Economic study of agrivoltaic greenhouses in Spain and the Netherlands

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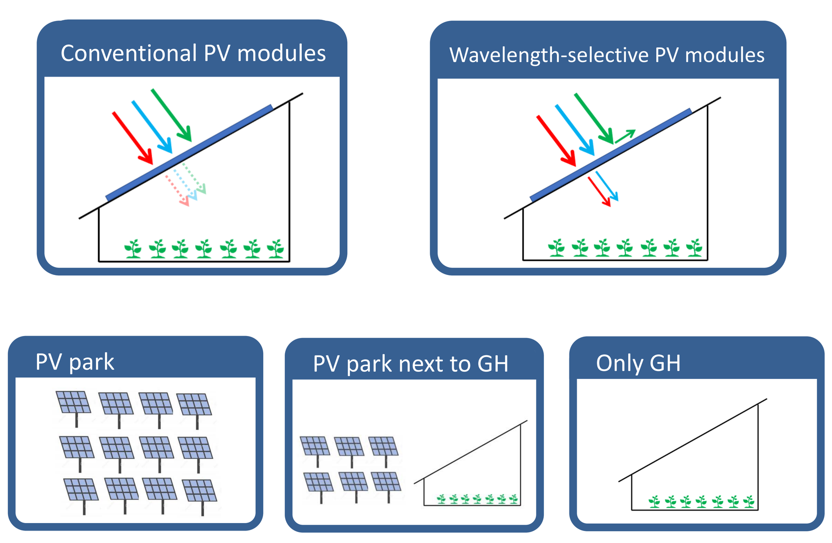
1. Motivation: Potential of photovoltaics on greenhouses

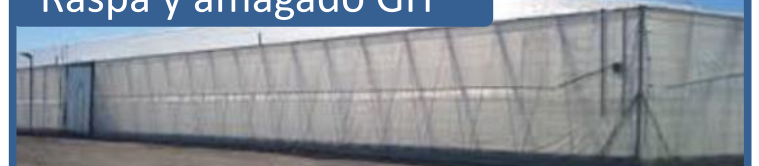
- In Spain (ES) and the Netherlands (NL), horticultural crop production contributes strongly to the gross domestic product (46k ha and 10k ha covered by greenhouses (GH) in Spain and Netherlands)
- For regions with high irradiation levels (e.g. Southern Spain) or reduced land availability and high electricity consumption (e.g. Netherlands) → PV modules on top of horticultural greenhouses (APV GH) is a promising concept
- Advantage: Diversification of farmers' income (highly fluctuating horticultural market)
- This study investigates economic feasibility of APV GH concepts for El Ejido, Spain and Bleiswijk, Netherlands

2.a) Greenhouse and PV Combinations



Typical values for GH size, investment and O&M costs for PV and GH installation and electricity selling prizes taken from [1], [2].

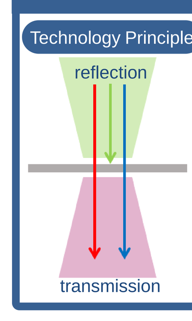
Raspa y amagado GH [3]



Multitunel GH [4]

NL type glass GH [5]

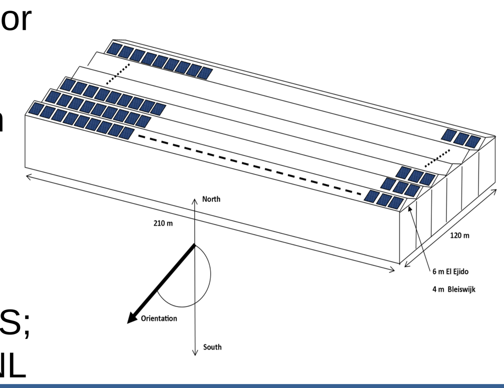
2.b) Wavelength-selective PV (WSPV)



- photosynthesis mostly driven by blue & red fraction of spectrum
- a spectrally selective solar cell (SSSC) technology using an ultra-thin a-Ge:H based pin cell embedded in an optical cavity was developed by DLR [6]

2.c) PV yield modeling

- performed with System Advisor Model (SAM)
- gable roof greenhouse, south side covered by PV modules
- Typical Meteorological Year by PVGIS
- tilt angles: 10°, 20°, 25° for ES; 20°, 25°, 30° for NL



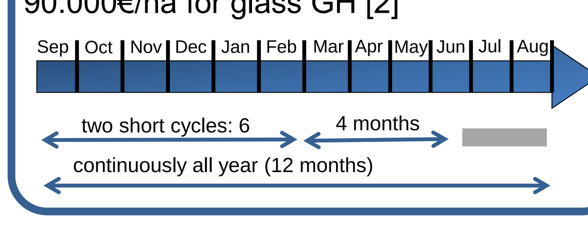
- WSPV scenario: 99% of available surface covered with WSPV (assumed efficiency 7%) → installed capacity of 1004kWp (NL) and 885kWp (ES) per gh
- Conventional PV scenarios: efficiency 21%, adopted to same installed capacity as WSPV scenario

2.d) Crop yield modeling

Assumed crop income and cycles:

ES: two short crop cycles → income: 24.000€/ha for raspa y amagado, 27.400€/ha for multitunel [1]

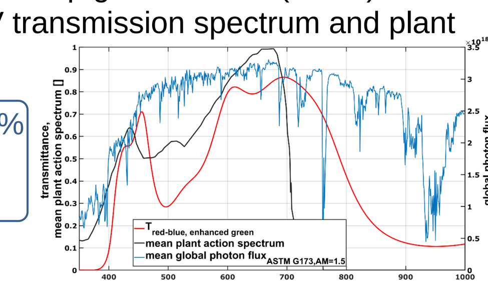
NL: one continuous cycle → income: 90.000€/ha for glass GH [2]



Assumed income reduction due to shadowing:

WSPV scenario: Calculation of crop growth factor (0.645) according to optimized WSPV transmission spectrum and plant action taken from [7]

0.7% income reduction per 1% irradiance reduction [8], [15]
ES: only if reduction > 30%



→ ES: no income reduction
→ NL: ~11% for conv. PV and ~5% for WSPV scenarios

3. Results: Economic Benefits of AgriPV concepts

3.a) Energy self-consumption and heating

- Assumed annual energy and heat demand: NL type GH energy and heat demand 10x higher than ES greenhouses [1], [2], [9], [10]
- AgriPV scenarios: PV yield used for energy self-consumption, remaining surplus then used for heating, remaining excess then sold to grid.
- Typical values for electricity and oil prices, subsidies taken from [11], [12]

	% Electricity covered by PV	% Heat covered by PV
NL WSPV glass GH	21	0
NL conv. PV glass GH	20	0
ES WSPV raspa y amagado GH	47	15
ES conv. PV glass GH	45	12
ES conv. PV raspa y amagado GH	45	12

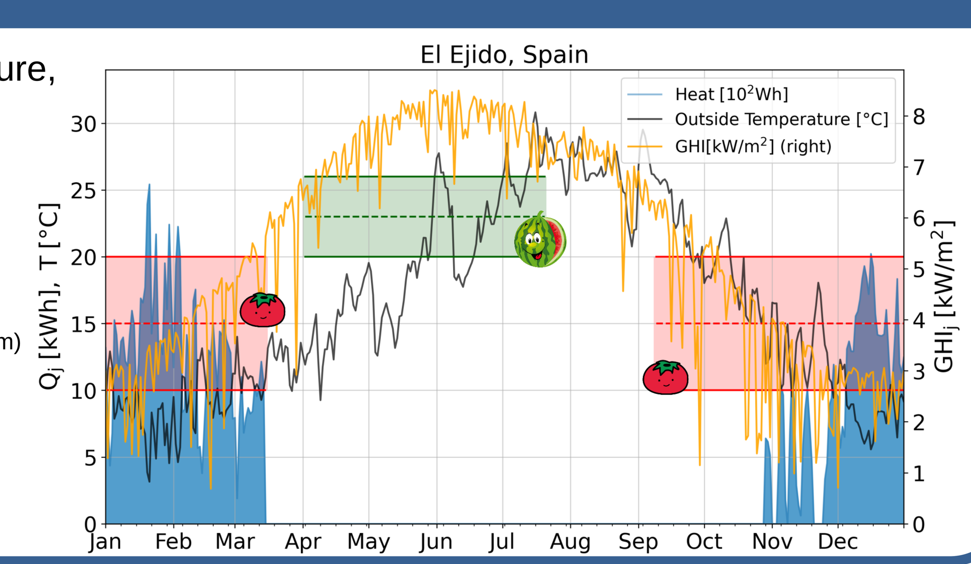
Estimation of heat demand in ES

Usage of correlation of solar irradiance, outside temperature, crop requirements and GH parameters [10]

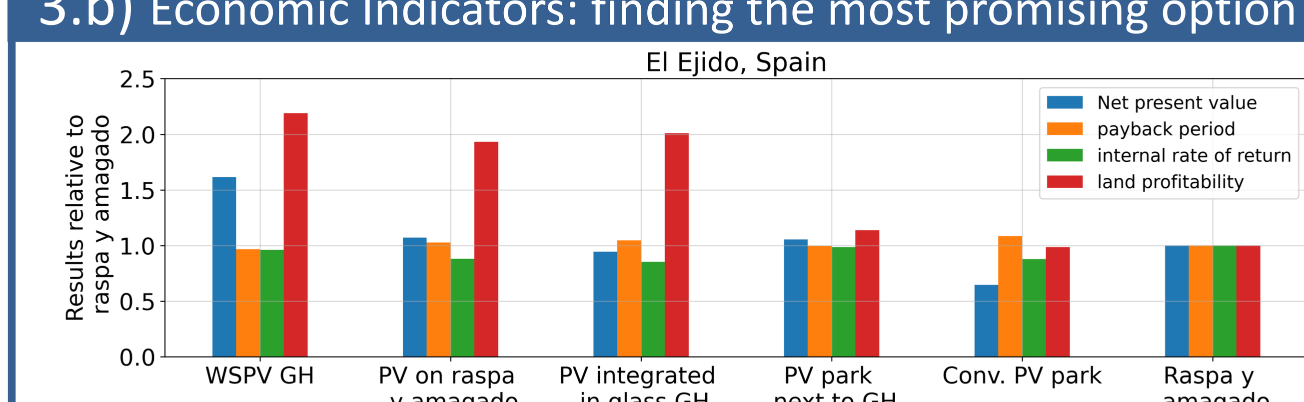
$$Q_{h,j} = \max[\, U_L((T_{sp}-\Delta T_c) - T_{a,j}) - \tau_1 \alpha GHI_j,\ 0]$$

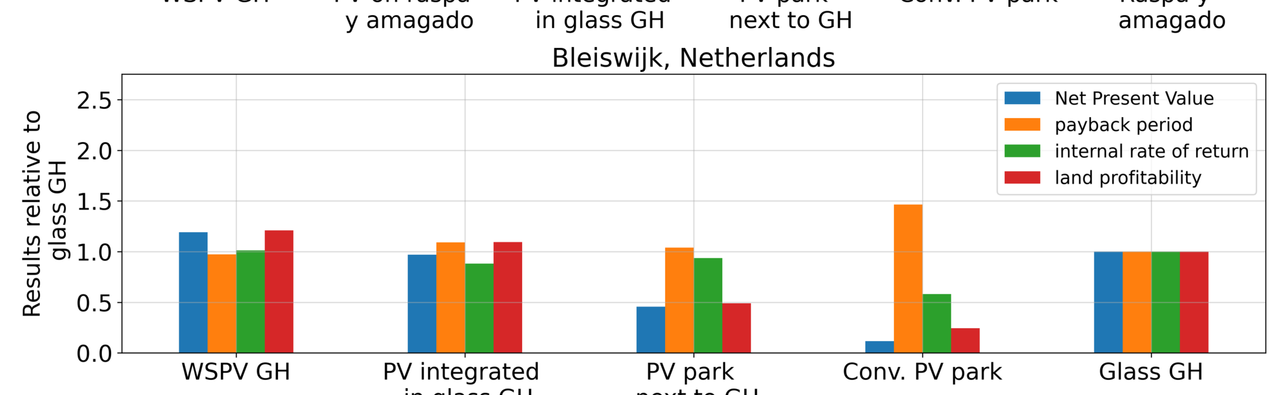
U_L	(kWh/m²/K)	GH heat loss coefficient	$T_{a,j}$	(°C)	outside temperature per hour j
T_{sp}	(°C)	crop dependent temperature distinguish between night and day	τ_1	(-)	GH cover transmittance
			α	(-)	GH absorbance
ΔT_c	(°C)	crop cultivation range	GHI_j	(kW/m²)	solar irradiance for hour j (sum)

→ GH is heated if $T_{a,j}$ drops below crop specific cultivation range: tomatoes $T_{day} = (15 \pm 5)$°C, $T_{night} = 5$°C
watermelon $T_{day} = (23 \pm 3)$°C, $T_{night} = 10$°C



3.b) Economic Indicators: finding the most promising option for a horticultural company with limited amount of land available





Economic analysis has been performed based on the model of [13]. The results are shown relative to the "GH only" scenario

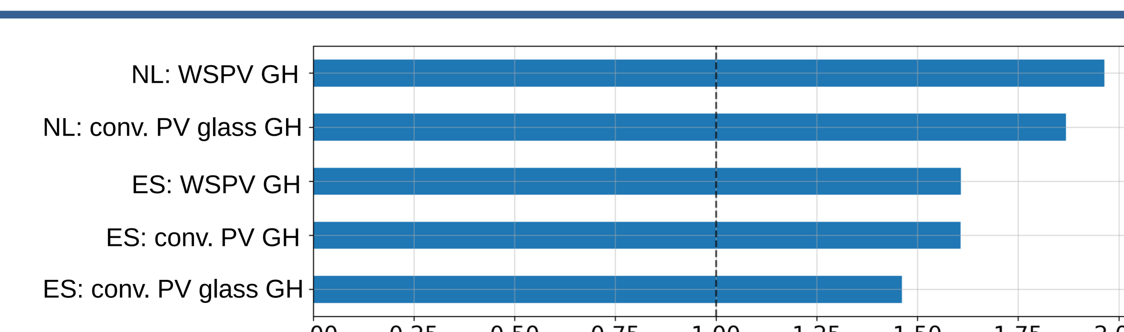
- WSPV GH scenario outperforms other scenarios in all economic indicators
- Also promising results by conventional PV modules integrated in glass greenhouses scenario
- dual-use of land+GH structure and reduction in O&M costs increases land profitability by a factor of 2.2 for WSPV GH scenario in ES
- investment costs are decreased by replacement of glass roof cover by PV modules
- Expected low costs of WSPV modules in the future play major role in analysis

Land Equivalent Ratio LER [14]

Combination of PV and agriculture leads to an increased spatial efficiency:

$$LER = \frac{Yield_{agri\_AgriPV}}{Yield_{agri\_onlyGH}} + \frac{Yield_{el\_AgriPV}}{Yield_{el\_onlyPV}}$$

LER > 1 indicates increased productivity



4. Conclusion and future improvements

- PV for greenhouses is an attractive investment for farmers in the near future
- climate change and frequent extreme weather situations, i.e. persistent heat during summers, enforced soiling events or hail and storm support this statement
- in El Ejido, for example, PV installations can replace the white painting for GH, which usually reduces damaging levels of irradiation
- APV GH lead to a diversification of the growers' income by reduced dependency on fluctuating market situation for horticultural products
- electricity and heat self-production and consumption leads to a higher independence from increasing oil and electricity prices
- WSPV modules on greenhouses outperform the 'only greenhouse' scenario at the two sites in ES and NL
- scenarios with conventional PV modules on greenhouses also show promising results
- further improvements on crop and PV yield modeling will improve the accuracy of the developed model
- the complex interplay of irradiation, GH microclimate and biological processes will be resolved more accurately
- influence of reduced irradiance and altered spectrum will be further investigated

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DLR Deutsches Zentrum für Luft- und Raumfahrt

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