{dual})}{301.032 \text{ kWh}(\text{mono})} - 0.083 = 1.86
\]

• Crop: potatoes

• 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

  • \( s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \)

  • Targeted light homogeneity area reached from between 26° SW and 28° SW
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
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: Next2Sun GmbH

Source: BayWa r.e
Thank you very much for your attention!

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