International Workshop on
“The water-energy-food-ecosystems nexus: trade-offs and foresight analysis for policy and investment decisions”

Harnessing Solar Energy for Sustainable Water, Energy, Food, and Environmental Nexus (WEFE)

Santosh S. Mali

Senior Scientist, ICAR

ICAR-Research Complex for Eastern Region, Patna, India

The WEFE Development goals

Present

- 2.0 billion people have no access to safely managed drinking water (2023)
- 0.74 billion people have no access to electricity (2023)
- 2.4 billion people are food insecure (2023)

- Achieving security independently endangers sustainability and security the other sector(s)
  - Increasing coal based electricity production
  - Intensifying agricultural production

Future demands !

- Population growth, economic development
  - Food (50% in 2050 over 2020)
  - Energy (9% in 2030 over 2020)
  - water (40 % in 2030 over 2015)
- Strive to enhance the resilience of agriculture to CC

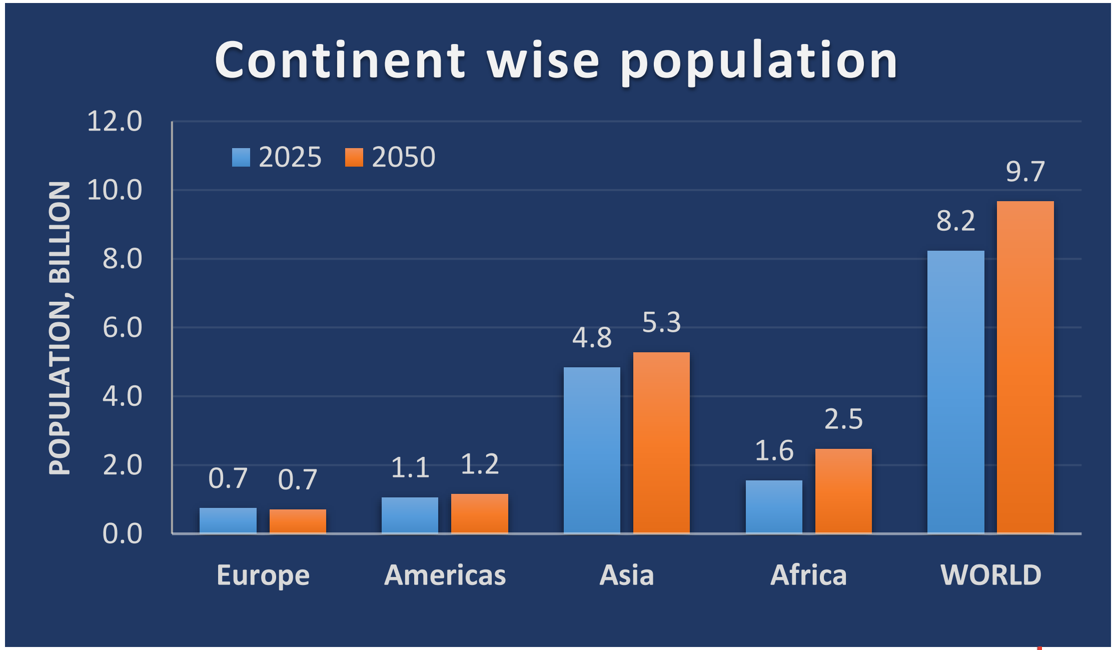
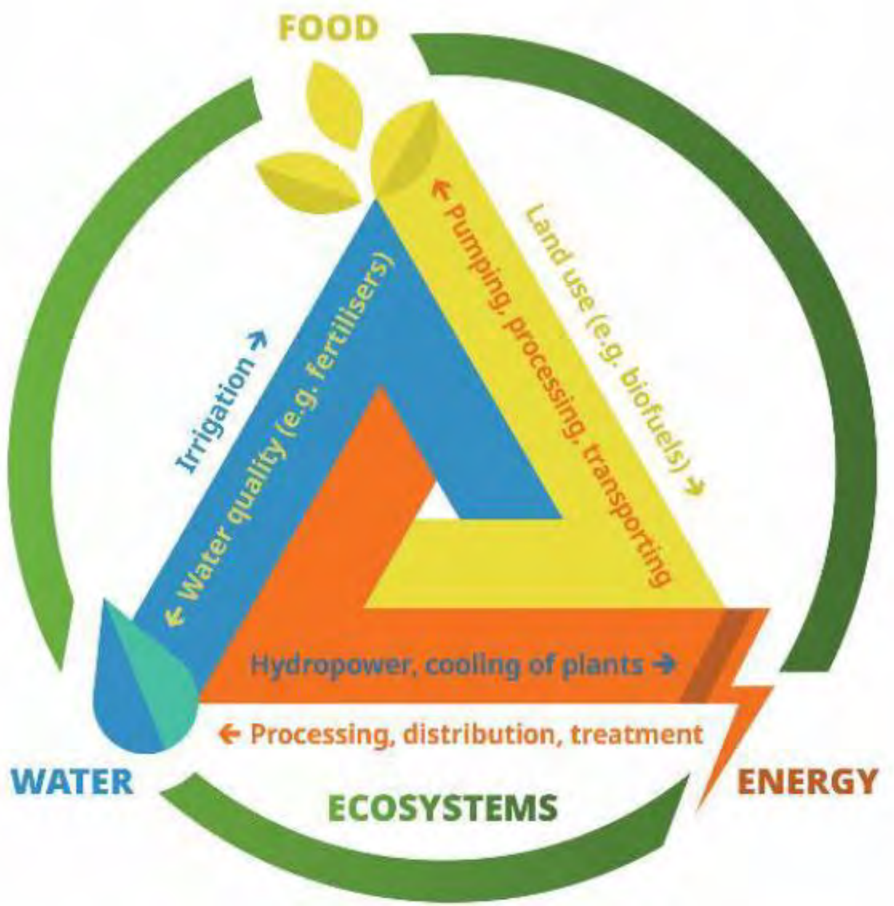


Image data source: ined

The WEFE Nexus

- WEFE: critical framework for understanding the complex interconnections
  - Agriculture: ~70% of total global freshwater withdrawals
  - The energy sector: 10% to 15% of the global freshwater withdrawal
  - Agriculture & food chain: ~ 33% of global energy demand
- WEFE: Aims to reduce trade-offs and enhance the efficiency of the entire system through synergies, while maintaining the integrity of our ecosystems
- Responds to resource concerns and addresses development challenges.



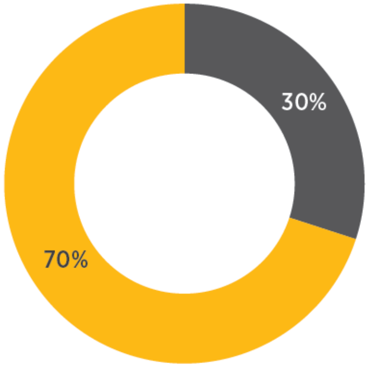
GWP, 2019

The WEF Nexus provides a holistic and integrated approach in order to secure access to water, energy and food in the long term.

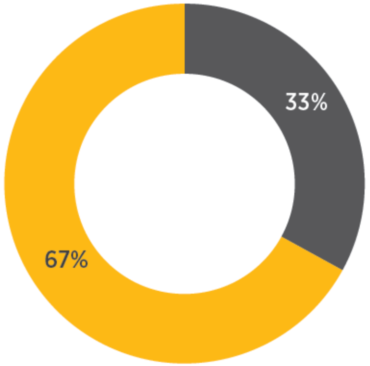
– Global Nexus Secretariat, 2020

Energy in WEFE nexus

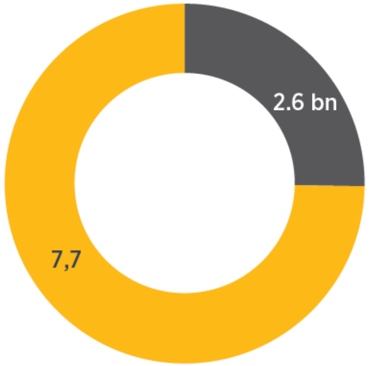
- Energy is essential for food security and development
- Finding green and resilient solutions that can support sustainable food system transformation and agricultural innovation
- **The challenge:** disconnect fossil fuel use from food system transformation without hampering food security



Share of food systems in global energy consumption

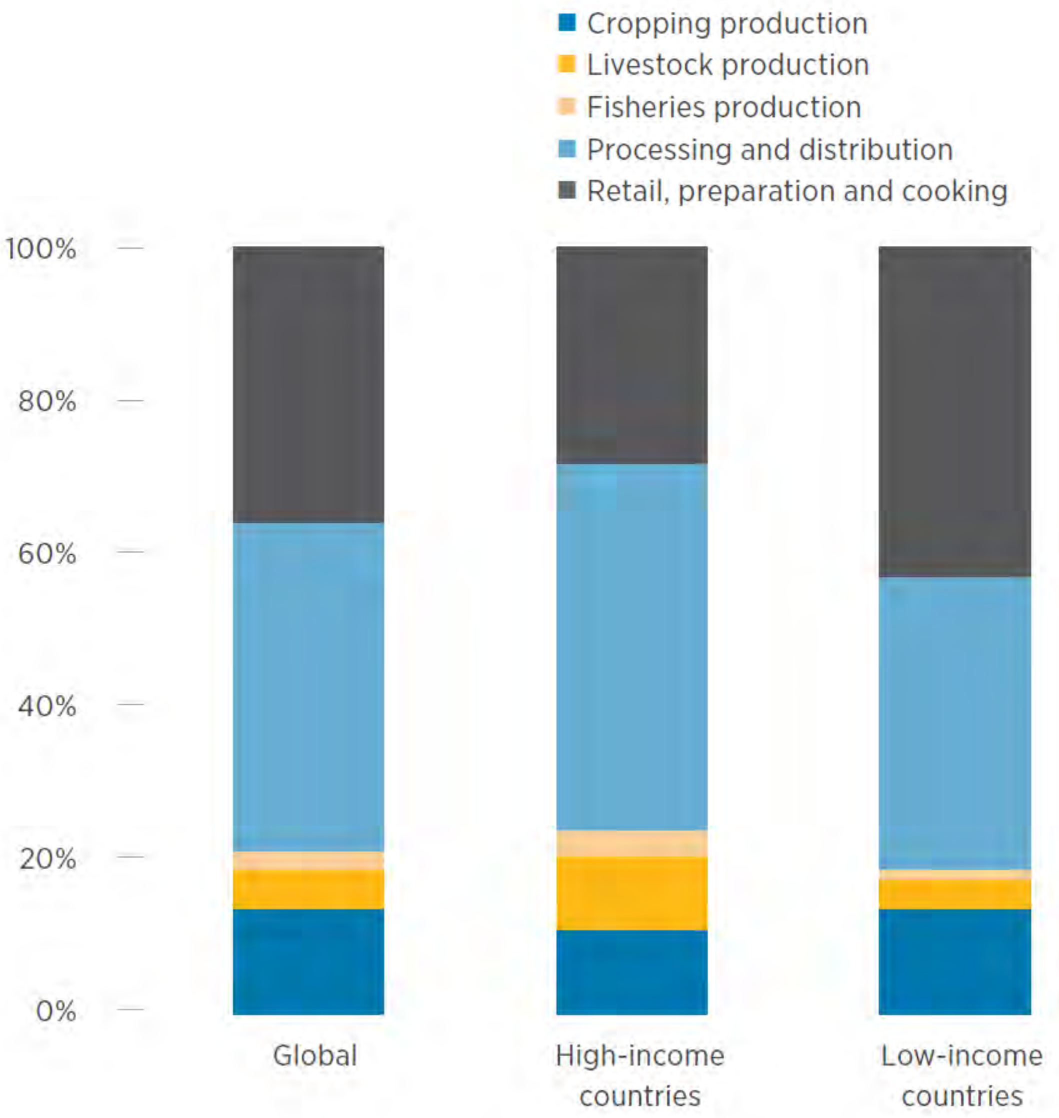


Share of energy in total GHG emissions from food systems



Population relying on traditional fuels for cooking

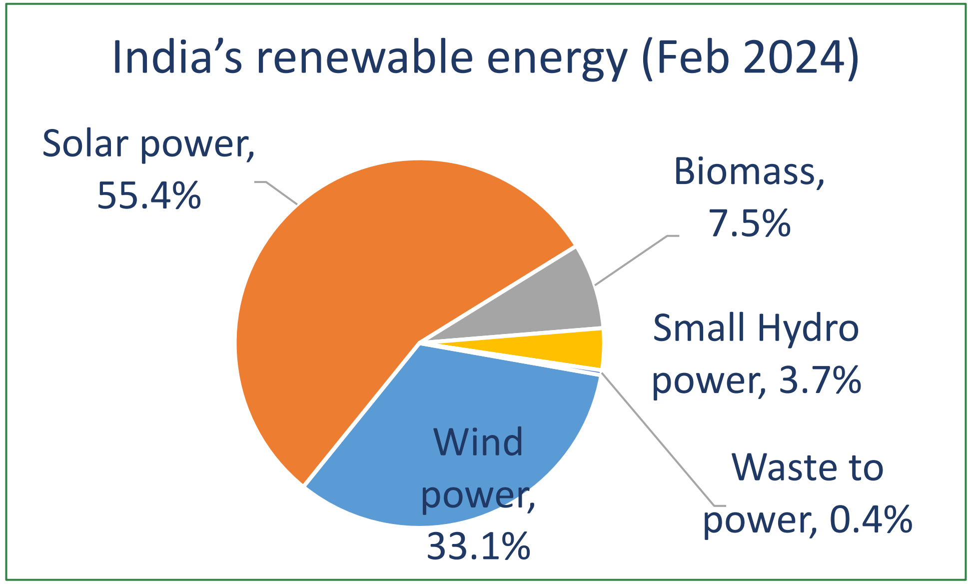
Crippa *et al.* (2021); IEA, IRENA, UNSD, World Bank and WHO (2021).

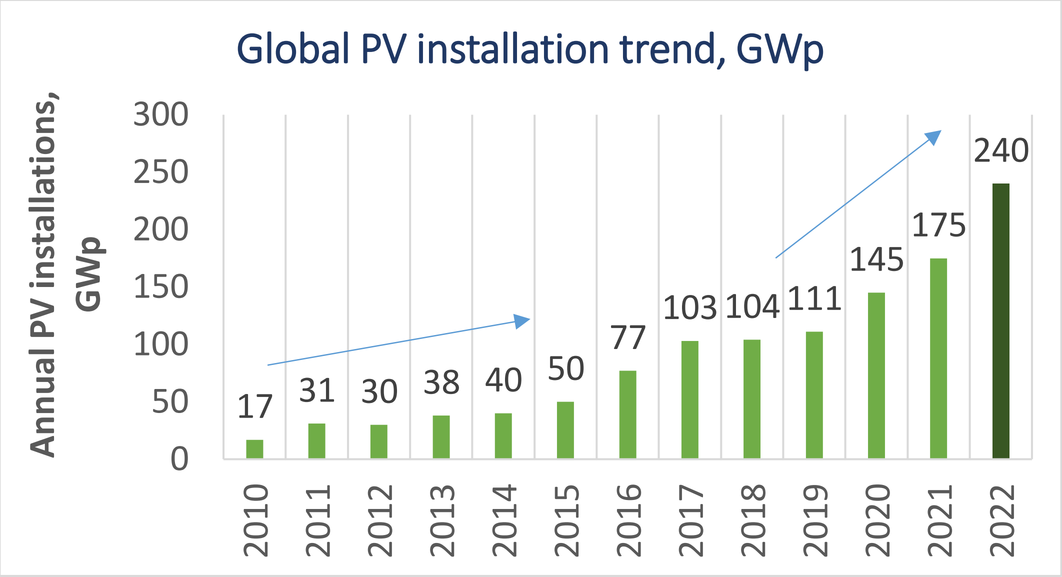


Energy consumption in Agri-Food Systems

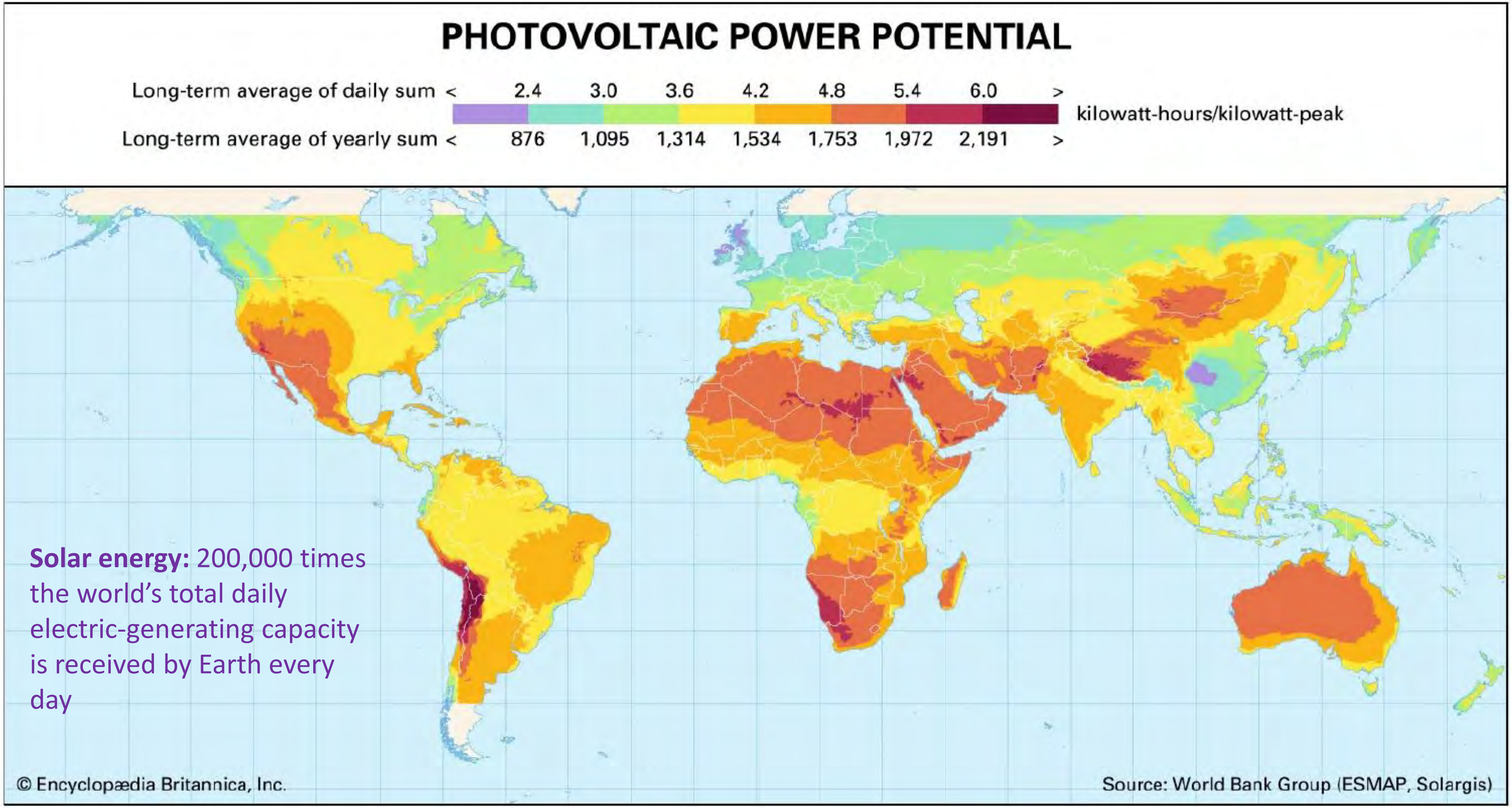
Solar Energy

- Clean, Green, Sustainable Resource
- Offers potential to address energy challenges and create opportunities
- 7 times cheaper to produce than it was just 12 years ago
- Assured energy supply
- Reduce dependency on fossil fuels
- Decentralized Solar Power for Rural Areas





- Global PV generation in 2022 was up by 26% compared to 2021.
- **India** installed 18 GW of solar PV in 2022, almost 40% more than in 2021.



Solar energy: 200,000 times the world's total daily electric-generating capacity is received by Earth every day

Solar energy: pivotal role in WEFE nexus

Solar Energy in WEFE Nexus

Food
- Improved productivity
- Sustainable systems
- Food Security
- Climate Resilience

Energy
- Energy independence
- Reduced fossil fuel use
- Reduced carbon footprints

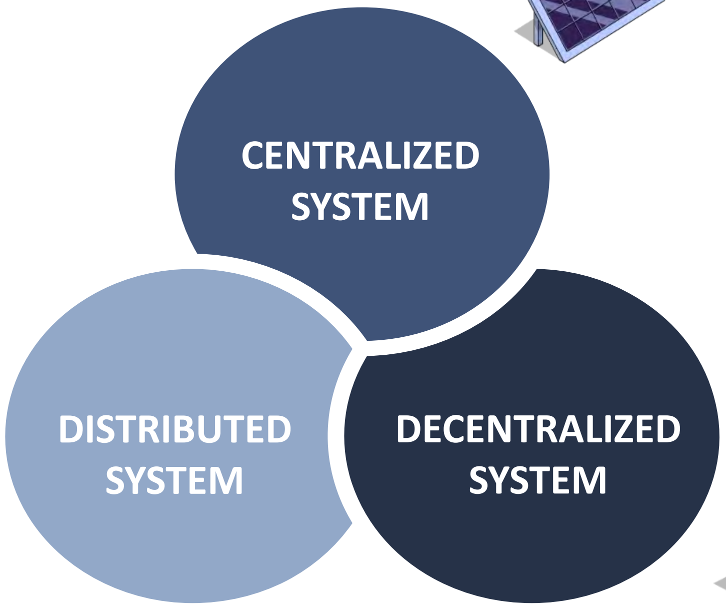
Water
- Improved access to water
- Better livelihoods

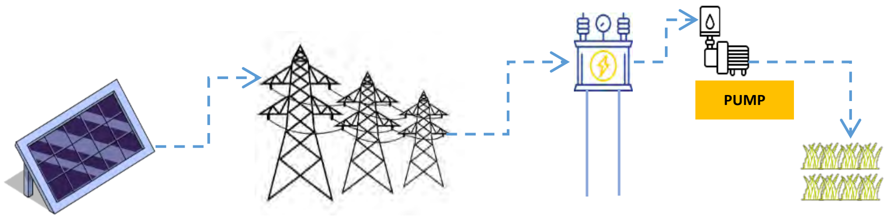
Ecosystem
- Pollution reduction
- Habitat preservation
- Biodiversity conservation

Implementing Solar Energy in the WEFE Nexus

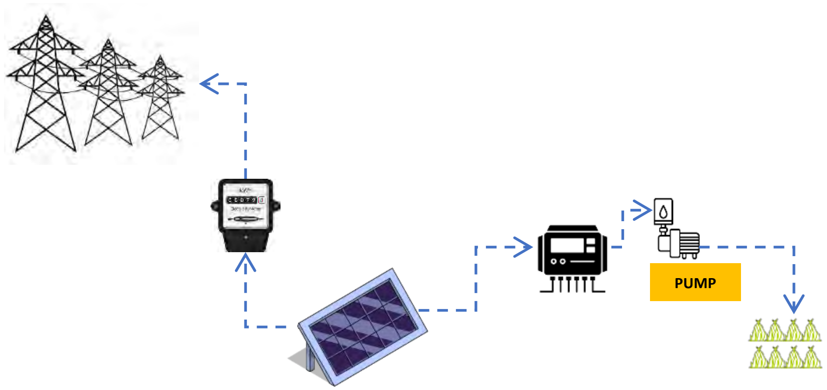
Solar Pumping Systems

Solar Pump deployment approaches

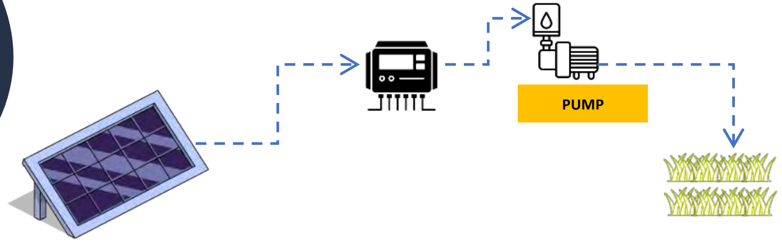




- Solar energy is supplied to the main grid
- Farmers gets energy from grid supply



- Energy utilized for pumping irrigation water and any excess is supplied to the grid.
- Provides additional income to the farmers by selling extra electricity to the DISCOM



- The solar pump only used for irrigation
- Not connected to the grid

Decentralised pumping systems in Bihar, India

The Eastern Gangetic plains

- Limited access to irrigation: limits multiple harvests
- Energy remains a critical constraint
- High pumping cost– 120-140 ₹/hr
- Underutilized groundwater resources (37.2%)
- Vast expanse of land is left fallow, cropping Intensity < 120%

Photos: Frazer Sugden, IWMI

Technical Interventions

Supported with Improved cultivation practices and irrigation scheduling, nutrient management

Interventions and Impact

Social Interventions: Collective farming in command area of solar pumping systems

- Collective planning
- Resource sharing
- Collective farm operations
- Knowledge sharing
- Collective investments and marketing

Impacts of technical and social interventions

- **Water:** Improved access to irrigation water
- **Food:** Cropping intensity increased from 110% to 230%, yields > 50%
- **Economic:**
  - Increased family income by 41%
  - Payback period for the irrigation infrastructure < 6.5 years
- **Ecosystem:** Reduced irrigation carbon footprint by 1593 kg/ha
- **Social impact:** Collective management of irrigation resources
- Reduced male out-migration

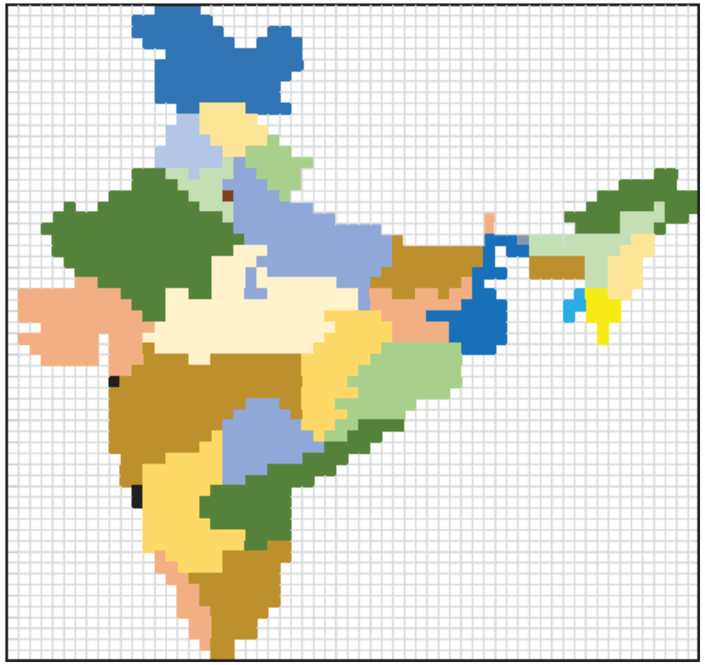
Solar Irrigation Pump Sizing (SIPS) tool

- **Govt of India launched PM-KUSUM -** Component B aims for installation of **20 lakh standalone Solar Power Agricultural Pumps** – An ambitious program in WEFE context
- Need to avoid negligent under sizing and unnecessary oversizing of pumps

SIPS tool

- Decision support tool for right sizing of SIPs in India
- **Inbuilt databases:** crop (40), soil and climate
- **System discharge** based on average of 10-year daily CWR
- **System head:** suction head, irrigation systems, friction losses, topography
- Adopted by MNRE in PM-KUSUM
- Tool is applicable all over India
- **Potential users:** State Implementing agencies, Banks, Developers

Smart tools can significantly support WEFE nexus development goals



Solar Cooperatives

- About 89.4 % of Indian farmer households own less than two hectares of land – limited capacity to buy and install solar
- **Cooperatives:** will enable and empower individual farmers to **participate** in solar energy generation, **invest** according to their capabilities, and then **receive benefits**
- IWMI-Tata Water Policy Program and CGIAR pilot project at Dhundi village in Gujrat, India
- **Objective:** increasing access to irrigation using solar pumps and enhancing farm income
- A 6-farmers cooperative was formed (+ 3 joined later)
- **Infrastructure:** Solar irrigation pumps with a capacity of 56.4 kWp
- Used energy for pumping and **sold surplus to grid (7.13 Rs/KWh)**

Dhundi Saur Urja Sahkari Mandali, 2018

Impacts

- **Water Conservation:** Reduced the solar energy used for irrigation (40%) and have increased units evacuated to the grid
- **Stable Income:** Cooperative earned turnover of INR 1,120,332 (USD 13,490) and profit of INR 250,067 (USD 3,010) from energy sales.
- No significant change in farm income but **increased overall income by 60%**
- **Climate resilience:** Free from market and climate risks
- **Ecosystem gains:** Saved around 15,214 litres of diesel and avoided **39,556 kg of CO_2 emissions**
- **Policy Impact:** Gujarat government launched a scheme
  - Suryashakti Kisan Yojana (SKY) program targeted to solarize 137 agriculture feeders
  - Covering 12,000 farmers with a total capacity of 175 MW.

Solar panels in a members' farmer field ©DSEPCS

Grid-connected solar pumps have the potential to become a remunerative crop for farmers

Tripathy, K.K., and Wadkar, S.K. 2023
Dhundi Saur Urja Sahkari Mandali, 2018

Photovoltaic Greenhouse

- Greenhouse cultivation and photovoltaic panels are compatible..!!
- **Energy intensive:** ventilation, cooling, heating and humidification
- Solar panels can be effective solution to meet energy needs
- Greenhouse roofs are ideal surface to install panels

Impacts

- **Energy Efficiency:** Reduce reliance on external energy sources, potentially lowering operating costs
- **Extended Growing Seasons:** can support year-round cultivation (Improved production)
- **Environmental Impact:** Reduced carbon footprint

Table: Electricity requirements of greenhouses

Authors	Country	Crop	Electricity use	Specific electricity consumption (kWh/m^{2}year)
Department for Environment, Food & Rural Affairs	UK	Tomato	Water circulation, irrigation, fertigation, ventilation, air re-circulation	10
		Cucumber		10
		Sweet pepper		10
		Lettuce		10
		Celery		10
		Mushroom	Cooling	261.5
Souliotis et al.	Greece	–	Ventilation (fan), cooling (fan), lighting	19.8
Al-Ibrahim et al.	Saudi Arabia	Tomato cucumber	Ventilation (fan), water circulation, control system	26.5
Rocamora et al.	Greece	Peppers	Ventilation (fan), irrigation, fertilization, window opening, climate control, pesticide applications	6.65
Campiotti et al.	Mediterranean area	–	Low energy operations	2
			Heating, cooling, ventilation	9
Ureña-Sánchez et al.	Spain	Tomato	Automatic opening and closing of the windows, running of the fertigation pump	4
Vadiee and Martin	Sweden	–	Ventilation, water circulation, artificial lighting	140
Yildirim and Bilir	Turkey	Tomato	Heating and cooling , lighting	149.8
		Cucumber		165.3
		Lettuce		137.3
Okada et al.	USA	Lettuce	Cooling (via evaporative fan and pad cooling system)	11.7
Bambara and Athienitis	Canada	–	Artificial lighting	123.2

Photovoltaic Greenhouse

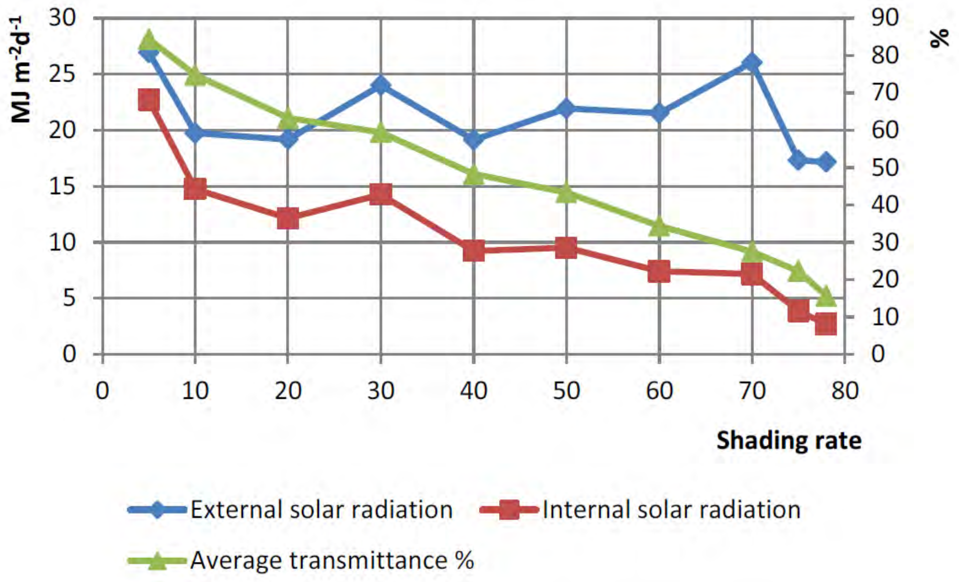
- Shade effects on crop growth??
  - Optimizing geometric designs to maintain optimal amount of direct sunlight
    - Linear arrangements: better energy yields, lower crop yields.
    - Checkerboard arrangement: optimal direct sunlight to maintain yields, with lower but satisfactory energy yields.
  - **Shading** = f(Arrangement on the roof, degree of transparency, panel inclination)
  - **Crop Choice** under shades (75 to 90%): Mushroom, Spinach, Swiss chard, kale, collard greens, orchid, hydrangea, or cyclamen

Impact of integration of PV installations

Reference	Location	Area (m2)	Type of cover	Crop	Technology	ηPV (%)	EPV (kWh /m2 year)	EPV/ ELOAD(%)	Effects of on yield	Payback Time, years
Yildirim and Bilir	Turkey	150	Double glass	Tomato	mono-Si	17.0	143.4	95.7	-	7.2
Ureña-Sánchez et al.	Spain	384	Polyethylene	Tomato	a-Si thin film	5.8	14.4	>100	No yield reduction	-
Barbera et al.	Italy	10835	-	Algae	mono-Si	19.8	63.1	>100	Significant reduction (26%)	6.7
Cossu et al.	Italy	960	PVC	Tomato	poly-Si	14.2	112.4	-	Significant reduction	-
Kadowaki et al. Yano et al.	Japan	86.4	Polyolefin	Onion	a-Si thin film	**7.0**	13.1	-	Significant reduction	**> 20**
Hassanien and Ming	China	26.25	Polyethylene film	Lettuce	semi-transparent mono-Si	8.25	24.3	24.5	No effects on growth	-
Trypanagnostopoulos et al.	Greece	10000	Glass	Lettuce	poly-Si	-	37.6	37.6	No effects on growth	-
Hassanien et al.	China	26.25	Polyethylene film	Tomato	semi-transparent mono-Si	8.25	24.3	-	No effects on growth	9
Marucci and Cappuccini	Italy	9.13	Glass	Tomato	poly-Si	14	122.7	-	Improved yields (summer)	6

Variable shading PV greenhouse: Making crop friendly microclimates

- Greenhouse microclimate: critical to achieve better quality and yields
- Rotating panels: making dynamic panel system dynamic
- Reflective aluminum mirrors to improve energy production
- Degree of shading: f (crop, latitude, time of the day, weather)
- **Able to maintain crop-specific internal microclimates in response to the external climatic**



Tuscia University in Viterbo, Italy, Moretti and Marucci, 2019

Agrivoltaics: Agriculture + Renewable Energy

- **Competition for land:** solar farms (2 ha/MW) compete with agriculture
- **Agrivoltaic** play important role in strengthening the water–energy–food relationships
- **Concept:** Co-location of agriculture production and solar power generation with mutual benefits
- **Agrivoltaics attempts to solve multiple problems at once**
  - Renewable energy production (reduced carbon footprints)
  - Increasing sustainable food production
  - Ecological benefits (erosion, water harvesting and recycling, soil health)
- **Keep in Mind..!!**
  - Open space (%) available for cultivation
  - Threshold yield penalty
  - Disruption to farming activities/machinery movement
  - Farmers income > sole agriculture + standalone energy plant
  - Local policies for grid connectivity and energy buy-back arrangements

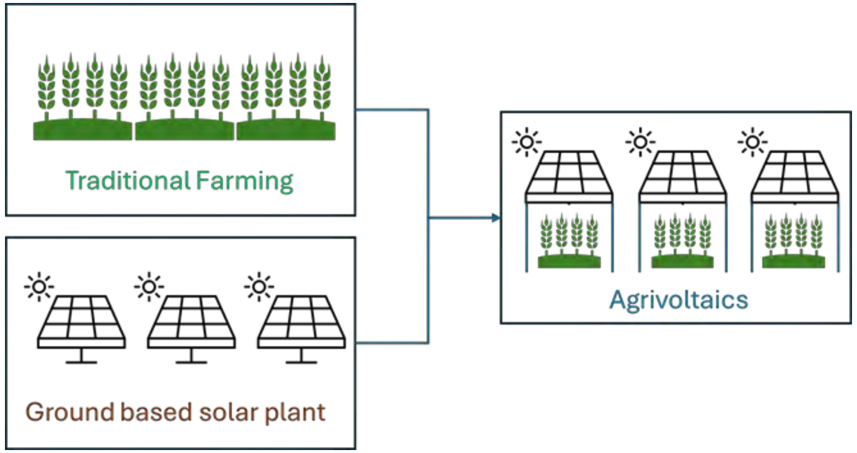


Photo: Santra P (ICAR- CAZRI)

Agrivoltaics experiences from ICAR-CAZRI, India

Agrivoltaic models evaluated under 105 kW plant:

- 1 row with 100% PD (3 m interspace)
- 2 row: 1st with 100% PD and 2nd with 60% PD (6 m interspace)
- 3 row: 1st and 2nd with 100% PD and 3rd with 60% PD (9 m interspace)

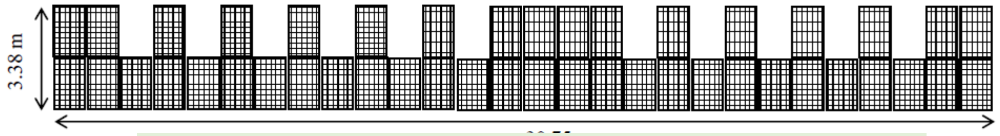
Crops in cultivable area: interspace 49%; below PV area: 24%

- **Interspaces:** Mung bean, Moth bean, Cluster bean, Chickpea, Cumin, Spinach, Amaranthus, Brinjal, Senna, Aloe vera, Isabghol
- **Below PV modules:** chilli, cabbage), onion, garlic, cowpea, water melons, cucumbers

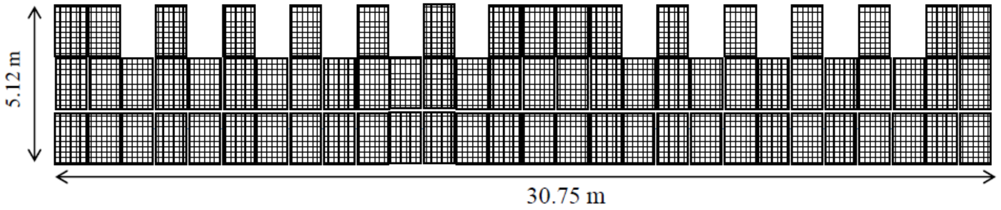
Water harvesting: stored water used for cleaning PV panels and supplemental irrigation

100% Panel density

100% PD in 1st row and 60% PD in 2nd row



100% PD in 1st and 2nd row and 60% PD in 3rd row



Santra et al., 2020

Model Performance and Impacts

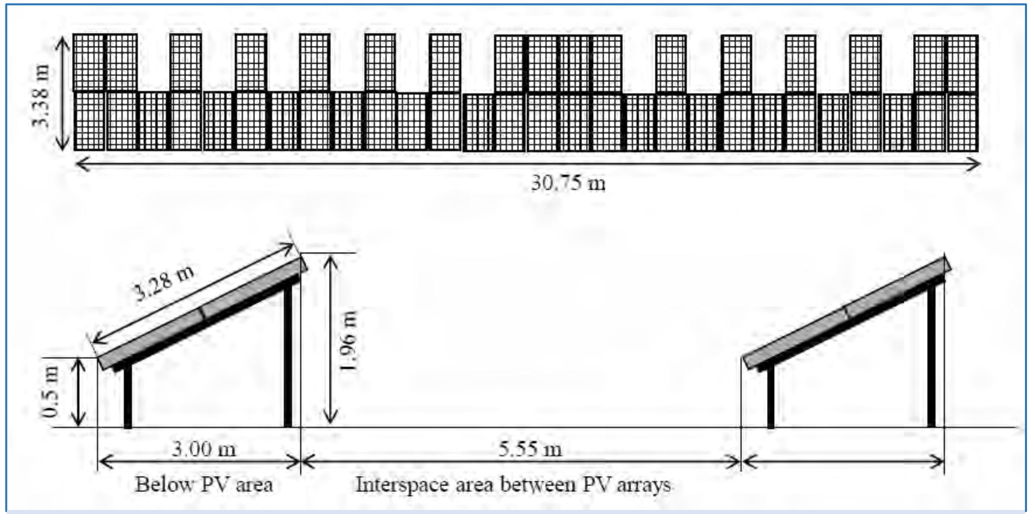


Fig. Best Model – 2 Row with 60% PD in 2nd row

Table: Best performing crops

Plantation area	Season	Crop	Yield
Interspace area	Kharif (June-Sept)	Moong bean	438 kg/ha (18% lower)
	Rabi (Nov-Feb)	Isabghol	582 kg/ha (18% lower)
Below PV Module	Rabi (Nov-Feb)	Spinach, Amaranthus	

Best model (double row model: 1 ha 400 KWp)

- **Energy**: 5,84,000 kWh/year
- **Water harvesting:** 5,60,000 litre/year (69.2 % WH efficiency)
- **Income:**
  - Crop: Rs. 80,349/-
  - Energy generation: Rs. 29,20,000/-
  - SPBP: 5.87 years
  - DPBP: 10.4 years
- **Ecosystem**:
  - **Reduced annual carbon footprint by 479 ton CO_2e**
  - Reduced soil erosion in plot
  - Maintained favourable microclimates for PV generation
  - Enhanced resilience of agricultural to impacts of climate change

Santra et al., 2020

Agrivoltaic Systems – focus areas

- **Optimal Solar Panel Placement and Configuration:** panel height, spacing, and angle to balance light exposure for plants and efficient solar energy capture.
- **Crop Selection and Management:** understanding crops response
- **Soil Health and Water Management:** solar panels effects on soil temperature, moisture levels, erosion and irrigation practices.
- **Economic Viability and Cost-Benefit Analysis:** comparing dual land use versus standalone agriculture/solar farms (business models).
- **Biodiversity and Ecosystem Impact:** affects wildlife, plant diversity, and overall ecosystem health.
- **Energy and Agricultural Productivity Optimization:** optimize the trade-offs between energy production and agricultural productivity.
- **Technological Innovations:** Automated shade management technologies for managing both energy and crop production.

Conclusions

- Educating stakeholders about the WEFE Nexus can foster better decision-making and resource management practices.
- Research on technologies in WEFE context calls for establishing and maintaining multi-institutional, multi-national collaboration and contribution
- Solar energy innovations and large scale adoption needs national and regional strategies, action plans, and programs.
- Agrivoltaics has potential to transit towards more sustainable and integrated solutions to energy and food production, needs policies and regulatory frameworks

Strategies for Scaling Solar Energy in WEFE Nexus

- **Integrated Planning and Policy Frameworks**
  - **Develop Nexus-Oriented Policies:** interconnectedness, synergies and trade-offs
  - Incorporate Solar Energy into Integrated Resource Planning (Feeder segregation)
- **Technology and Innovation**
  - **Support R & D:** Improving efficiency and durability in diverse environments.
  - **Water-Efficient Solar Technologies**: Reduce water use in panel cooling and cleaning
  - **Nexus-Based DSS:** integrate data across WEFE domains, generates scenarios and provide holistic insights and recommendations.
- **Financial Mechanisms and Investment**
  - **Develop Innovative Financing Models**: finance models that attract investment in solar energy
- **Leverage Public-Private Partnerships**
  - **Encourage collaborations:** governments, private companies, and NGOs
- **Infrastructure and Grid Integration**
  - **Enhance Grid Flexibility:** Develop smart grids and energy storage solutions
  - **Invest in Off-Grid Solutions:** solar microgrids and decentralized energy solutions

Thank You...

Santosh.Mali@icar.gov.in
+91-8092556024