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הפקולטה להנדסה ע"ש איבי ואלדר פליישמן אוניברסיטת תל אביב

Agrivoltaics: Achievements and Challenges

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First Challenge:

- **Agrovoltaics ?**
- **Agrivoltaics ?**
- **Agri-Photo-Voltaics (APV) ?**
- **Agri-Solar ?**

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The Need in Israel

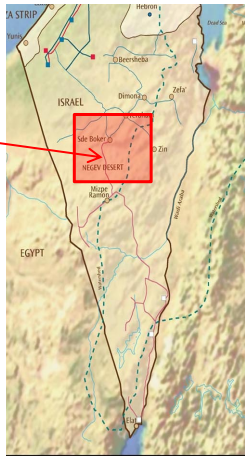
Solar energy needs much land area

100% solar electricity for Israel:

≳ 1 000 km²

Land use in Israel

Military 40%
Agriculture 20%
Nature reserves 12%
Residential 6%



Dual use of area

Residential rooftops
Commercial / industrial rooftops
Highways, parking lots
Agriculture

Agricultural land in Israel: **~ 4 000 km²**

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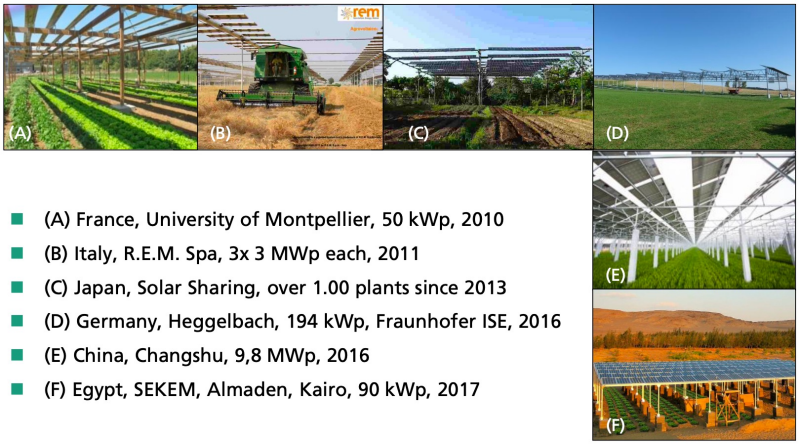
APV Backgroubd

Proposed by A. Goetzberger, 1981



- (A) France, University of Montpellier, 50 kWp, 2010
- (B) Italy, R.E.M. Spa, 3x 3 MWp each, 2011
- (C) Japan, Solar Sharing, over 1.00 plants since 2013
- (D) Germany, Heggelbach, 194 kWp, Fraunhofer ISE, 2016
- (E) China, Changshu, 9,8 MWp, 2016
- (F) Egypt, SEKEM, Almaden, Kairo, 90 kWp, 2017

S. Naik, Fraunhofer ISE, 2019

World installed capacity in 2020: **2.8 GW**
(Fraunhofer Inst., 2020)

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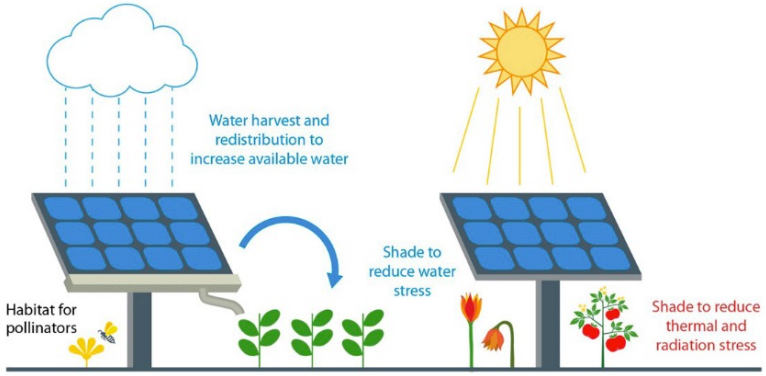
APV Benefits

- ❖ **Siting opportunities for solar deployment**
- ❖ Improve economic viability of agricultural activities
- ❖ Provide beneficial ecological services

(Hernandez et al. 2019, https://doi.org/10.1038/s41893-019-0309-z)



Davis & Macknick. 2022. NREL/TP-6A20-83442

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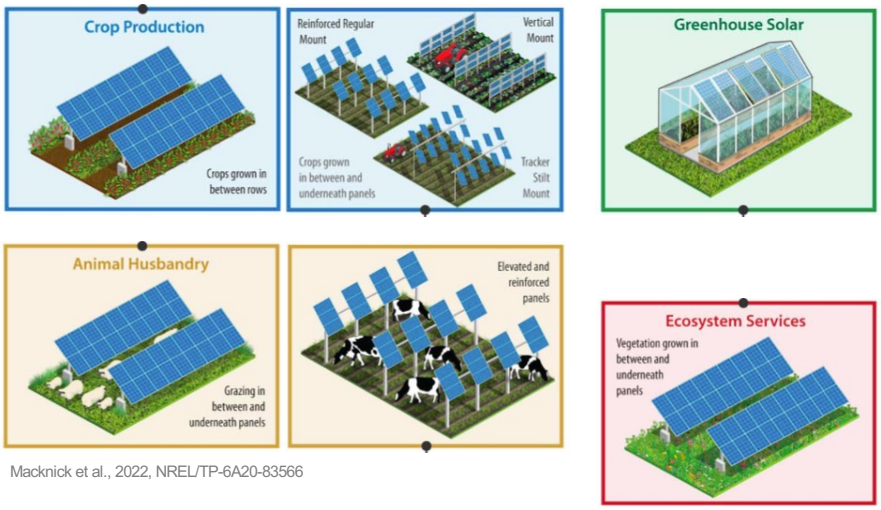
APV Types



Macknick et al., 2022, NREL/TP-6A20-83566

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Non-Crop APV

Solar Grazing

Part of '**Regenerative Agriculture**'

- Maintain and renew soil quality
- Livestock benefits: free roaming, natural diet, shade

PV: little or no adjustment needed

- Great PR at minimum cost

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Non-Crop APV

"Pollinator-friendly" Solar Farms

Type of **Ecosystem Service**

Bees, other insects

Requirements:
Original soil & vegetation
Native plants
Variety: year-round flowering
Flowering native hedging

https://beecityusa.org/solar-sites-going-pollinator-friendly/

PV: little or no adjustment needed
- ❖ Great PR at minimum cost

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Non-Crop APV

Solar Aquaculture

Fish, crustaceans, etc.

Benefits to aquaculture:
Reduce waves
Reduce evaporation
Reduce bird predation

https://www.pv-magazine.com/

PV: some adjustment needed
- ❖ Floats / Foundations
- ❖ Spacing – sunlight for fish
- ❖ Height – aquaculture operations

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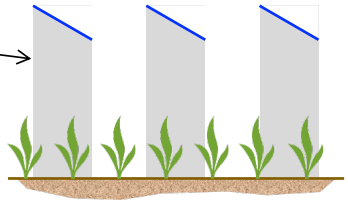
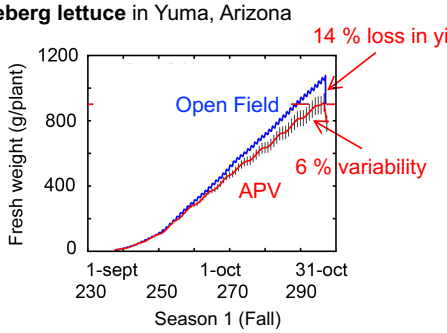
APV with Open-Field Crops

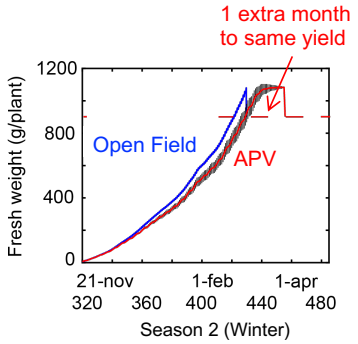
Shading by PV panels
→ Less light for crop
→ May reduce photosynthesis

Soil compaction
Block / constrain agricultural operations



Ravishankar et al. (NCSU)
AgriVoltaics 2022, Piacenza
Iceberg lettuce in Yuma, Arizona





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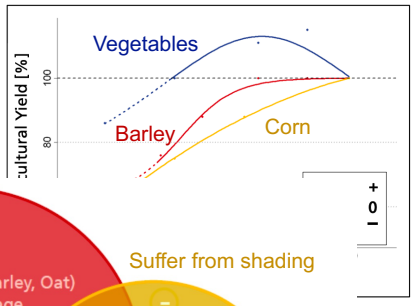
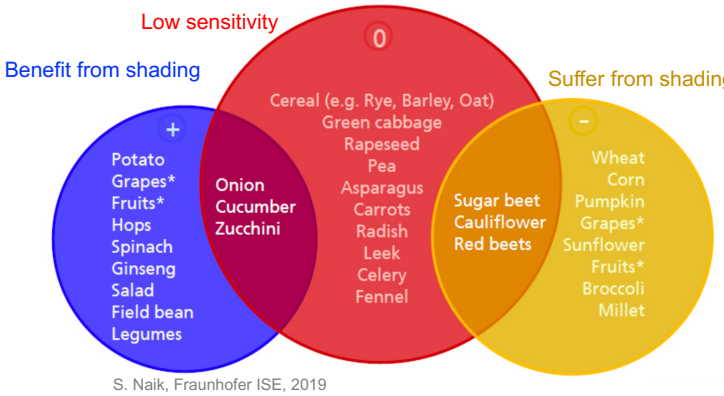
Effect on Crops

Impact of shade on crop yield





S. Naik, Fraunhofer ISE, 2019

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Crops & Areas in Israel

Ronen Eran & Gur Mittelman, 2022 (Afeka College)

Land area per crop:

Israel Ministry of Agriculture GIS

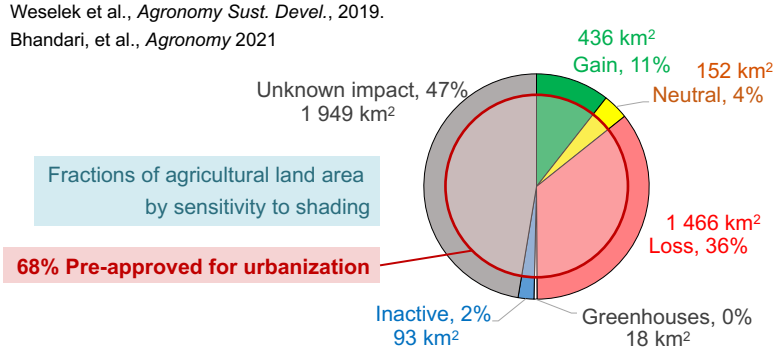
Total area: 4,114 km²

Shading response for specific crops:

Fraunhofer ISE, 2017

Weselek et al., *Agronomy Sust. Devel.*, 2019.

Bhandari, et al., *Agronomy* 2021



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Regional Areas for APV

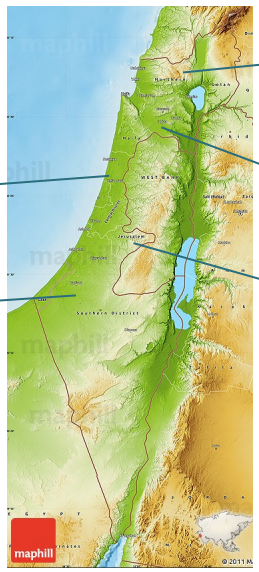
Land area in km²

Crop response to shade:

Gain

Neutral

Loss



	Gain	Neutral	Loss
גליל וגולן	265	14	71
עמקים	407	21	68
שפלה והר	130	3	30
מרכז	95	6	36
נגב	568	109	221

- Existing crops
- Crops with known impact
- Subject to urbanization

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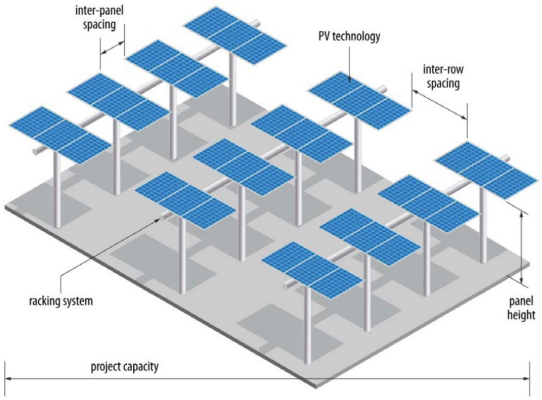
APV Field Design

Height
Spacing rows / panels
Tracking / stationary
Panel type



Davis & Macknick. 2022. NREL/TP-6A20-83442

Constraints:

- ❖ Agricultural operations / machinery
- ❖ Crop shading, microclimate
  - ➢ Structure / foundation cost
  - ➢ Electricity per unit area

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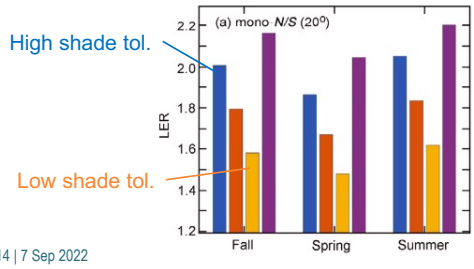
APV Field Design

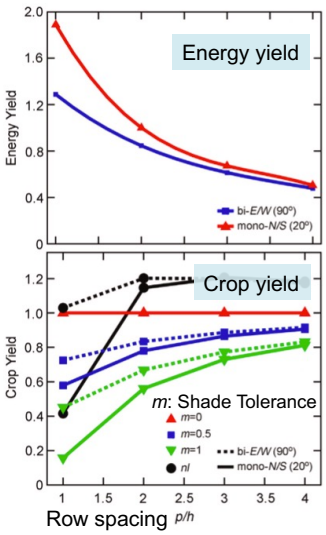
Riaz et al., 2021:
Effect of row spacing, tilt angle
Crop yield: simple linear / quadratic model

Metric for comparison
Two outputs: electricity, crop

Land Equivalent Ratio (LER)

$$LER = \frac{Y_c(AV)}{Y_c(OF)} + \frac{Y_e(AV)}{Y_e(PV)}$$





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Regulation

Threats in wide adoption of APV

- ❖ Reduction in crop productivity
- ❖ Electricity replaces agriculture

Germany DIN SPEC 91434 (2021)
Crop yield ≥ 66% of reference yields without solar

France AFNOR (2021)
Crop yield ≥ 80% of reference yields without solar

Italy CREA/ GSE/ ENEA/ RSE (2022)
Agriculture **land area ≥ 70%** of the total project area
Annual electricity ≥ 60% of a standard solar plant

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Main Challenge

- ❖ **No universal APV solution**

Feasibility and technical approach depends on:
Local site conditions – soil, climate, topography, infrastructure
Agricultural practices – machinery, irrigation
Crop selection – response to APV presence
Local value – crop vs. electricity, farmer's attitude

Performance validation
Warranty ?
- ➢ Crop side
- ➢ Validity for other sites

https://www.dw.com/en/farmers-reap-double-benefits-with-solar-power-in-fields/

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Non-Conventional APV

Vertical Bifacial

Minimal impact on agriculture operations

Better uniformity illumination, soil moisture

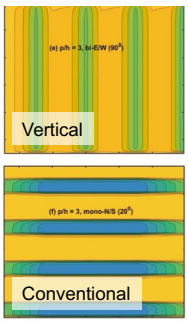
Less dust accumulation

https://www.next2sun.de/

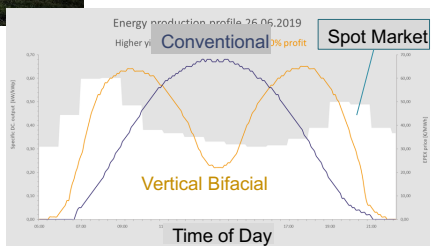
Ground illumination

GCR=0.33

Riaz et al., 2021



- Match morning/evening peak
- Claim 5% - 15% more electricity



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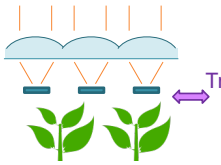
Non-Conventional APV

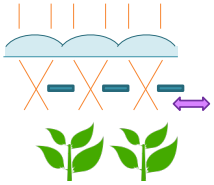
insolight

Tracking: linear movement



https://insolight.ch/product/

Crop priority mode:
Max. light transmission (MLT)



Experiment with lettuce:

Increase in product yield

- MLT mode
- Conditional on season

Vaccaro & Jäger (2022)
doi:10.21256/zhaw-2427

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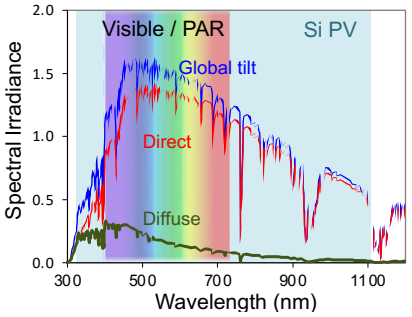
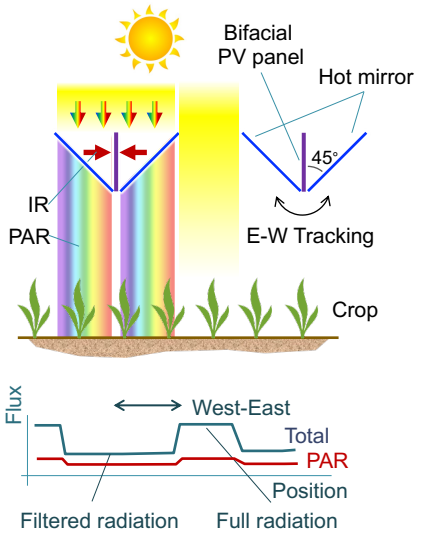
Non-Conventional APV

Mittelman et al. 35th *EU PVSEC* 2018

Shalom et al. – Poster today





Split the spectrum of direct radiation

Mirror at 45° to panel

Single-axis tracking

Panel: less incident radiation

Bifacial with symmetric input

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APV Status & Future

Science base incomplete

- Especially on crop side
- Insufficient long-term experience

No standard / preferred PV configuration

- Copying standard PV — ? — Original ideas

Unclear economics

- Extra costs (supports, lower GCR…)
- Difficult to evaluate crop side
- Land shortage predicted but not accounted

Need more: Research

- Innovative configurations
- Long-term field experience
- Regulatory / financial rules

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