D2.1 Tools and specifications for modelling agri-PV landscape integration

Symbiosyst

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PARTNERS’ SPECIFIC CONTRIBUTIONS: SUMMARY

- ENEA: a **trans-disciplinary GIS-based tool** that integrates a spatially centric descriptive methodology (supported by EURAC contribution);

- ABOVE: aerial agri-topography techniques, including aerial topographical mapping and 3D modelling analysis, which will map the landscape to inform of pre-existing agricultural plantations, crops/trees height, horizon mapping, and shading from nearby structures (buildings, trees, etc.);

- TUD: tool that is capable to render a macro vision map of the optimum angle and arrangement ranges for fixed and tracking agri-PV bifacial systems across Europe.

ENEA

EXTENDED DESCRIPTION: ENEA

WHAT: ENEA led, supported by EURAC, the development of a **trans-disciplinary GIS-based tool** that integrates a spatially centric descriptive methodology

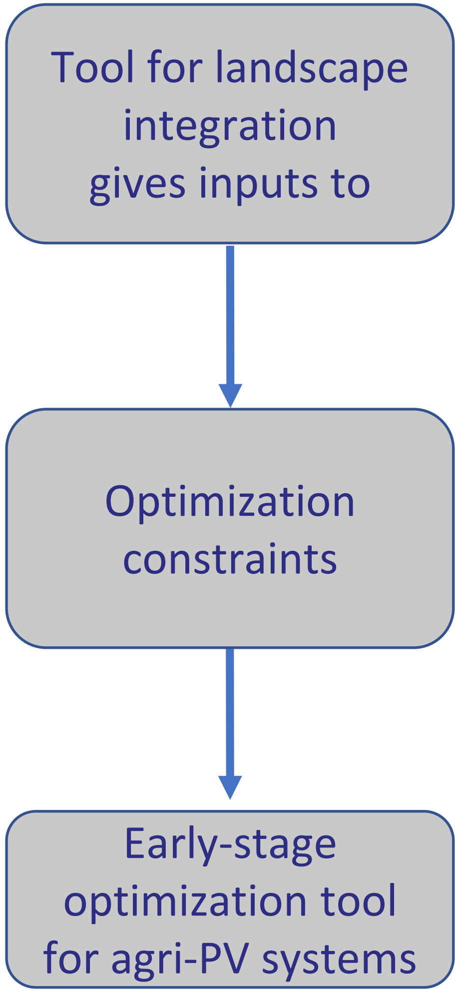
OBJECTIVE: facilitating and enhancing the integration of agrivoltaics into the landscape pattern. The pattern description is based on key geometrical elements, which are to be quantified.

METHODOLOGY: Based on this spatially explicit approach, a quali-quantitative analysis of the landscape provides preliminary inputs for the design of the agrivoltaic pattern to fulfill the most relevant landscape integration criteria, e.g., shape and size of the whole agrivoltaic systems, porosity of the system, etc., based on archetypes.

The results have been implemented through **a tool,** which has been **applied on selected exemplary sites**.

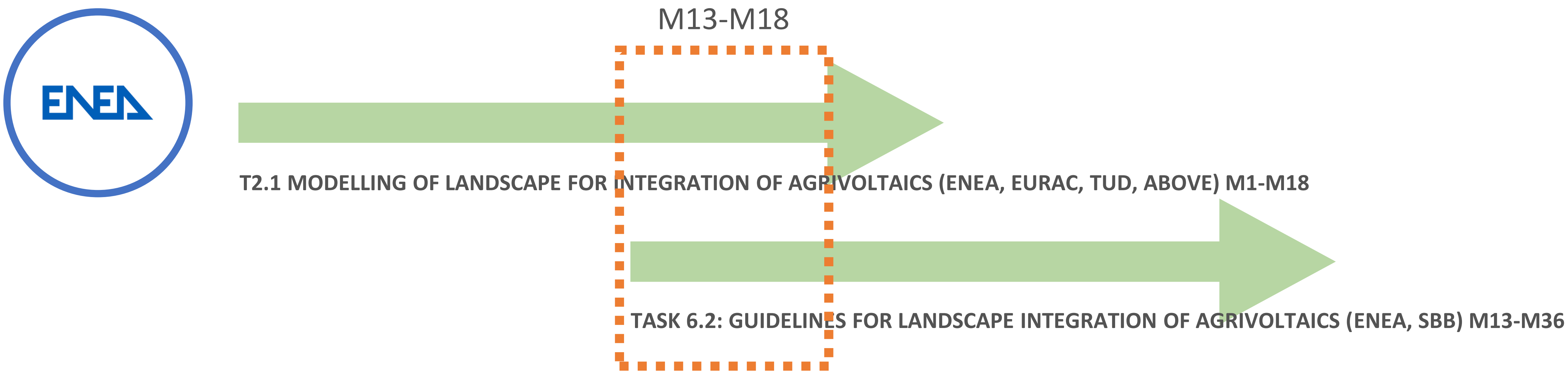
Links to other tasks

- In Task 2.1 ENEA developed a tool to maximize the **landscape integration** of agri-PV
- EURAC collaborates to develop a methodology to **set the constraints** for the early-design agri-PV optimization tool
- Goal: the optimized system configuration will already be **compliant** with **preliminary landscape integration criteria**



T2.4
EURAC, ENGIE-LAB, KUBO, LUCISUN, KUL, LAIMBURG, UPC, EFSOLARE, M7-M36

Links to other WPs



TASK 6.2: Guidelines for landscape integration of agrivoltaics (ENEA, SBB) M13-M36

- This task develops **landscape suitability criteria and preliminary landscape design guidelines aimed to support the decision-making process of different stakeholders** (i.e., local authorities in regional planning, and agrivoltaic developers), **based also on results from T2.1. SBB will elaborate site specific criteria (for South Tyrol)** together with landscape planners and/or other experts.

Methodology (1): the trans-disciplinary descriptive tool

METHODOLOGY

1. HOW TO DESCRIBE AGRIPV IN THE LANDSCAPE
2. SETTING CRITERIA FOR AGRIPV LANDSDCAPE INTEGRATION
3. GIS-TOOL DEVELOPMENT
4. TOOL APPLICATION ON CASE STUDY

Fattoruso, Grazia & Scognamiglio, Alessandra & Venturo, Andrea & Toscano, Domenico & Nardella, Giulia & Fabbricino, Massimiliano. (2023). Modeling of Landscape for the Integration of Agrivoltaics Using a GIS Approach. 10.1007/978-3-031-37123-3_6.

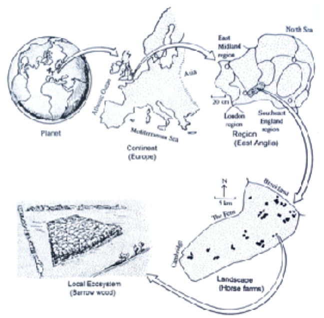
Fattoruso, Grazia, Domenico Toscano, Andrea Venturo, Alessandra Scognamiglio, Massimiliano Fabbricino, and Girolamo Di Francia. 2024. "A Spatial Multicriteria Analysis for a Regional Assessment of Eligible Areas for Sustainable Agrivoltaic Systems in Italy" *Sustainability* 16, no. 2: 911. https://doi.org/10.3390/su16020911

Background (1): (visual) landscape as a barrier

- Many installations are stack because of barriers along the permitting process, due to landscape preservation and land use concerns (i.e. agricultural areas)
- Along the permitting process, the assessment given by certain decision makers is mainly **qualitative**
- **I. e.,** Landscape related issues are mainly approached from a qualitative, **visual** point of view, whereas agrivoltaics features correspond to a design based on quantitive optimisation
- The engineering and the environmental, and visual descriptive vocabulary are not immediately compatible, thus a comprehensive **spatially based** visual description is needed

CREDITS: Alessandro Visalli. Progetto Verde
Webinar Rete Nazionale Agrivoltaico Sostenibile, Sistemi agrivoltaici tra autorizzazioni, paesaggio ed energia, 27 May 2022

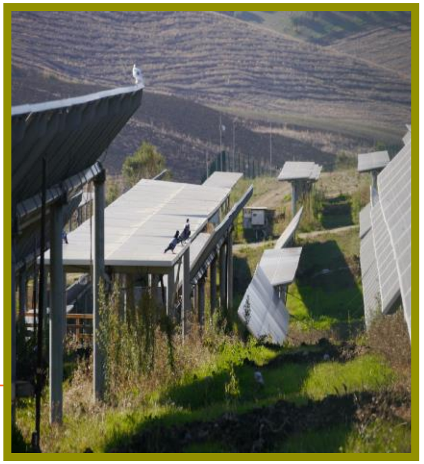
Background (2): Cross scale design



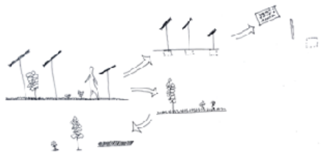
SPATIAL HIERARCHY, SCALES AND INFORMATION CONTENT (MAPS)

Richard T. T. Forma, Land mosaics, The ecology of landscape and regions,
Cambridge University Press, 1995.

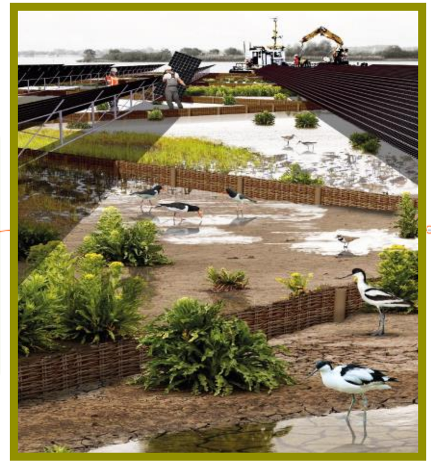
REGION → LANDSCAPE → LOCAL ECOSYSTEMS



Photovoltaic Park Monreale, Palermo, IT, 2009.
Design: Progetto Verde, Fabrizio Cembalo Sambiase, Alessandro Visalli.
Photo courtesy of Dirk Oudes, HDEL research group - Amsterdam Academy of Architecture



SPATIAL HIERARCHY, SCALES AND INFORMATION CONTENT (DETAIL MAPS AND DRAWINGS)



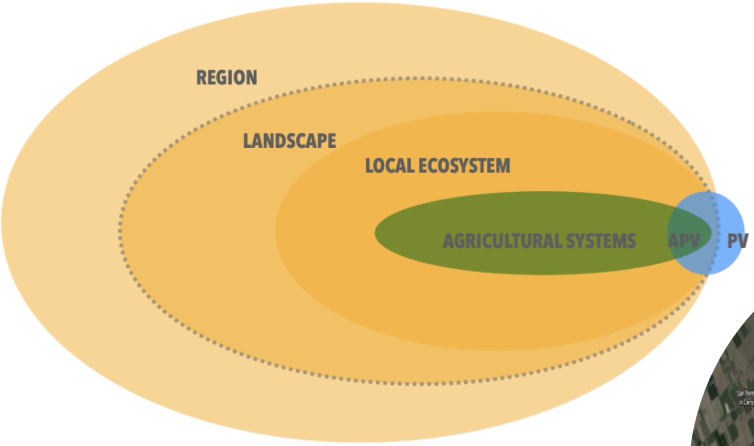
David de Boer, Solar Archipelago , 1st price 2020 IFLA Europe student competition, Wageningen University, June 2020. Supervisors: Sven Stremke, Paolo Picchi

PHOTOVOLTAIC SYSTEM AND PORE SPACE

- PORE SPACE SUB-SUBSYSTEMS
- PHOTOVOLTAIC SYSTEMS SUB SUBSYSTEMS

THE AGRIVOLTAIC LANDSCAPE PATTERN

%



ARRANGEMENT BASED ON:

Scognamiglio A., , ‘Photovoltaic landscapes’: Design and assessment. A critical review for a new transdisciplinary design vision,
Renewable and Sustainable Energy Reviews, Volume 55, 2016, Pages 629-661, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2015.10.072

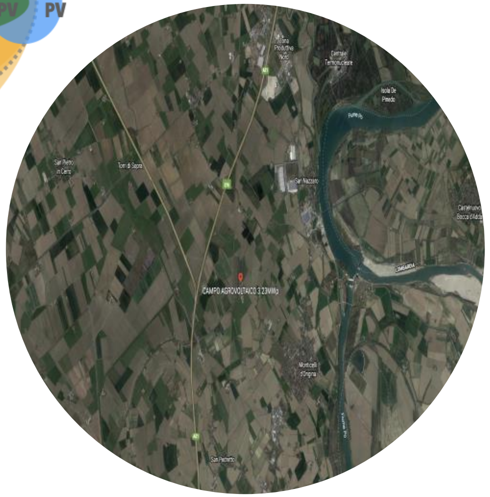
Toledo, C.; Scognamiglio, A. Agrivoltaic Systems Design and Assessment: A Critical Review, and a Descriptive Model towards a Sustainable Landscape Vision (Three-Dimensional Agrivoltaic Patterns). Sustainability 2021, 13, 6871. https://doi.org/10.3390/su13126871

PLANNING

WHERE?

SITE SELECTION

scale? regional, local
who? local authorities, developers, etc...
what tools? GIS mapping, multi criteria decision supporting systems...
what data? resource inventories, restrictions, etc.



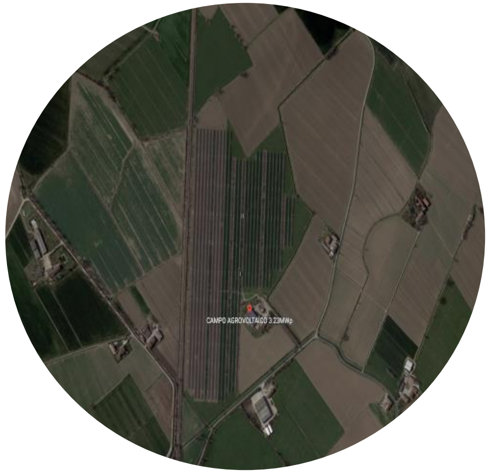
LANDSCAPE DESIGN

HOW? (SYSTEM)

(AGRI)PHOTOVOLTAIC LANDSCAPE PATTERN

Design strategies are oriented to the optimal ecological performance and to the provision of additional ecosystem services.

The main spatial related parameters are:
1. patch: area; small or large?; fractality;
2. grain (degree of artificiality, connectivity): fine grain (high land occupation ratio), coarse grain (low occupation ratio);
3. prevalent orientation of the rows of modules.



ARCHITECTURE DESIGN

HOW (SUB-SYSTEMS AND COMPONENTS)

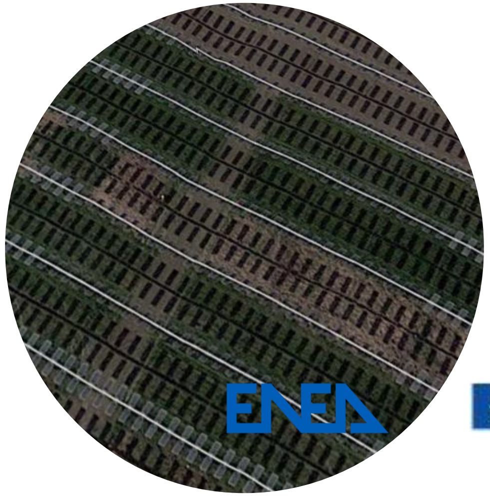
(AGRI)PHOTOVOTAIC SYSTEM TRIDIMENSIONAL PATTERN

1. energy features: technology, nominal power (MW_p); density of power (MW_p/m^2); annual energy generation per land unit ($MWhm^2/y$); normalized energy generation ($MWh/MW_p/y$).

2. engineering features: land cover underneath the modules (grazing, grassland, cement, etc.); supporting systems (materials, weight, technology); foundations (materials, weight, technology).

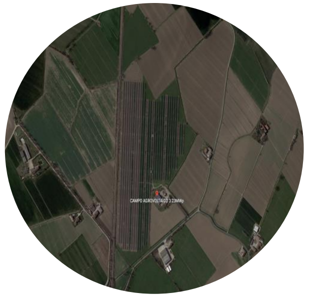
3. spatial related features: azimuth angle (°); tilt angle (°); area (m^2); shape (island arrangement, parallel stripes arrangement); pattern; distance between the stripes (m); length of the stripe (number of modules in the same stripe in the vertical, transversal direction); width of the stripe (number of modules in the same stripe in the horizontal, longitudinal direction); grain (small patches, large patches); height of the modules from the ground.

4. morphological and technological modules features: technology, shape, dimension, colour.

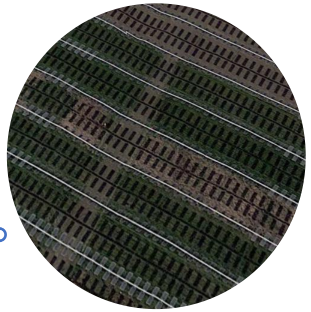


T2.1 tools at the regional, landscape and system scale

Advances in the development of a **trans-disciplinary GIS-based tool** that integrates a spatially centric descriptive methodology in order to realize a sustainable integration of the agrivoltaic systems in the landscape. Definition and quantification of landscape pattern description based on key geometrical elements, such as shape, size, borders, pattern type, etc. will be provided. **ENEA + (EURAC)**



Advances in **aerial agri-topography techniques**, including *aerial topographical mapping* and *3D modelling* analysis, for the mapping of the landscape to inform of pre-existing **agricultural plantations**, crops/trees height, horizon mapping, and shading from nearby structures (buildings, trees, etc.) **ABOVE**



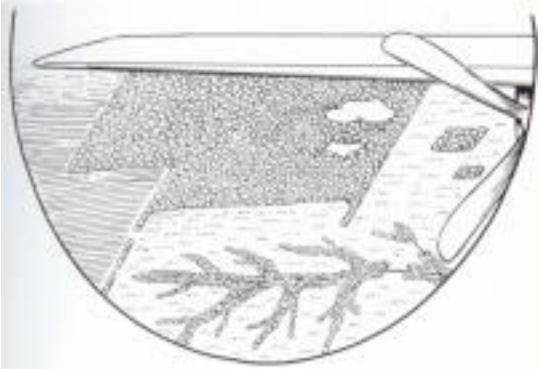
Advances in a tool that is capable to render a macro vision map of the **optimum angle and arrangement** ranges for fixed and tracking agri-PV bifacial systems across Europe. **TU Delft**

Methodology (1): the trans-disciplinary descriptive tool

- The proposed methodology considers the agri-PV plant as a part of the landscape mosaic. This allows to consider into an unique descriptive tool both the landscape and the agriPV system.
- This approach is based on the basic principles of Landscape Ecology, as theorised by Forman through the so called "Patch-Corridor-Matrix model"

- Forman, R.T.T. (1995) Land Mosaics. The Ecology of Landscapes and Regions. Cambridge University Press, Cambridge.
- Scognamiglio A.,'Photovoltaic landscapes': Design and assessment. A critical review for a new transdisciplinary design vision, Renewable and Sustainable Energy Reviews, Volume 55, 2016, Pages 629-661, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2015.10.072.

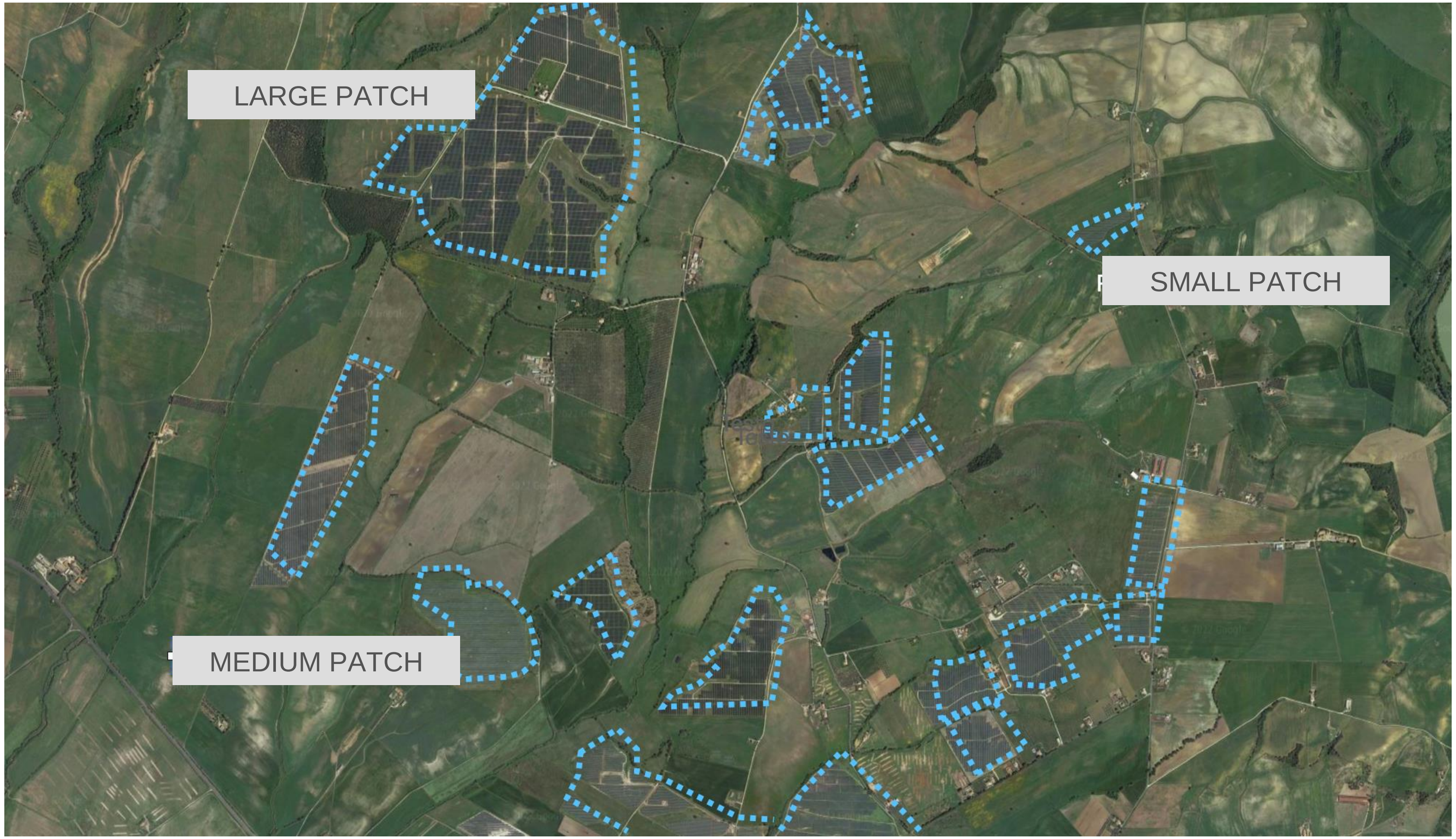
Methodology (1): Patch-Corridor-Matrix model



Patch-Corridor-Matrix model. “From an airplane, land almost always appears as a mosaic. The glorious mosaics of St. Marks in Venice or the University of Mexico appear as a ***pattern*** of colored patches and strips, usually with a background matrix. Tiny stones of different colors are aggregated to create the patches, strips, and matrix. (...) Mosaic patterns are found at all spatial scales, from submicroscopic to the planet and universe”

(Forman, R.T.T. (1995) Land Mosaics. The Ecology of Landscapes and Regions. Cambridge University Press, Cambridge.)

Methodology (1): Example of PV patches in the landscape mosaic pattern



Methodology (2): Landscape integration, official normative & guidelines

- In general, Landscape integration criteria have not been formulated in a systematic way yet, because of their mainly qualitative nature
- Nonetheless, the Italian guidelines for agrivoltaic plants (MiTE. June 2022) include the consideration of the landscape integration of agriPV as a recommendation for their design; moreover the UNI PdR 148:2023, includes a chapter giving some preliminary guidelines for landscape integration of agriPV. These guidelines are based on documentation from permitting procedures at the Italian cultural heritage offices, from the Ministry of Culture
- These guidelines represent a first attempt to consider some qualitative (mainly visual) criteria of agriPV for allowing its harmonisation with the landscape
- The main criterion can be summarised in: **Coherent to the existing landscape pattern**; this criterion has been structured in a set of sub-criteria, referring to the regional, landscape and system scale

Methodology (2): official references

1. Linee Guida in materia di impianti agrivoltaici, Ministry of the Ecological Transition, June 2022
https://www.mase.gov.it/notizie/impianti-agri-voltaici-pubblicate-le-linee-guida

2.Landscape integration of agrivoltaic systems, in uniPDR 148: 2023, “Sistemi agrivoltaici - Integrazione di attività agricole e impianti fotovoltaici”
https://store.uni.com/uni-pdr-148-2023

1

2


PRASSI DI RIFERIMENTO UNI/PdR 148:2023

Sistemi agrivoltaici - Integrazione di attività agricole e impianti fotovoltaici

Agri-voltaic systems - Integration of agricultural activities and photovoltaic implants

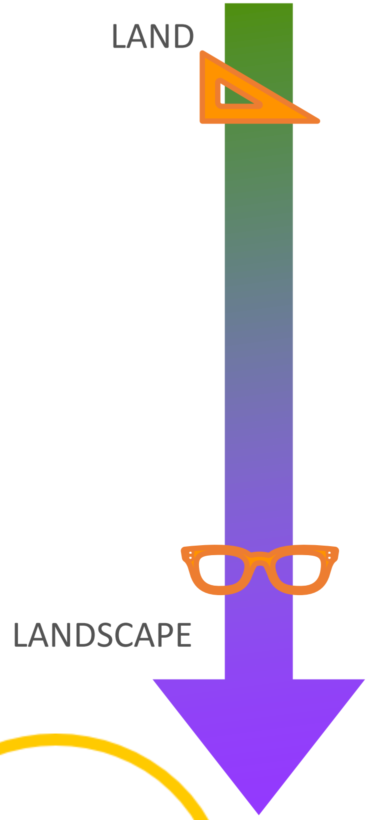
La prassi di riferimento si propone di fornire requisiti relativi ai sistemi agrivoltaici partendo dal contesto tecnico normativo esistente in materia di impianti fotovoltaici e attività agricole, con particolare attenzione agli aspetti specifici correlati all'ambito di applicazione degli impianti agrivoltaici e sviluppo della tecnologia associati a tali impianti e relativi progetti.
Si definiscono inoltre i requisiti di base per la redazione e presentazione di progetti inerenti impianti agrivoltaici e analisi multicriteria per la valutazione dei suddetti progetti.

Pubblicata il 3 agosto 2023

ICS 27.160, 65.020.01

ENEA UNIVERSITÀ CATTOLICA del Sacro Cuore remTEC uni

Methodology (3): GIS tool development



The tool performs **quantitative analysis (land and landscape metrics) supporting qualitative design choices**, based on a spatial explicit approach, for classifying landscape structure, and composition.

Tool capabilities:

3.1 SITE SUITABILITY MAPPING: Identification of suitable **lands** for agrivoltaic systems according to a properly defined set of solar and agricultural criteria

3.2 REVERSING VISIBILITY ASSESSMENT: Assessment of visual impacts to **landscapes** by a re-conceptualization of visibility analysis

3.3 LANDSCAPE SPATIAL PATTERN MODELLING: Modelling and quantification of the **landscape** elements by Reality Mapping and GeoAI based on original **landscape** metrics supporting a proper preliminary design choices for integrating agrivoltaics in the **landscape** (e.g. patch size, geometry, orientation…)

Methodology (4): The case study, Trentino Alto Adige

Trentino-Alto Adige is an autonomous region of Italy, located in the Northen part of the country. The region is made up of 2 provinces: the province of Trento, commonly known as Trentino (NUTS2-ITH20) and the province of Bolzano, commonly known as South Tyrol (Alto Adige in Italian; NUTS2-ITH10).

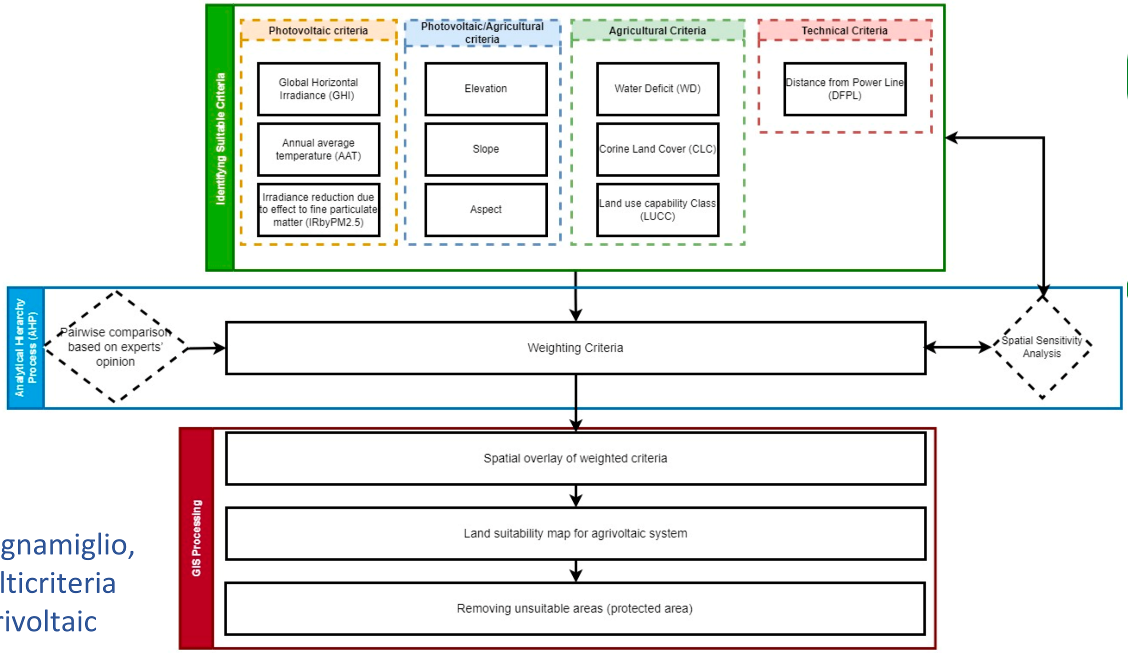
Population: 1.029.475 abitanti
Area: 13.606 kmq
Density: 76 habitants/kmq
Territory: mainly mountainous
Climate: continental – alpine
Agriculture: fruit growing, viticulture, arable land

Methodology (3.1): AgriPV Land Suitability Mapping

- A **spatial multicriteria analysis** approach, based on the integration of a multi-criteria decision-making (**MCDM**) method as the analytic hierarchy process (**AHP**) with geographic information systems (**GIS**) has been developed as **tool capability** for **mapping the eligible available lands for agrivoltaic systems at regional level**
- The land eligibility has been evaluated **quantifying the appropriateness of the land unit** to produce the optimal PV power output and crop yield by using an agrivoltaic system while **minimizing its potential impact** to landscape.

The developed approach consists in three main steps:

1) selecting a proper suitable criteria set;
2) weighting selected criteria by AHP method;
3) combining the selected criteria as geographical variables by weighted spatial overlay in a land suitability index for agrivoltaic systems



Fattoruso, Grazia, Domenico Toscano, Andrea Venturo, Alessandra Scognamiglio, Massimiliano Fabbricino, and Girolamo Di Francia. 2024. "A Spatial Multicriteria Analysis for a Regional Assessment of Eligible Areas for Sustainable Agrivoltaic Systems in Italy" *Sustainability* 16, no. 2: 911. https://doi.org/10.3390/su16020911

Methodology (3.1): Suitability Criteria for agrivoltaic deployments

- An **original set of suitable criteria** (and constraints) has been properly defined and implemented. These criteria intend to capture the **geophysical, technical, environmental, and meteorological factors** that can affect both the solar PV potential of a unit of land and the crop yields, along with **agriculture-oriented factors** such as the land agricultural use, land capability and water deficit.

- The choice of criteria was based on experts' knowledge (*both scientists and stakeholders as designers, developers, decision-makers in the energy and agricultural fields*) and the current agrivoltaic literature

SUITABILITY CRITERIA

	PV	*AGRICULTURE*
GLOBAL HORIZONTAL IRRADIANCE (GHI)	x	
ANNUAL AVERAGE TEMPERATURE	x	x
SLOPE	x	x
ASPECT	x	
ELEVATION	x	
WATER DEFICIT		x
LAND USE CAPABILITY CLASS		x
LAND USE/LAND COVER		x

CONSTRAINTS

CRITERIA	*TRESHOLD VALUE*
GHI	>900kWh/m^2/y
SLOPE	<4%
CORINE LAND COVER	Class 2
NATURA 2000	-
HERITAGE SITES	-

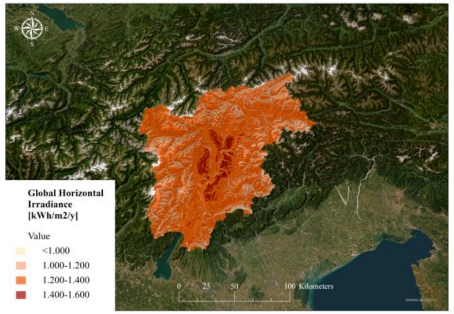
ENEA

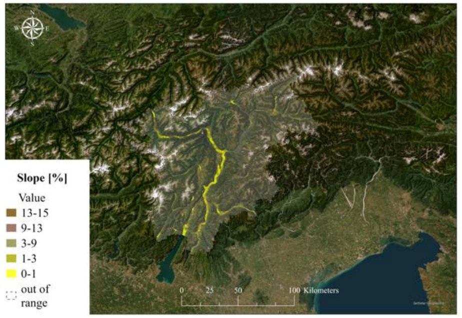
Methodology (3.1): Geospatial data and sources

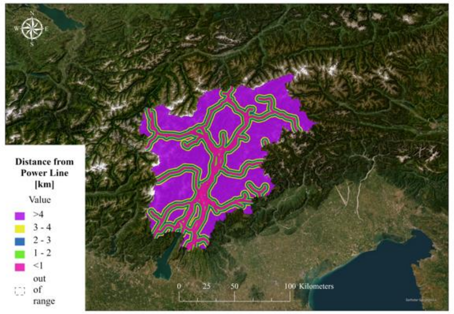
Geospatial data and sources used for tool application on the study case are **official national open datasets** at regional spatial resolution

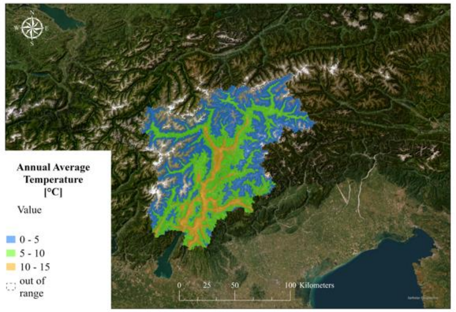
Data	Data Type	Data Resolution	Units	Data Range in Campania	Source	Open Data
Global Horizontal Irradiance	raster	200 m × 200 m	$kWh/m^2/y$	997–1664	www.globalsolaratlas.info (accessed on 19 November 2023)	✓
Annual Average Temperature	raster	700 m × 700 m	°C	5.4–18.3	www.globalsolaratlas.info (accessed on 19 November 2023)	✓
Irradiance reduction by PM2.5	raster	30 m × 30 m	%	3.5–8.1	Derived by spatial analysis method@ENEA https://doi.org/10.1007/978-3-030-58802-1 (accessed on 19 November 2023)	
Elevation	raster	25 m × 25 m	m s.l.m	0–1904	https://land.copernicus.eu/imagery-in-situ/eu-dem/ (accessed on 19 November 2023)	✓
Slope	raster	20 m × 20 m	%	0–544	Derived by DEM	
Aspect	raster	20 m × 20 m	degree	-	Derived by DEM	
Water Deficit	raster	1 km × 1 km	mm/y	1.8–504.8	https://groupware.sinanet.isprambiente.it/ (accessed on 19 November 2023)	✓
Corine Land Cover	vector	25 ha/100 m	-	-	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018 (accessed on 19 November 2023)	✓
Land Use Capability Class	vector	-	-	-	www.agricoltura.regione.campania.it (accessed on 19 November 2023)	✓
Distance from Power line	vector			-	www.openinframap.org (accessed on 19 November 2023)	✓

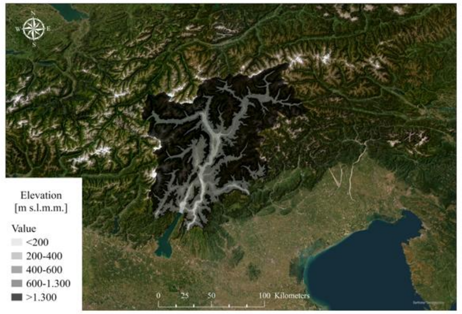
Methodology (4): Mapping agriPV suitability criteria for Trentino Alto Adige

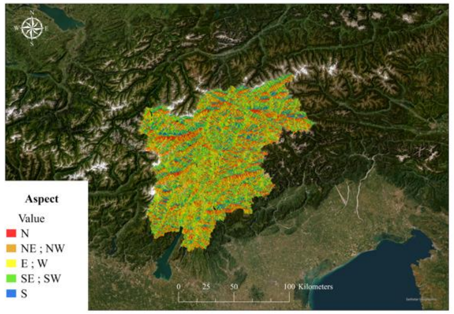


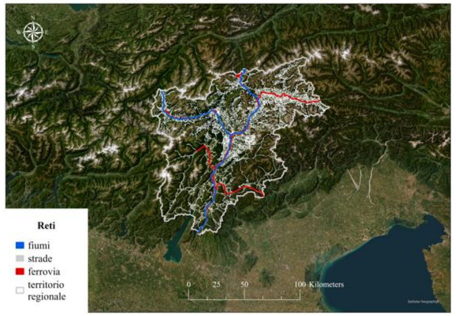


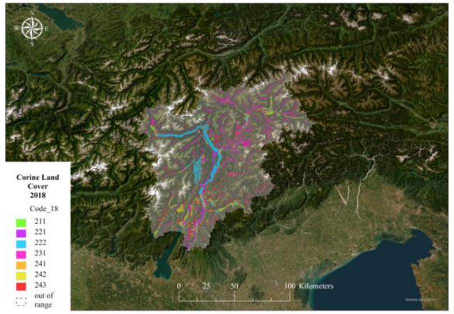


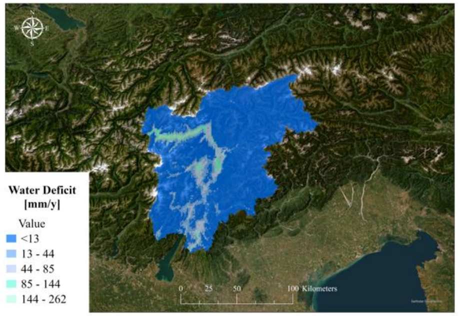


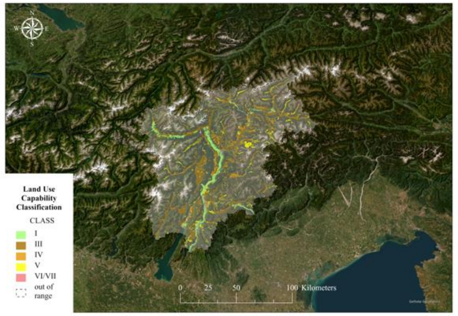


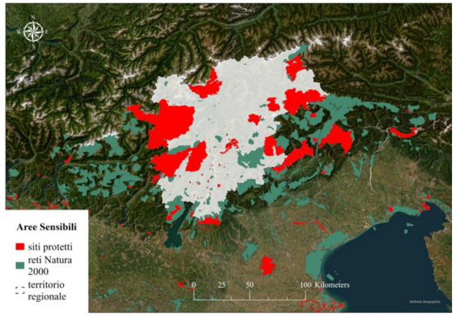








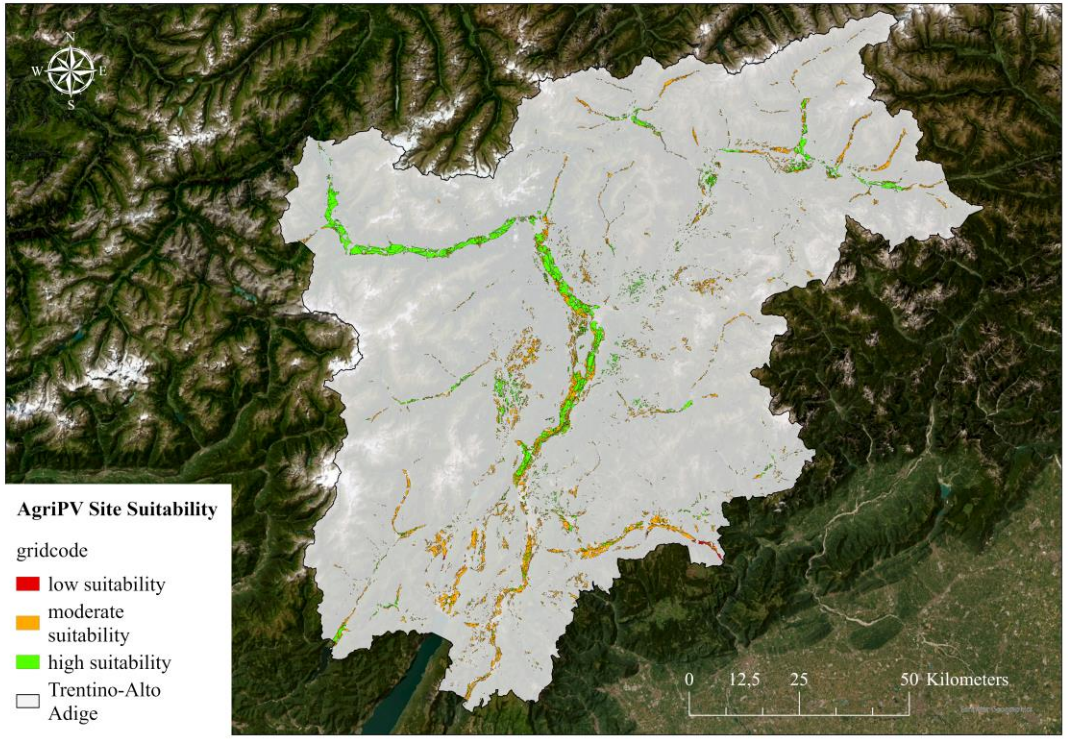




ENEA

Methodology (4): AgriPV Land Suitability Map of Trentino Alto Adige

- Applying the developed tool, the **land suitability map for agrivoltaic systems in the Trentino Alto Adige region** has been generated, classifying eligible available lands into five levels of suitability (very low, low, moderate, high and very high)
- These levels represent the different priorities to allocate agrivoltaic systems.
- It is to notice that there are not lands categorized as very low or very high in suitability.

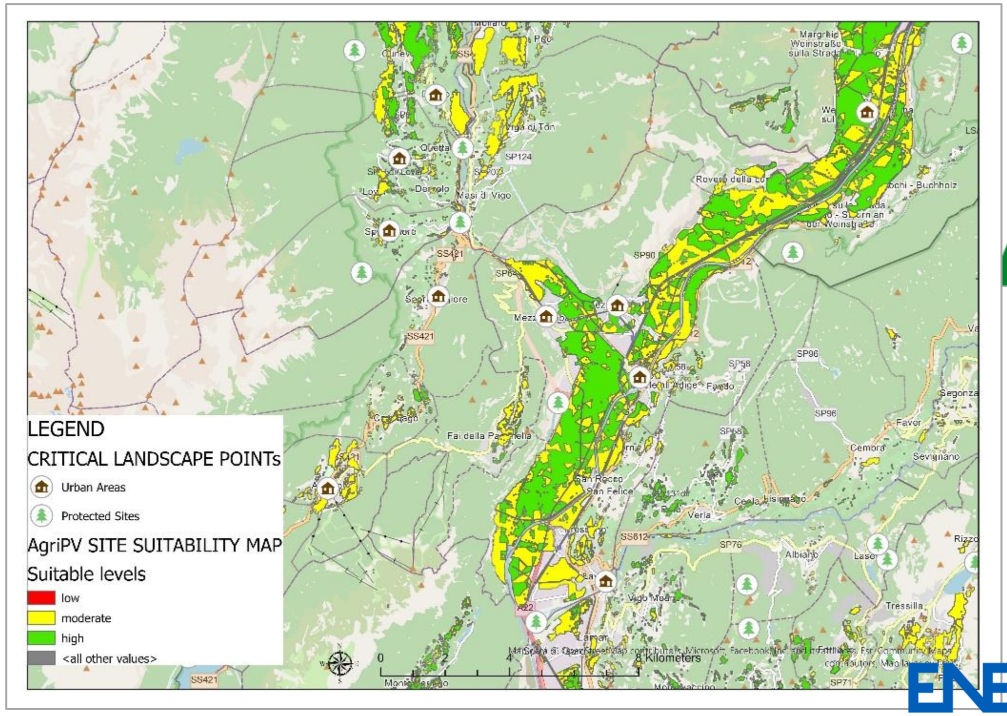


Methodology (3.2): REVERSING VISIBILITY ASSESSMENT

…*ex ante* evaluation of potential landscape visual impacts of agrivoltaic projects

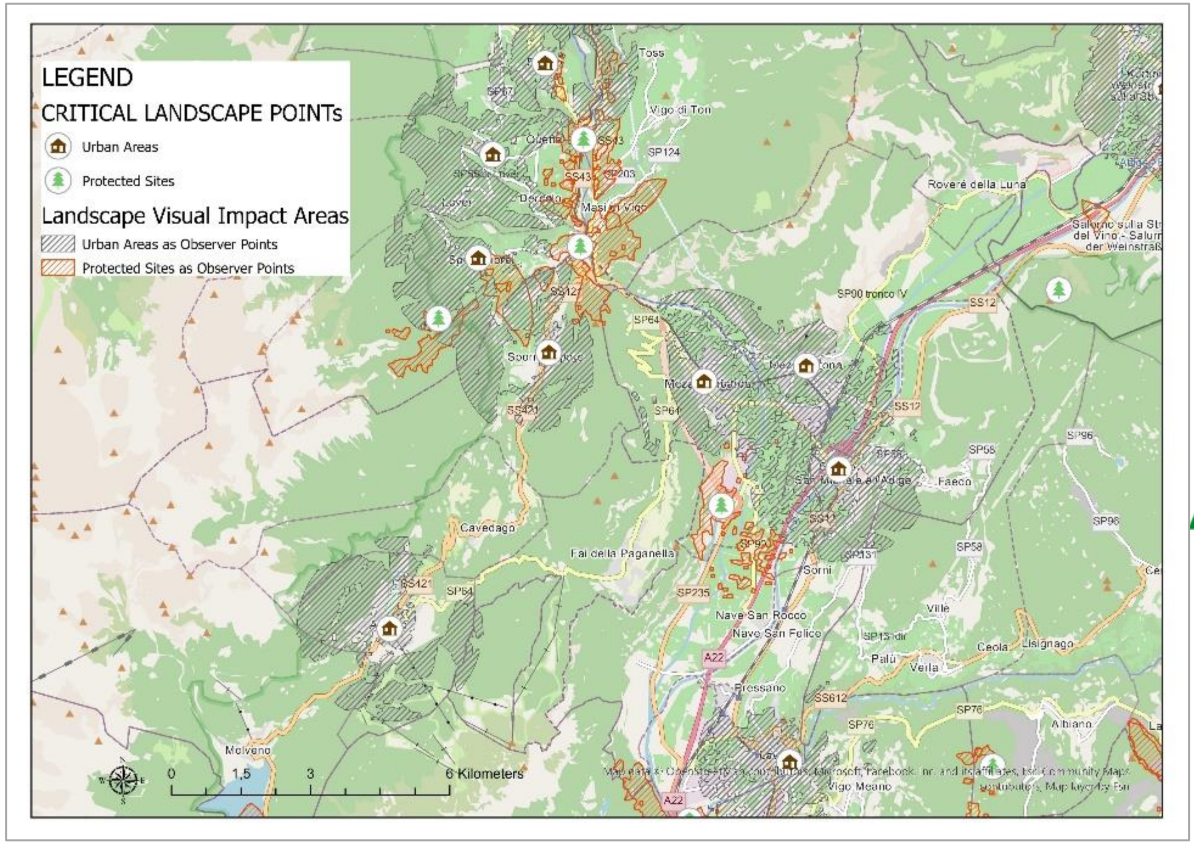
- A **reversal visibility analysis** has been developed as **tool capability** for allowing the earlier identification of impactful agriPV projects, to improve and accelerate the process of mitigating landscape impacts of agrivoltaic systems development

- The proposed **Reverse Visibility Analysis** is practically investigated for the agriPV eligible lands of Trentino alto Adige, generating R-ZTV maps for critical landscape elements, properly selected, across the area of interest.

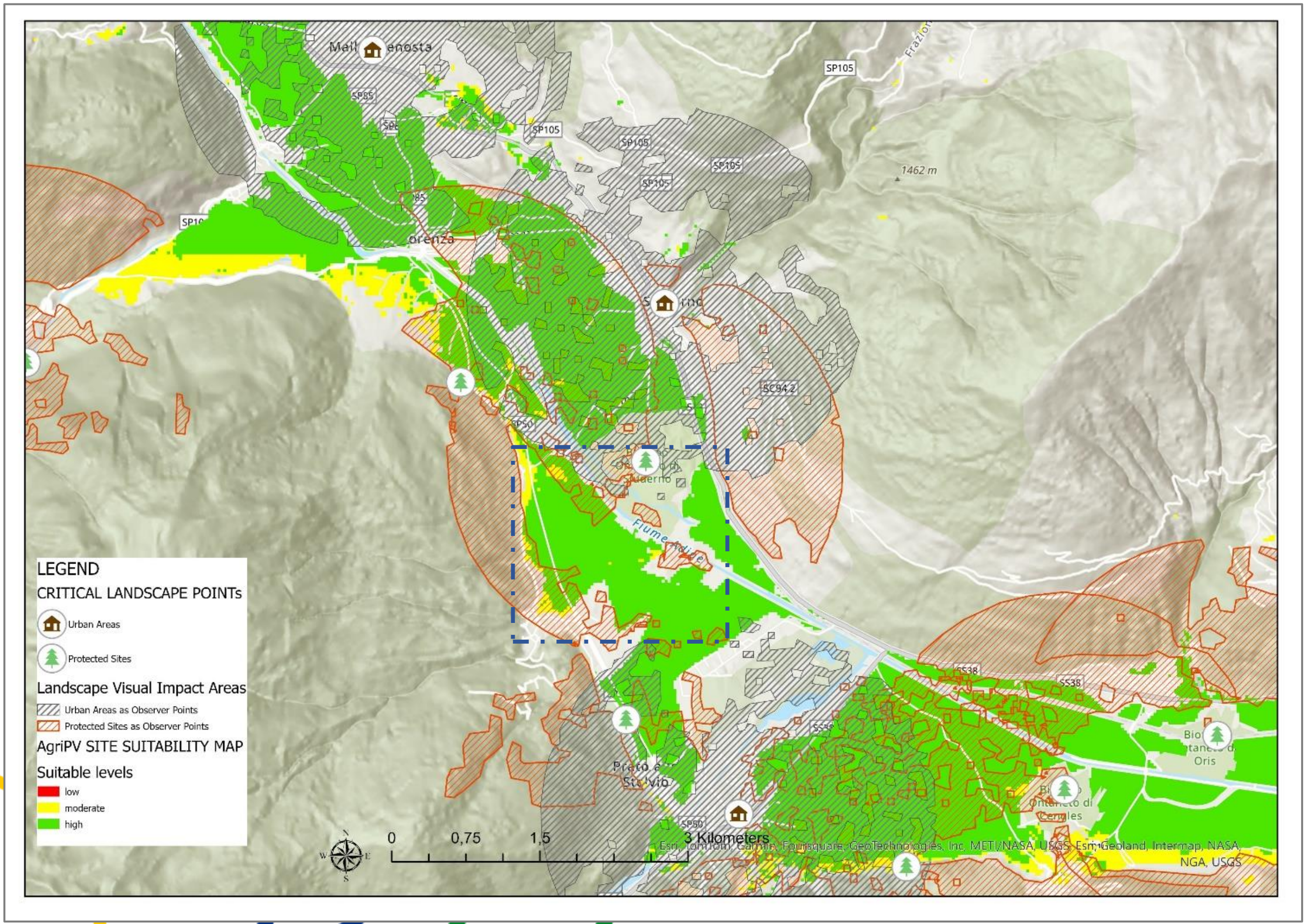


Methodology (4): R-Zone Theoretical Visibility Maps

R-ZTV maps have been generated for *heritage sites* and *major urban areas*, identifying those agriPV eligible lands with greater potential visual impacts



Methodology (4): Maps of R-(agriPV eligible) Zone Theoretical Visibility – Trentino Alto Adige



Zooming in the agriPV eligible lands outside the visibility zones (e.g. dashed area), the landscape unit is spatially modelled by extracting and evaluating the geometry and the arrangement of the agricultural patches fallowing into it

Methodology (3.3): LANDSCAPE SPATIAL PATTERN MODELLING

An original approach based on Reality Mapping and GeoAI has been developed for modeling landscape elements, within the agriPV eligible zones, including single agricultural patches.

This approach is based on the following main steps: a) to recognize and extract land units, classified as suitable for agrivoltaics, from satellite images (segmentation technique); b) to identify and separate landscape features (i.e. agricultural patches); c) to extract the spatial landscape pattern, patch by patch, from satellite image

a) b) c)

- McGarigal K., SA Cushman, and E Ene. 2023. FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical Maps. Computer software program produced by the authors; available at the following web site: https://www.fragstats.org
- Segment anything , Meta AI - arXiv:2304.02643v1 [cs.CV] 5 Apr 2023

Methodology (3.3): QUANTIFYING THE LANDSCAPE STRUCTURE

- A relevant set of quantitative landscape metrics has been selected to classify the landscape structure, its composition and spatial arrangement aimed at supporting proper preliminary design choices for integrating agrivoltaics in the landscape

- *The most effective way to plan the proper integration of agrivoltaics into the landscape context is to ensure that the landscape, including the agrivoltaic systems, resembles the pre-existing one as much as possible, according to the criterion of "minimum visibility and maximum verisimilitude“*

- The evaluation of these metrics is implemented as tool capability on the basis of the vector spatial layers of landscape features, performed by of the landscape segmentation tool

Methodology (3.3): DEFINING THE LANDSCAPE METRICS - Landscape levels

Metric	Area	Perimeter	Perimeter-Area Ratio	Shape Index	Fractal Dimension Index

PATCH metrics

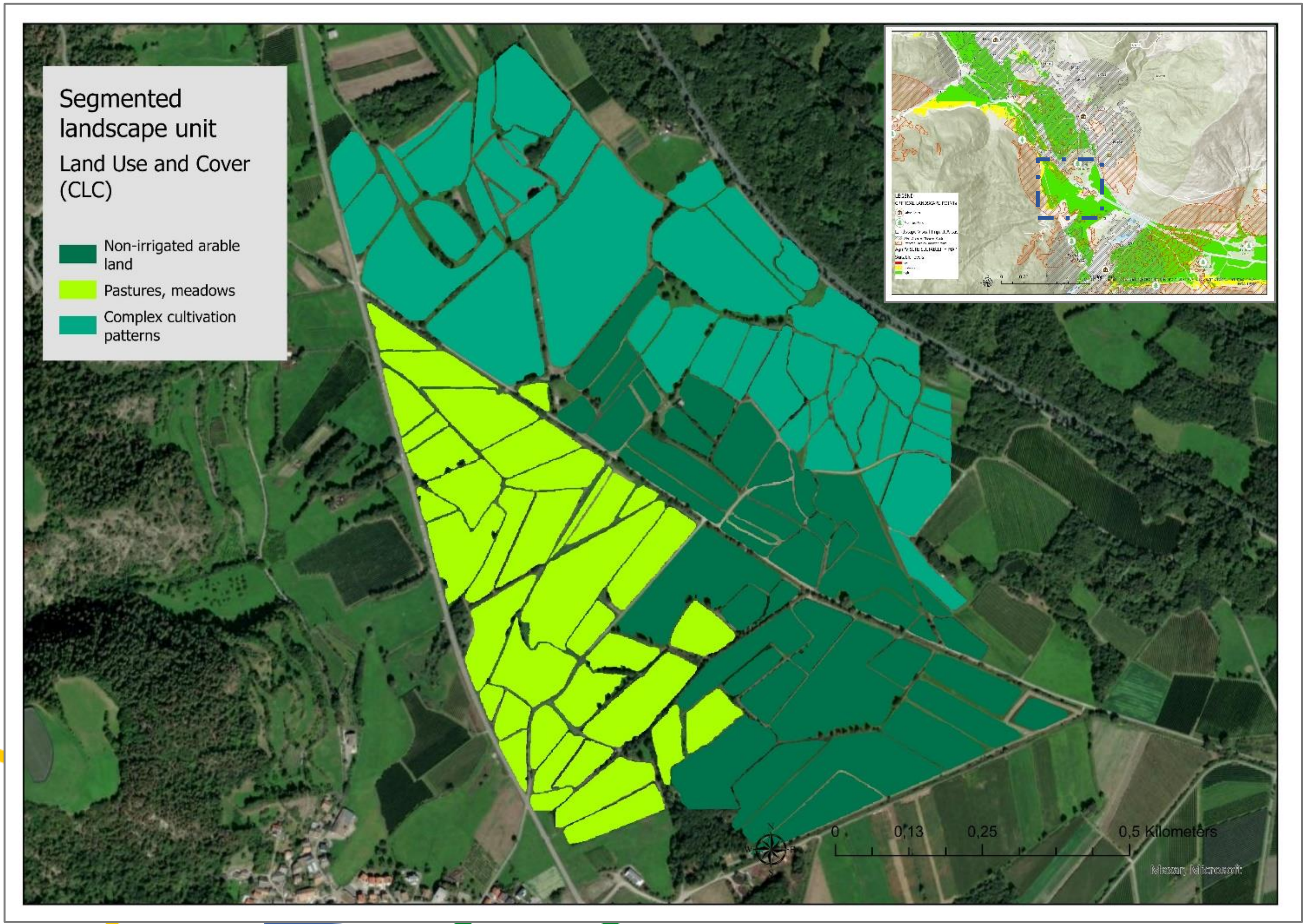
Metric	Total (Class) Area	Largest Patch Index	Percentage of Landscape	Total Edge	Edge Density	Perimeter-Area Fractal Dimension	Landscape Division Index	Splitting Index	Effective Mesh Size	Number of Patches	Patch Density

CLASS metrics

Metric	Patch Richness	Patch Richness Density	Relative Patch Richness	Shannon's Diversity Index	Simpson's Diversity Index	Modified Simpson's Diversity Index	Shannon's Evenness Index	Simpson's Evenness Index	Modified Simpson's Evenness Index

LANDSCAPE metrics

Methodology (4): Modeling and quantifying the landscape structure for agrivoltaics integration – Case Study 1



- The landscape unit including agriPV eligible lands has been modelled and quantified by the developed GIS tools
- The selected metrics have been evaluated aimed at quantifying the structure of landscape unit suitable for agrivoltaics

- PATCH METRICS

	Area (ha)	Perimeter (m)	Perimeter-Area Ratio	Shape Index	Fractal Dimension Index
Mean	0,65	459,20	1730,80	1,55	1,11
Area Weighted Mean	1,27	648,63	704,46	1,55	1,10
Median	0,50	412,00	866,87	1,48	1,09
Range	4,75		39745,05	2,27	0,64
Standard Deviation	0,64	220,34	4884,78	0,29	0,06

- CLASS METRICS

Patch Type	Total Class Area (ha)	Largest Patch Index (%)	Percentage of Landscape (%)	Perimeter-Area Fractal Dimension	Landscape Division Index	Effective Mesh Size (ha)	Splitting Index	Number of Patches	Patch Density (#/100 ha)
211	27,55	1,06	12,05	1,08	1,00	0,13	1720,34	45,00	19,67
231	23,49	0,97	10,27	1,12	1,00	0,09	2455,45	38,00	16,61
242	31,74	2,08	13,88	1,03	1,00	0,23	976,79	44,00	19,24

- LANDSCAPE METRICS

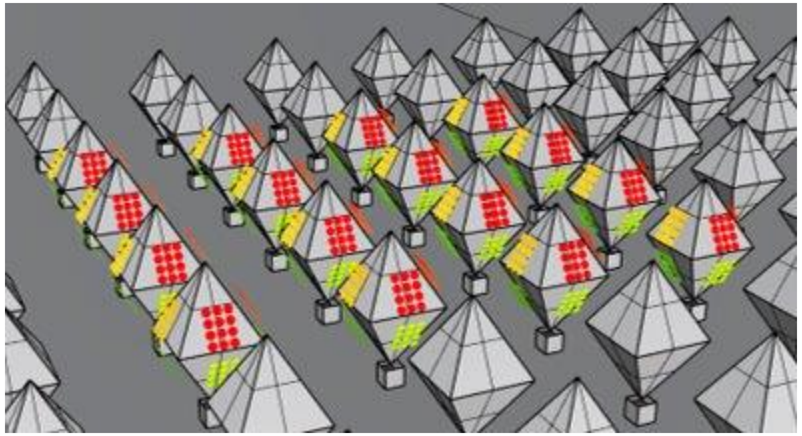
Total Area (ha)	Largest Patch Index (%)	Perimeter Area Fractal Dimension	Landscape Division Index	Effective Mesh Size (ha)	Splitting Index	Number of Patches	Patch Density (#/100 ha)	Patch Richness	Patch Richness Density (#/100 ha)	Relative Patch Richness (%)	Shannon's Diversity Index	Simpson's Diversity Index	Modified Simpson's Diversity Index	Shannon's Evenness Index	Simpson's Evenness Index	Modified Simpson's Evenness Index
228,74	2,08	1,08	1,00	0,46	496,94	127,00	55,52	3,00	1,31	42,86	1,09	0,66	1,08	0,99	0,99	0,99

EURAC

Objective

Develping a **quick tool** to **analyse** at an **early design** stage:

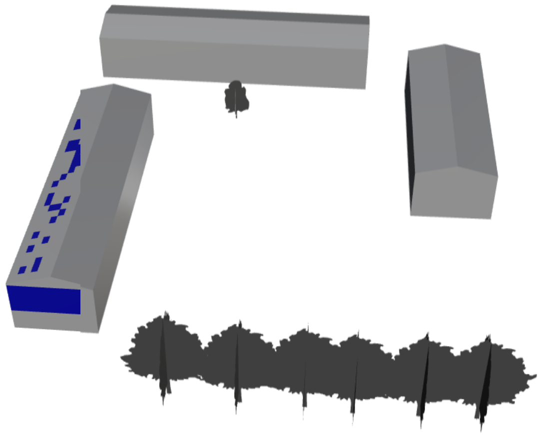
- Incident radiation on plants
- PV Plant production
- Annual, monthly or daily evaluation

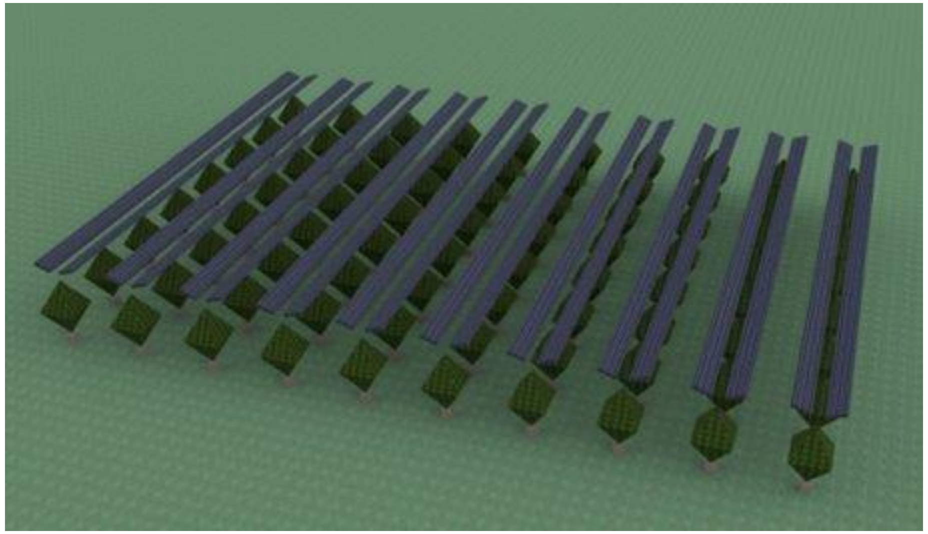


eurac research

Idea

Applying a tool, developed and validated by EURAC Research's PVS group to study BIPV solutions, to the Agri Voltaic field, adapting it to a structure that changes its geometry over time

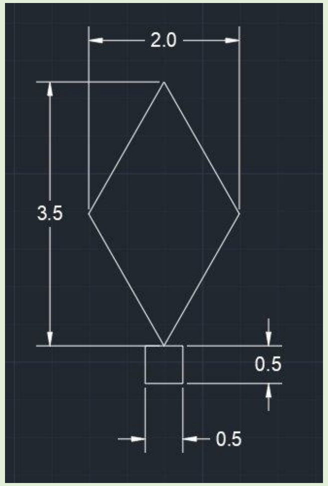


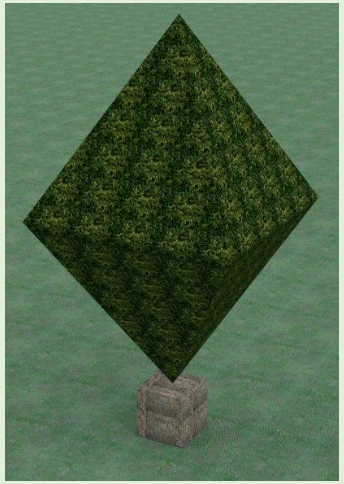


Main features

- Timestep – 1hr
- Evaluates the total energy on every single surfaces during the timestep
- Possibility of modelling every type of trees following the indications of agronomists
- The tool also takes into account the environment recreating the surroundings (eg mountains) and soil characteristics (e.g. albedo)
- With regard to weather conditions, a TMY file is taken into account as input
- Exploit the Python library ‘Radiance’

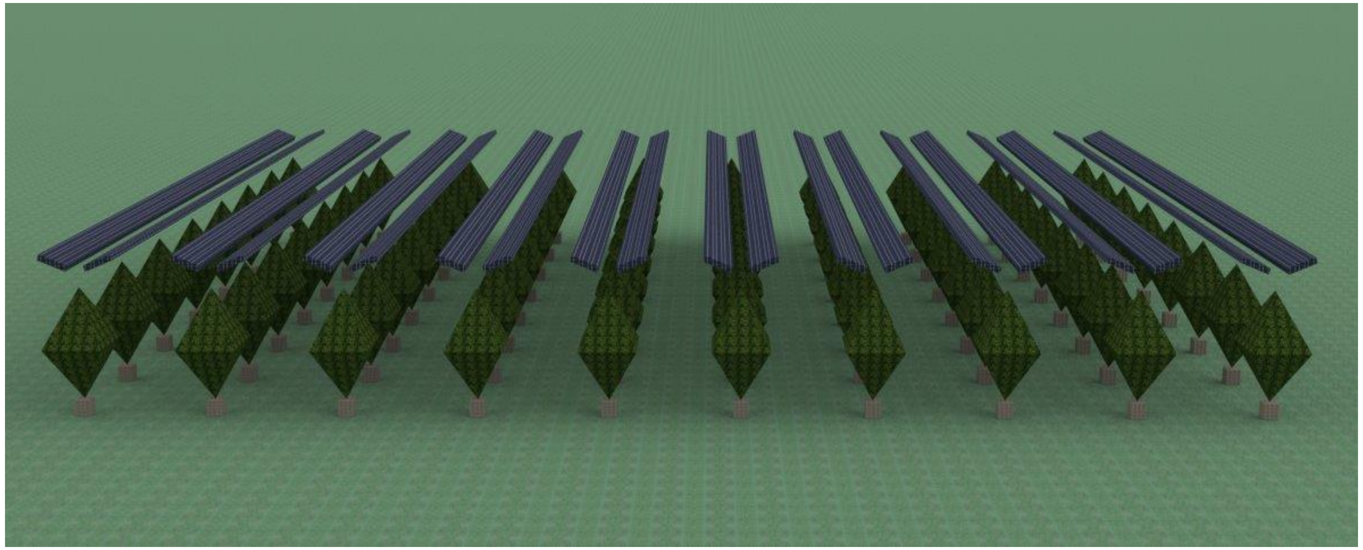
Tree model example



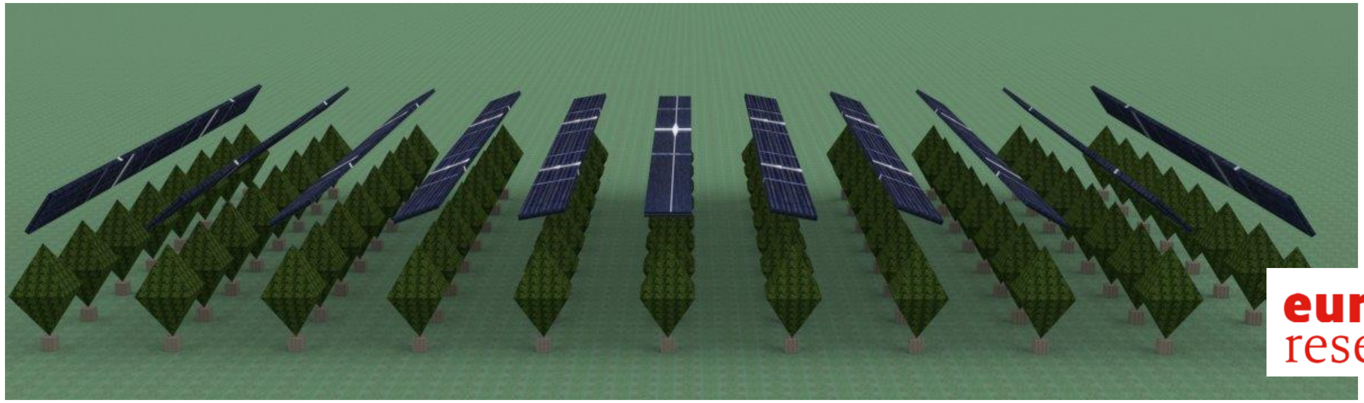


Examples of the AgriPV plant model

FIXED STRUCTURES



TRACKING SYSTEM



Application (what our tool allows to)

The tool allows post-processing evaluation of irradiation on the modules and on the various areas of the plant canopy also for different movement logics of the tracker system (which also takes backtracking into account to avoid self-shading).

⇓

This allows input from agronomists regarding the best radiation strategy for the plant, including considering radiation at various canopy heights, as well as within the canopy.

⇓

This aspect makes it possible to evaluate various types of operating logic quite quickly, calculating irradiation on plants and energy production.

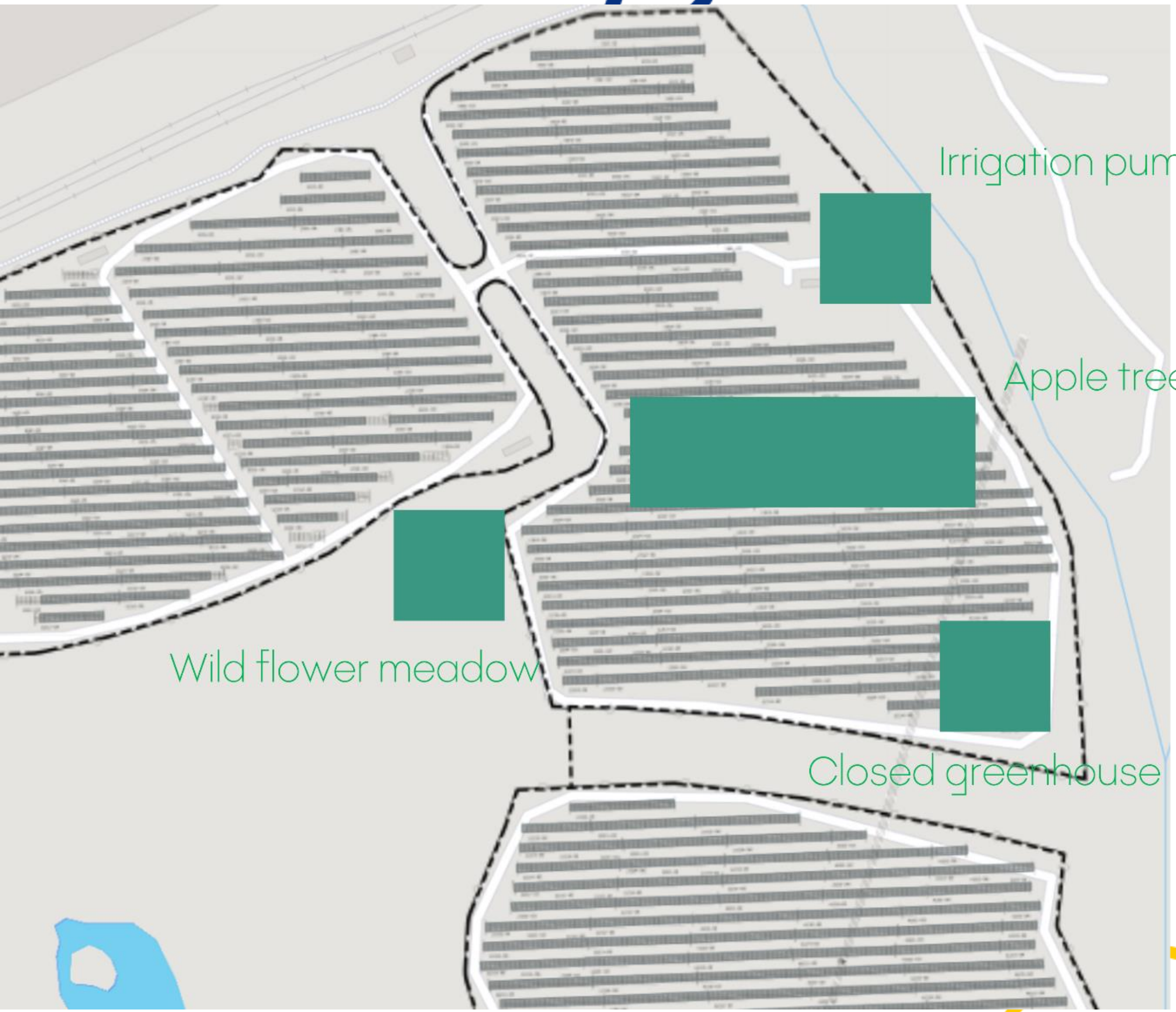
ABOVE

Methodology (4), Adding disciplinary contents to the visual analysis of the landscape, e.g. the Above’s agri-PV digital twin

- Above's digital twin software SolarGain is being developed to include agri-pv features.
- The patches are described as “agricultural patches”, and the tool is able to include in SolarGain (Above's digital twin software) some agri-pv features
- A list of agri-pv plant features is in the development phase in collaboration with UPC , such as: watering system, agricultural machinery, greenhouses, creeks, labelling for specific plantation areas (e.g. tomato, lettuce, zucchini, fava bean)

T2.1 Agri-PV Digital Twin

1. The image on the following slide slide introduces the agri-pv digital twin. Above's digital twin software SolarGain is being developed to include agri-pv features.
2. The diagram shows the digital twin of a solar plant in SolarGain (Above's digital twin software). The green squares represent some agri-pv features that Above is looking to integrate as "temporary layers". This is a web development task and is by no means straight-forward.
3. The list on the right was provided by UPC. It gives agri-pv plant features that UPC would like to see in a digital twin. Many of the features are already included in SolarGain. Features not yet included are watering system, agricultural machinery, greenhouses, creeks, labelling for specific plantation areas (e.g., tomato, lettuce, zucchini, fava bean).
4. Development of the agri-pv digital twin is ongoing. It requires coordination by Above’s Head of Product and a Business Analyst, who are gathering requirements from Above’s clients to ensure it is developed according to the needs of the wider market. They will prioritise the features that clients see as most important and useful in the efficient condition monitoring of an agri-pv plant.



Experimental field (with or without PV)

- **Landscape**
- **PV cells**
- **Agricultural field**
- **Watering system**
- **Sensors**
- **Dataloggers**
- **Living organisms (plants)**
- **Tomato**
- **Lettuce**
- **Zucchini**
- **Fava bean**
- **Agricultural Machinery**
- **Tractor**

Surroundings:

- **Landscape**
- **Bushes**
- **Trees**
- **Concrete buildings**
- **Other concrete features**
- **Road**
- **Greenhouses**
- **Creek**

Others:

- **Energy-related features**

Above is a list of Agri-PV plant features created by UPC

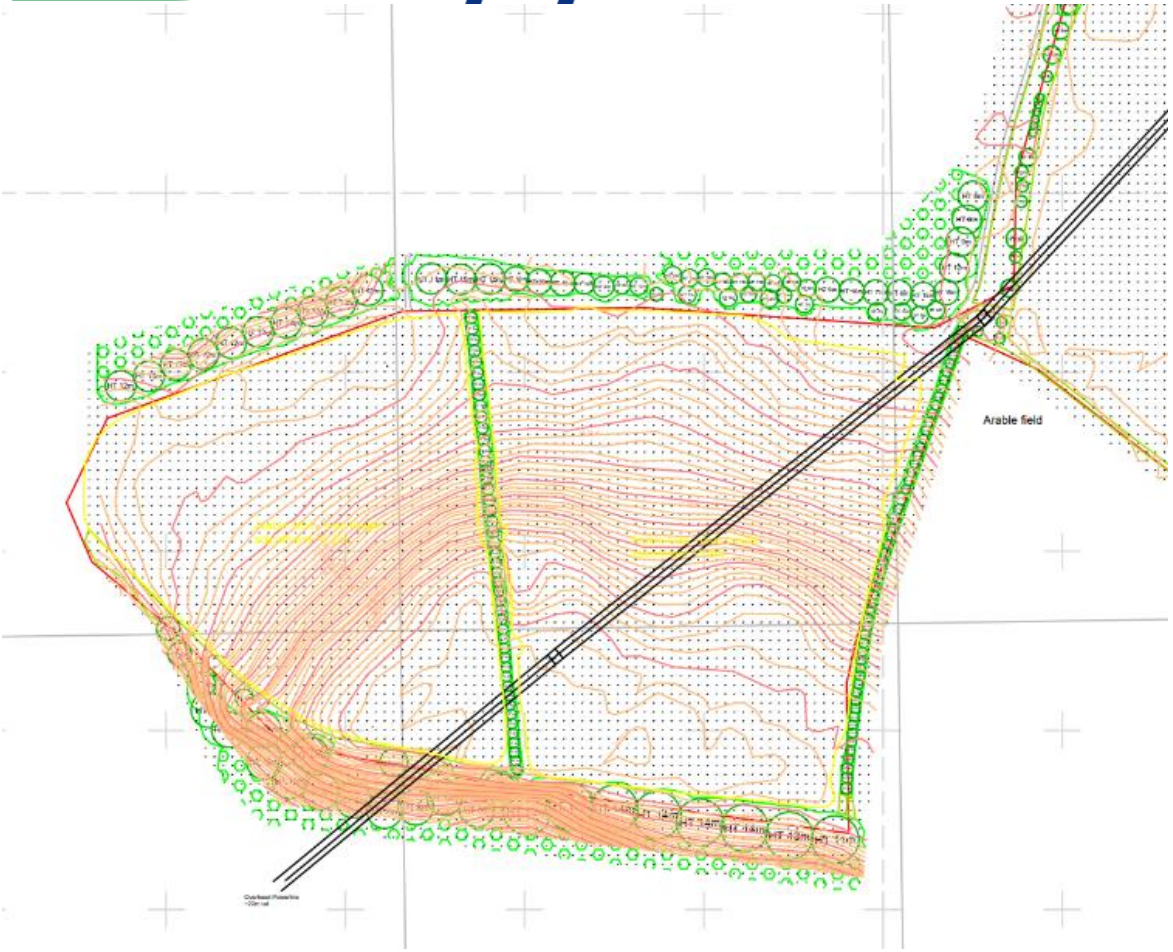
New features may be implemented as "temporary layers" in the digital twin SolarGain

Above automatically adds component names to the geojson during onboarding of the plant into SolarGain using CAD drawings – we will check whether this works for Agri-PV features

T2.1 Agri-Topography (Introduction)

1. The following slide introduces agri-topography and how line diagrams of an agri-pv site are created. The line diagrams are used in the detailed design of a plant, to ensure correct positioning of crops and other plantations, and the optimal spacing and tilt of rows of PV modules to maximise energy generation.
2. The image on the left of the slide shows a topography line diagram of an open field, containing land relief contours, trees, hedges, power lines.
3. The image on the right is an orthomosaic of thousands of aerial visual images taken by a drone at approx. 75m. These orthomosaics are used to generate the topography line diagrams.

T2.1 Agri-Topography (Introduction)



Example topo from a UK plant – line diagram - Contains contours, tree / feature heights - Feed into plant design and yield modelling

Orthomosaic of aerial visual images taken at the same UK plant as the image on the left – the aerial data feeds into the creation of the line diagram

T2.1 Agri-Topography Developments

1. The following slide shows the developments made to the agri-topography process to make it faster to implement and to make the line diagram more accurate. The photo shows a tree, hedgerows and land relief contour lines.
2. Tree heights used to be measured by hand in QGIS. By combining QGIS modules into an automation tool chain, the heights can now automatically be measured. Above has considered using this for measuring crop heights, but it would be extremely difficult, because crop fields tend to present as flat pieces of land, and it is difficult to find true ground reference points to use as the base of the crops.
3. Hedgerows used to be marked manually in QGIS. Above's CAD team now has access to the "array command" in AutoCAD. The user can now trace the mouse along the hedgerow and AutoCAD automatically marks the outline of the hedgerow.
4. Above is now in the process of implementing breaks in land relief contour lines – this will create a line diagram that shows agri-pv farm designers exactly where the land is available for solar array placement, by breaking the contour lines where there are trees, hedgerows, roads and other structures., plus existing crops and other plantations.

T2.1 Agri-Topography Developments

Tree heights for Lucisun/TUD/IMEC/EURAC/PVCase design software

- Automated measurement of tree heights using a selected set of QGIS modules combined into an automation tool chain
- CONSIDERING using for crop height, although very challenging as difficult to find reference points

Hedgerow marking

- Now using the "array command" in AutoCAD – we can now trace the mouse along the hedgerow and AutoCAD automatically marks the shape

Contour lines

- Implementing breaks in relief lines to better represent land under trees / structures / roads (allows designers to see where the land is available to place solar panels)

above

TU DELFT

EXTENDED DESCRIPTION: TU DELFT

WHAT: development of a multi-objective optimization tool for bifacial agri-PV systems that is specialized, but not limited to, orchards with customized PV modules.

OBJECTIVE: promoting the adoption of horticulture-based agri-PV systems featuring high-value crops with tall canopies that require protection from harmful weather conditions.

METHODOLOGY: the simulation framework consists of two parts. For irradiation modelling a raytracing-based approach was adopted to account for the complex interactions of light within such settings. Given the computationally intensive nature of such simulations,
a Bayesian optimization algorithm was utilized to obtain a set of promising solutions.

The tool has been applied on a specific case study as a preliminary demonstration of its capabilities.

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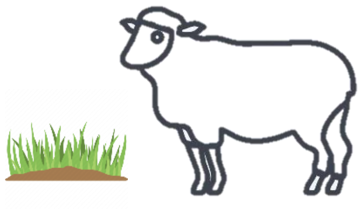
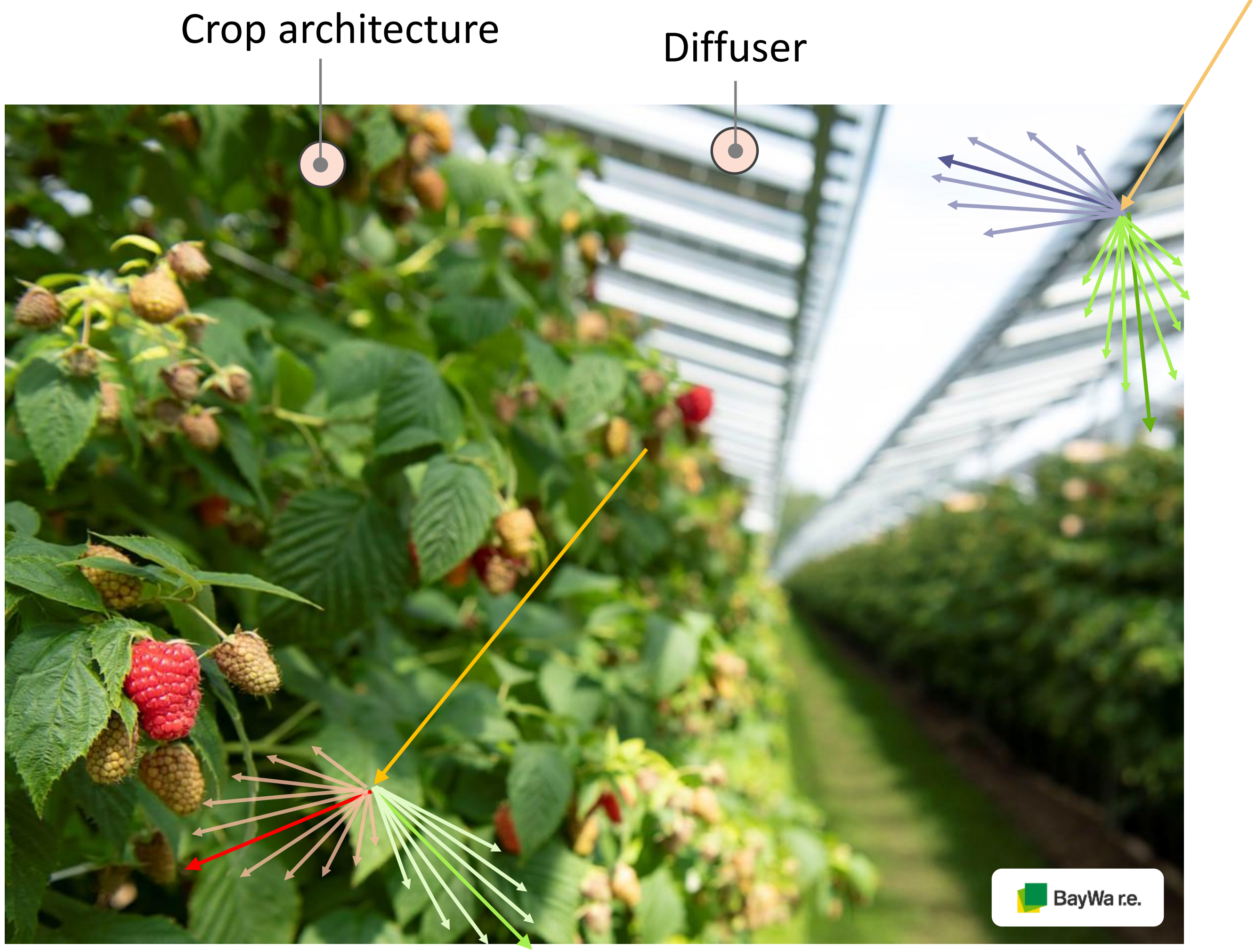
Taxonomy



System traits	Grazing	Vegetable farming	Orchards
Land potential	+++	++	+
Synergies	+	++	+++
PV design & modelling complexity	+	++	+++

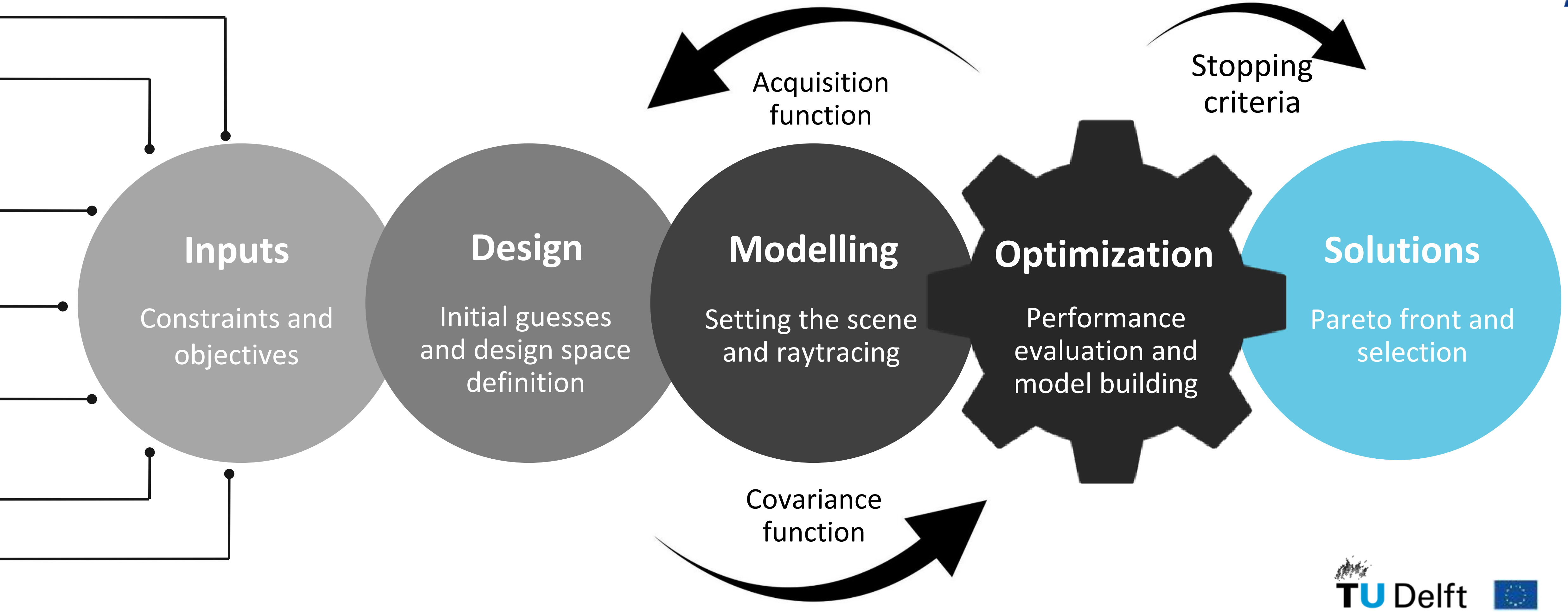
Orchards - irradiation modelling challenges

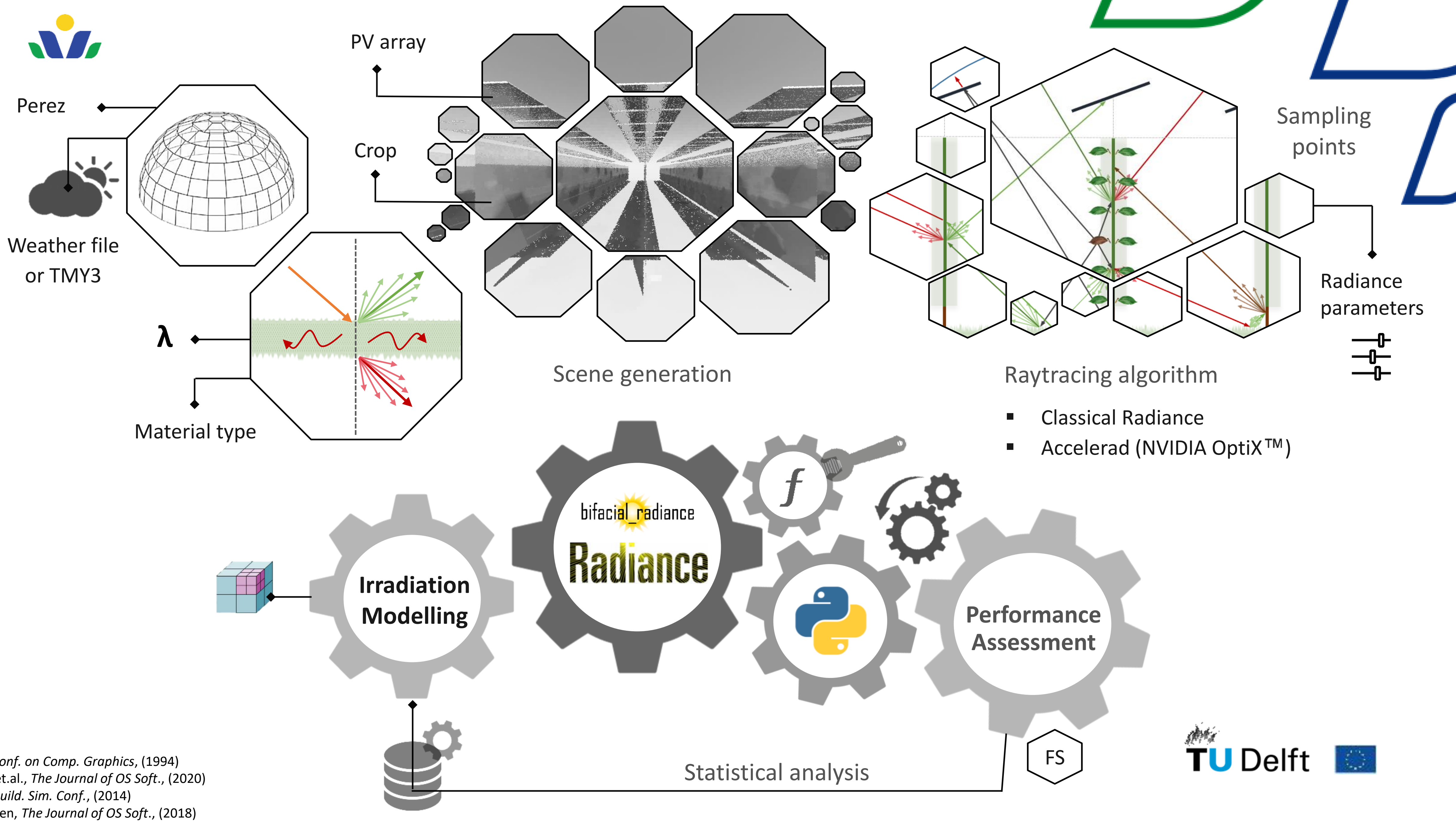


Current PV modelling software cannot account for the following:

- Detailed geometries
- Non-Lambertian surfaces
- Edge brightening effects

Simulation framework

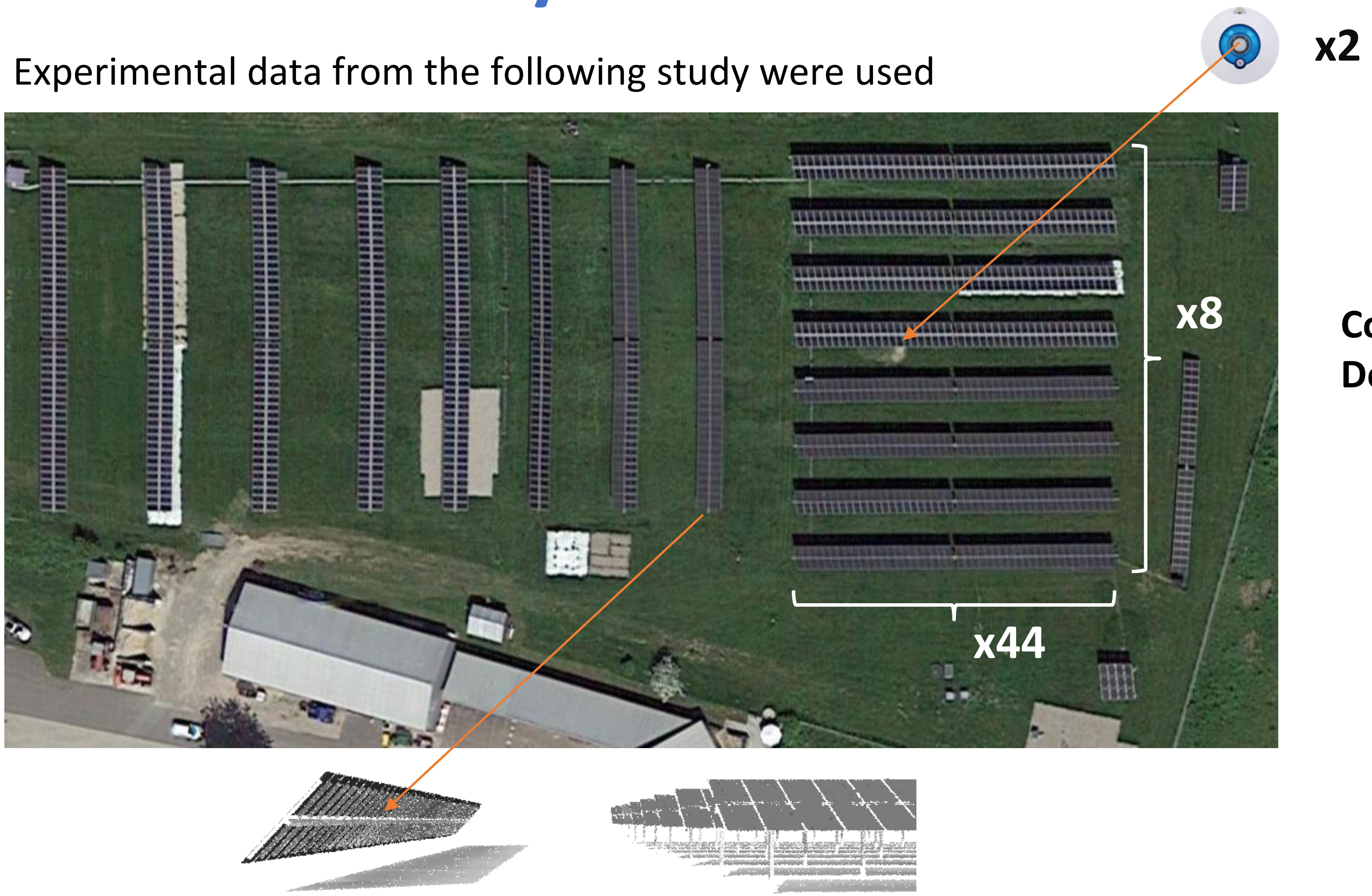




G. Ward, *Conf. on Comp. Graphics*, (1994)
S. Pelaez, et.al., *The Journal of OS Soft.*, (2020)
N. Jones, *Build. Sim. Conf.*, (2014)
W. Holmgren, *The Journal of OS Soft.*, (2018)

Validation study

Experimental data from the following study were used



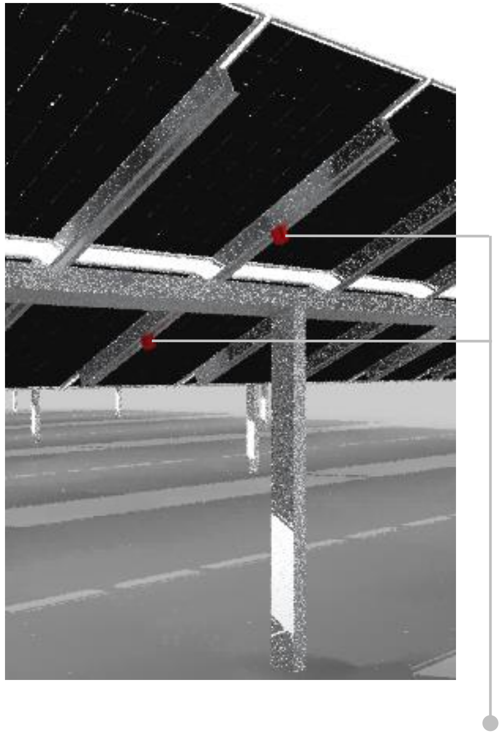
Copenhagen, Denmark

N. Reidel, et. al, Validation of Bif. PV Sim. Software, *Appl. Sci.* (2020)

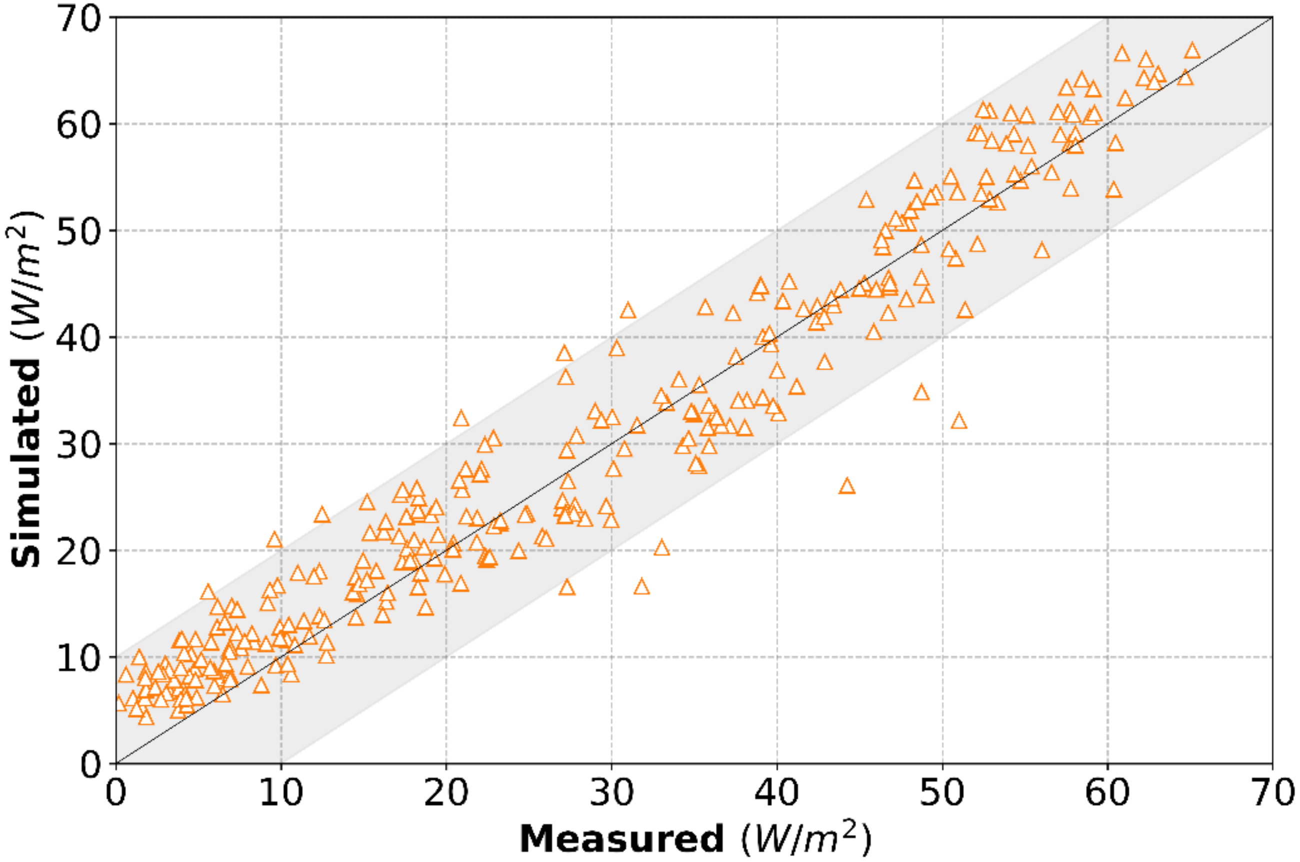
Hourly irradiance comparison

Mean Absolute Error: 4.2 W/m²

In agreement with literature



Pyranometer



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Case study – Apple orchard

Agri-PV

↓

Open

↓

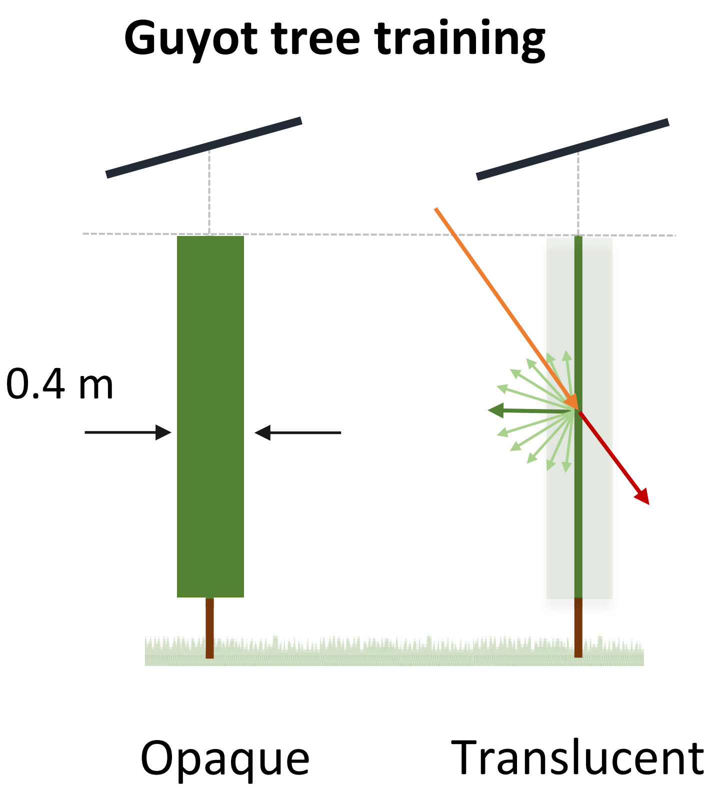
Overhead

Customised with fixed-tilt

Horticulture

Bolzano, IT

Geometrical modelling

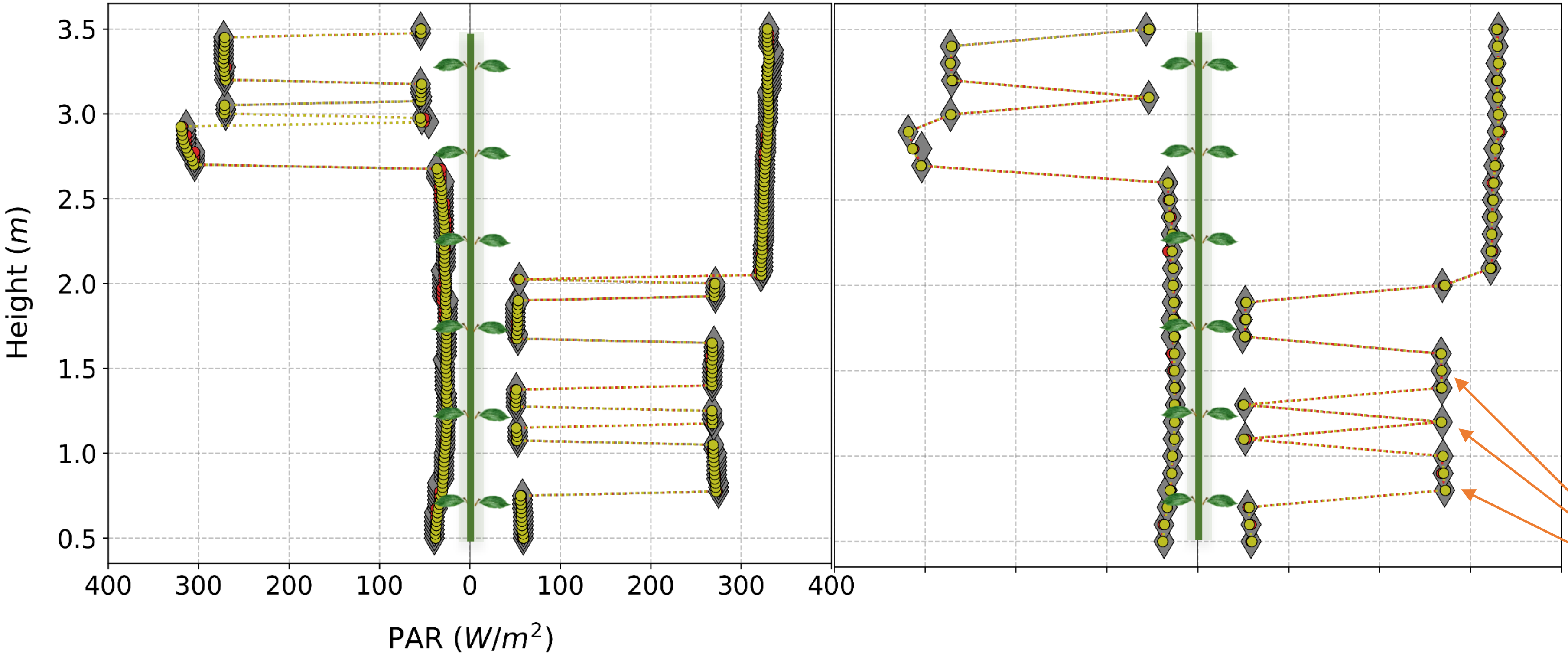


With this training system the orchard can be modelled in 2D as a thin translucent glass:

- Lambertian reflection
- Specular transmission

Following, light gradients along the height of the orchard will be displayed for various Radiance parameters and spatial resolutions under clear skies.

Light penetration profile – total leaf side



Simulation settings:

- Low
- Recommended
- High

Nearly identical results for all settings

Light leaks between cells

Lower spatial resolution with 10 cm spacing between sampling points (plot on the right) effectively captured light leaks between cells.

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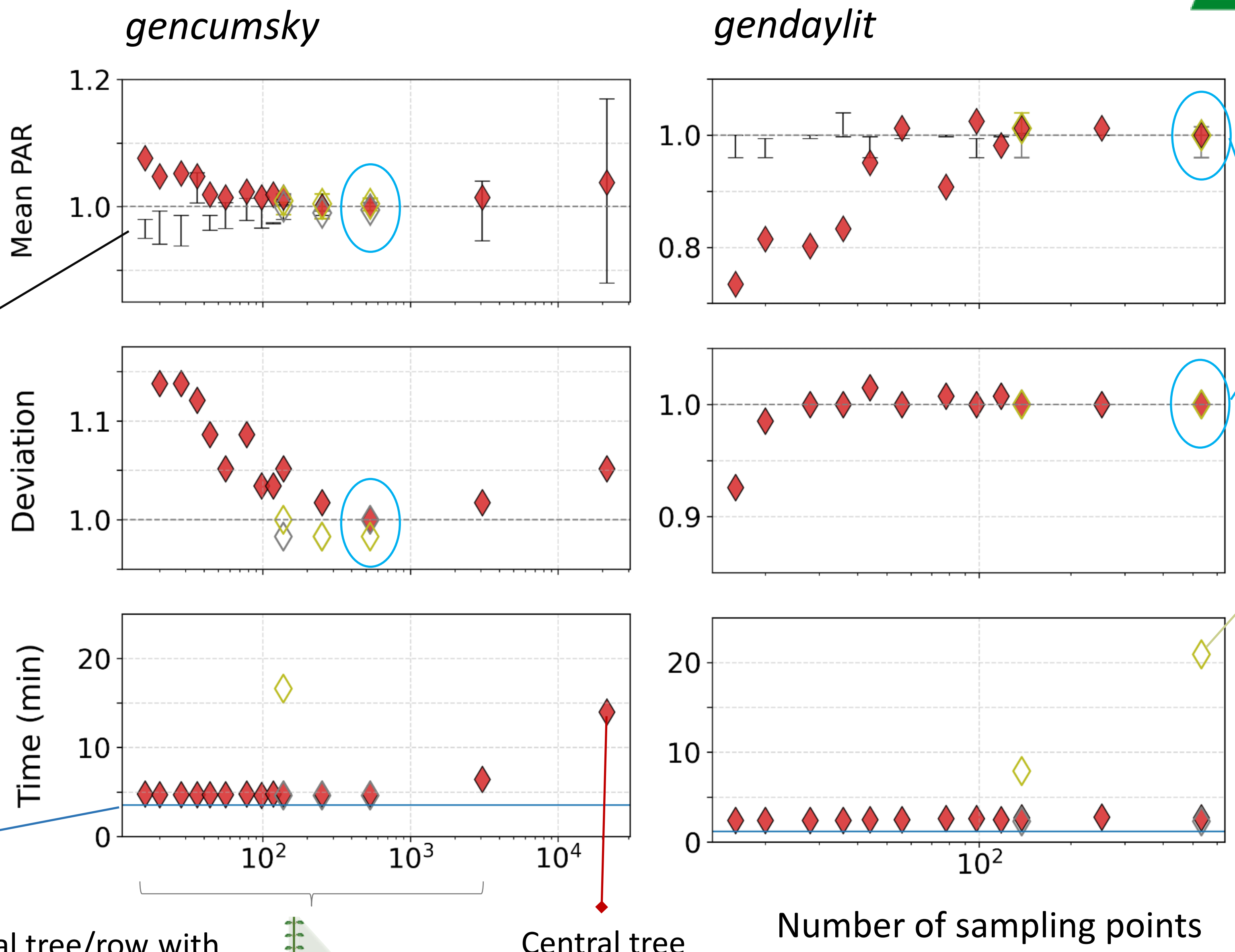


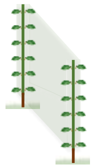
The bars represent the normalized min and max values

Normalized y-axis with respect to this point

High simulation settings

Average octree generation time

Central tree/row with varying spatial resolution



Central tree of every row within the farm

Sensitivity analysis

Explored the sensitivity of three parameters to the spatial resolution of light sampling points (virtual sensors) for two sky generation methods with an hourly, and a cumulative timestep, respectively.

Mean PAR represents the average illumination amongst all points sampled. Deviation represents the standard deviation in illumination amongst the sampling points.

- Mean PAR and deviation remain constant after a certain number of sampling points. However, due to the interpolation algorithm of Radiance, there is not any computational speed incentive in selecting a coarser spatial resolution.
- By sampling all rows a significant deviation in the min, max, and mean PAR as well as PAR deviation was observed. This signifies the importance of edge brightening effects.

Selection of optimization algorithm

Optimization workflows based on simulations with Radiance are computationally intensive due to the numerous design iterations required to identify the optimal agri-PV array configuration. Consequently, an efficient algorithm for exploring the design space is necessary.

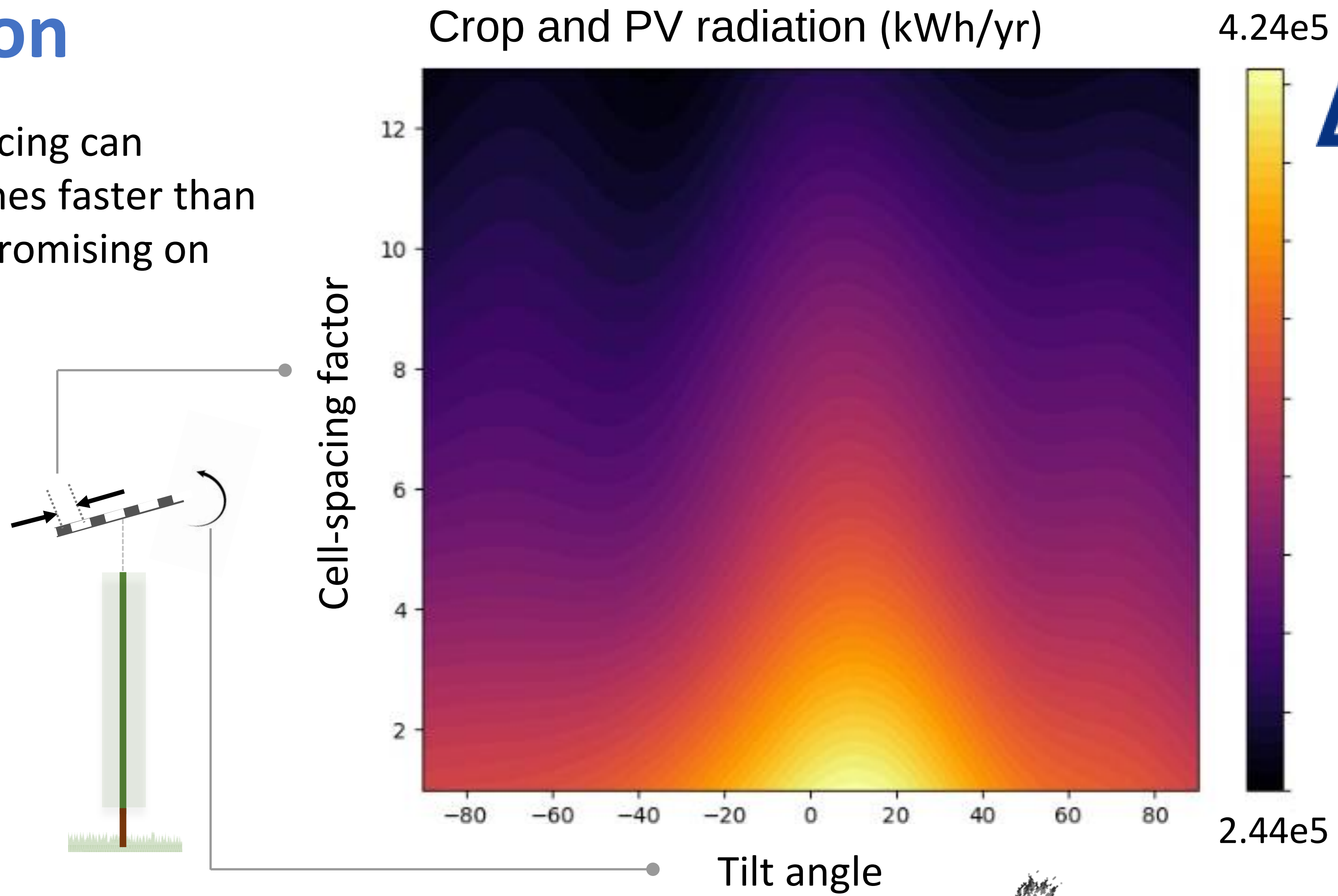
Unlike Evolutionary Algorithms and Particle Swarm Optimization, Bayesian optimization requires fewer iterations to reach a set of feasible solutions, known as the Pareto front.

Bayesian optimization is particularly suited for handling multiple objectives and is robust against noisy evaluations, a common characteristic of Monte Carlo-based raytracing simulations.

Design optimization

Gaussian process assisted raytracing can reproduce such heatmaps 15 times faster than classical Radiance without compromising on simulation accuracy.

- Crop radiation (400-700 nm)
- PV radiation (300-1200 nm)
- Bifaciality (100%)



Design space

TU Delft

Thank you!

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Partners

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