REGACE – Crop Responsive Greenhouse Agrivoltaics System with CO2 Enrichment for Higher Yields

Project Deliverable Report

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Executive Summary

This deliverable presents the environmental and economic aspects of the REGACE project. The study evaluates whether agri-voltaic greenhouses can simultaneously support renewable energy generation, maintain or improve crop productivity, and be economically feasible. Field experiments, surveys, and data analysis activities were conducted across five partner countries—Israel, Greece, Austria, Italy, and Germany—representing a range of climatic conditions and farming systems.

At the national level, agri-PV in greenhouses could contribute substantially to renewable energy goals—covering over 40% of projected PV targets in countries such as Israel, Romania, and Croatia, and about 23% on average in European countries.

Crop yield trials revealed a generally negative trend in productivity under PV panels compared to control greenhouses, with an average yield reduction of approximately 26.83%. CO_2 enrichment experiments did not offset shading effects but mitigated them so that the average yield reduction under PV was about 16%.

Monitoring of greenhouse pests and beneficial arthropods indicated that PV shading can influence pest populations, particularly mites, though the effects were species- and season-dependent.

Investment, installation, and maintenance aspects were analyzed using open-fields agri-PV projects as a benchmark. In open fields, mounting structures typically require reinforced concrete foundations and steel pillars, with investment costs averaging €1200/kW, in comparison to only € 912/kW (24% less) in REGACE technology. This is mainly due to the savings in the construction of a support system for the panels, which are hung on the greenhouse structure. The use of steel in open fields agri-PV leads to high carbon footprints, as the production of steel requires much energy. The mounting structure of agrivoltaics in open farmland consumes around 103 kg of iron, with a carbon footprint of 196 kg CO2/kW. In REGACE greenhouses, the mounting structure uses only about 48 kg of iron/kW, with a carbon footprint of 84 kg CO2/kW.

Surveys of farmers operating PV-integrated greenhouses highlighted a mixed perception: while 67% reported no significant impact on yields, some noted crop-specific or seasonal disadvantages. Most farmers (75–83%) observed no effect on product quality, pest pressure, or irrigation needs, suggesting that PV shading impacts are comparable to traditional shading practices already used in greenhouses.

The environmental and energy analyses demonstrated significant potential benefits of PV integration in greenhouses, for supplying on-farm energy from renewable sources. REGACE greenhouse systems achieved an average power density of 0.396 MW/ha, enabling renewable electricity production equivalent to or exceeding greenhouse electrical demands. However, heating requirements in colder climates limited the share of total energy covered to 20–33%. Emission reduction modeling showed that replacing 20% of greenhouse energy use with PV power could lower on-farm emissions by up to 7% in some countries.

In conclusion, REGACE demonstrates that integrating PV into greenhouses can deliver meaningful renewable energy production and climate benefits. The impacts on agricultural yields vary across crops, regions, and seasons, and can be partially mitigated through CO_2 enrichment. The findings highlight the importance of crop-specific strategies, technological innovation, and farmer engagement to optimize the synergies between food and energy production.

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Chapter 1 – Introduction

The objectives of this deliverable are:

Analysing and demonstrating the low environmental impact, and economic benefits, of the technology that is developed within the framework of REGACE. These objectives are divided into three chapters:

- Analysis of land impacts from PV systems
- Resource efficiency analysis
- Circularity potential analysis

The basic assumption is that environmental and economic impacts are interrelated and therefore can be analysed together. For example: land use has an impact on environmental aspects such as biodiversity and ecosystem services; and on economic aspects such as real estate and housing prices, or compensations that must be paid to farmers for using their land for other uses than agriculture. Efficient use of natural resources is an environmental goal and has economic aspects in lowering the costs of production. etc.

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Chapter 2 - Analysis of land impact from PV systems

Environmental impacts associated with solar energy include the large land requirements, specifically productive farmland, for installing utility-scale ground-based solar energy facilities, loss of wildlife habitat due to deforestation, bird mortality, visual pollution, use of chemicals to clean the panels, and water depletion (Pimentel Da Silva and Castelo Branco, 2018).

This chapter takes an overall view of land use analysis, and the impact of PV systems in the projects' partners' countries.

The questions that are addressed:

1. How much land is needed for PV systems to fulfill the respective countries goals for renewable energy, today and for the longer run (2030)?
2. How much farmland is there in the respective countries, and how is it divided between agricultural branches (field crops, plantations)? What is the land area of greenhouses?
3. What share of the farmland might turn into solar systems, if all were ground-based systems? How might this land use change effect the respective country's food security?
4. What is the potential for agri-voltaics? What is the share of farmland that can absorb agrivoltaic systems?
5. What is the potential for agri-voltaics in greenhouses? What share of the partner country's renewable energy goals can be fulfilled using agri-voltaic systems in greenhouses?
6. Comparison of the three technologies: ground mounted PV, Agri-PV in open fields and agri-PV in greenhouses; their land consumption and projected impact on farming.

Methodology

Literature study of the partners' countries goals for renewable energy, today and for the longer run.

Analysis of agricultural data of the partners' countries and selected European countries: size of farmland, of permanent crops (plantations) and greenhouses.

Calculation of the land needed for various PV systems to fulfill the respective countries goals for renewable energy, according to standard parameters of solar energy production.

Data sources

EU energy plans of recent years (since 2018); National renewable energy action plans of the participating countries.

FAO and EUROSTAT data regarding farmland.

Data of Israeli Ministries: Ministry of Agriculture, Ministry of Energy, Ministry of Environmental Protection.

Scientific publications and reports, as detailed in the References section.

Integration of the REGACE project findings.

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Results

Renewable energy goals in the partners countries

What are the renewable energy goals in the partners' countries, and specifically – the goals for solar energy development? How much land is needed for PV systems to fulfill the partner countries' goals for renewable energy?

As most of the partners' countries are members of the EU, the renewable policy of the EU will be described, following by the goals of specific countries.

The EU amended its renewable energy goals a few times in the last years. The Renewable Energy Directive 2018/2001/EU of 2018 established a binding target of at least 32% renewable energy for the EU for 2030, with a clause for a possible upwards revision by 2023 (European Commission, no date a; Directive (EU) 2018/2001). The directive was revised to meet the higher climate ambition set in the European Green Deal in December 2019. On May 2022 the Commission published the REPowerEU Plan, which proposed to increase the target to 45% renewable energy for the EU for 2030. This would bring the total renewable energy generation capacity (from all sources, including solar) to 1236 GW by 2030 (European Commission, 2022).

Directive (EU) 2023/2413 of 18 October 2023, which amends directive 2018/2001/EU, establishes a binding target of at least 42.5% renewable energy for the EU for 2030. However, it states that Member States shall collectively endeavor to increase the share of energy from renewable sources in 2030 to 45%.

Solar energy is one of the renewable energy technologies that are deployed in the EU, together with wind, hydropower, bioenergy etc. The REPowerEU Plan (European Commission, 2022) states that solar photovoltaics is one of the fastest renewable energy technologies to roll out, and therefore sets the target of almost 600 GW of newly installed solar photovoltaic capacity by 2030. The EU Solar Energy Strategy (European Commission, 2022) calls for an additional photovoltaic capacity of 450 GWp between 2021 and 2030, to reach the goal of 720 GWp by 2030 and several TWs by 2050 (Chatzipanagi et. al, 2023).

The following table presents the solar energy goals for the EU based on REPower EU and EU Solar Energy Strategy (both from 18 May 2022); and on summing up the individual goals of EU Member States (as detailed in the following table). As can be seen, the goals of the comprehensive EU policy plans are more ambitious than those taken on by the member states.

Table 1: Solar energy goals of the EU according to different policy papers

country / entity	goal for solar energy GW	to be achieved by (year)	Source of goal
EU	330	2025	EU Solar Energy Strategy
EU	730	2030	REPower EU and EU Solar Energy Strategy
EU	314	2030	Sum of the individual goals of the member states as detailed in the National Energy and Climate Plans (NECP) 2019
EU	592	2030	Sum of the individual goals of the member states that have new targets (more recent than NECP) + the individual goals of the member states that didn't change their goals from NECP 2019

Source of data: Chatzipanagi et al. 2023

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The individual solar energy goals of countries in the EU were published by each country within the framework of the country's National Energy and Climate Plan (NECP) in 2019. Since 2019, Several EU Member States have updated their goals, making them more ambitious, in accordance with the development of the EU renewable energy goals. Israel is the only REGACE partner that is not EU Member State. The renewable energy goal for Israel was set by Government Decision 456 of 25 October 2020. It sets a goal of producing 30% of all electricity from renewable sources, by 2030. Unlike European countries, the sources for renewable energy in Israel are limited mostly to solar energy, and some wind energy. The goal for solar energy production was set by the Israel Ministry of Energy on May 2022, within the framework of the Road Map to Renewable Energy in 2030 (Israel Ministry of Energy, 2022).
The following table presents the goals for solar energy for the partners countries and other European countries. The data is presented in order of the countries' population size (from large to small) the REGACE partner countries are highlighted in green. The updated goals for solar energy (for the countries who adopted them) are titled "New Policy Trends".

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Table 2: Goals for solar energy, 2030, the REGACE partner countries and selected Eurpean countries

Country	Goal for solar energy, GW, 2030	
	National Energy and Climate Plans (NECP) 2019	New Policy Trends (new targets that were announced by some countries, more recently than NECP)
Germany	70.51	215.00
France	25.00	47.30
Italy	51.12	72.00
Spain	44.00	92.00
Poland	7.30	30.00
Romania	5.89	
Netherlands	36.00	
Belgium	11.00	22.00
Czech Republic	3.98	
Greece	8.00	13.00
Hungary	6.00	6.50
Portugal	9.00	10.00
Sweden	2.50	3.5
Israel	17.1	
Austria	12.00	13.00
Bulgaria	2.90	3.20
Denmark	7.84	
Slovakia	1.20	
Finland	1.20	
Ireland	1.50	
Croatia	0.77	
Lithuania	1.53	
Slovenia	1.65	
Latvia	0.50	
Cyprus	0.80	
Estonia	0.42	
Luxembourg	1.11	
Malta	0.26	

Source for solar energy goals: EU countries: Chatzipanagi et al. 2023; Israel: Israel Ministry of Energy https://www.gov.il/he/departments/news/re_290522

Farmland and greenhouses

The production of solar energy requires a lot of land; although a portion of the solar energy can be produced in built-up areas (such as on roof tops), a large proportion of it is, and will be, produced in large, utility size plants, in open spaces. Due to physical convenience, and in some places - regulatory preference, in many countries solar plants are built on farmland. This highlights the competition and conflict over land use, since farmland is needed for another, equally important goal – the production of food. In the wake of the Covid-19 pandemic, the Russia-Ukraine war, and the recent crisis over the Red Sea international transportation – many countries aspire to strengthen both their independent food security and energy supply.

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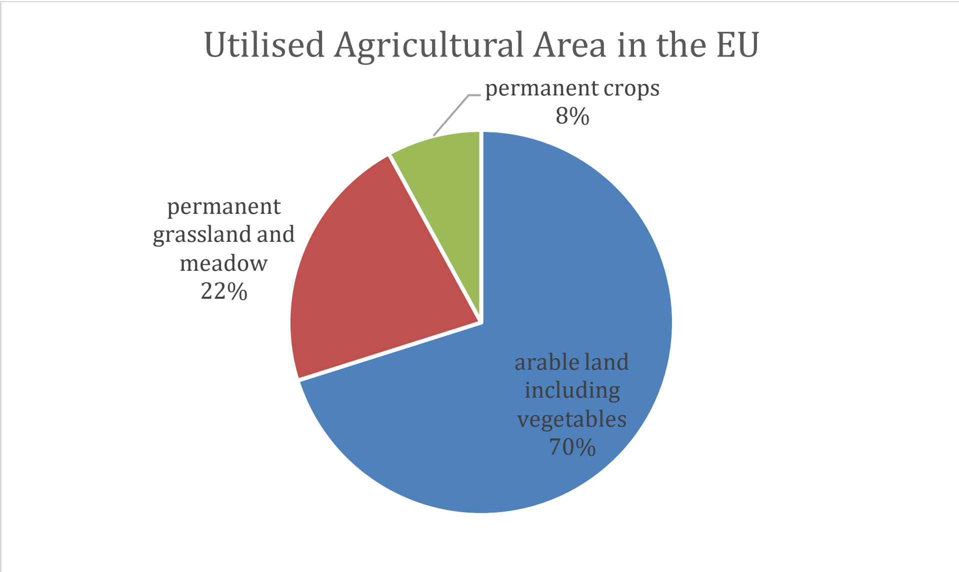
To portray the potential conflict between food security and renewable energy production in detail, the basic database will be set: How much farmland is there in the REGACE partner countries? What are its characteristics and main agricultural use?
As REGACE project develops a technology that will allow production of solar energy in greenhouses, data on the use of greenhouses in agriculture in the partners' countries and other European countries was examined in more details, including trends in recent years.
The following chart presents the Utilised Agricultural Area (UAA)[1] in the EU, and its components: Arable land[2]; Permanent grassland and meadow; and permanent crops (plantations). On average, 70% of the UAA of the EU is arable land, 8% are permanent crops and 22% are permanent grassland and meadow.

Figure 1: Farmland in the EU



Source: Analysis of data of EUROSTAT, https://ec.europa.eu/eurostat/databrowser/view/ef_lus_allcrops__custom_8818851/default/table?lang=en

The following table presents the UAA and its components for EU countries and Israel. The data is presented in order of the countries' population size (from large to small) the REGACE partner countries are highlighted in green.

[1] The Utilised Agricultural Area (UAA) is defined as the area used for farming. It includes the following categories: arable land; permanent grassland; permanent crops; other agricultural land such as kitchen gardens (gardens that are used for production of food for self-consumption). The term does not include unused agricultural land, woodland and land occupied by buildings, farmyards, tracks, ponds, etc (source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Utilised_agricultural_area_(UAA) , retrieved 29.12.2023).
[2] Arable land is defined as land worked (ploughed or tilled) regularly, generally under a system of crop rotation. Includes, among other crops, fresh vegetables, strawberries, flowers and ornamental plants (source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Arable_land, retrieved 29.12.2023)

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Table 3:Farmland in the EU, 2020, the REGACE partner countries and selected Eurpean countries

country / entity	Utilised Agricultural Area	arable land	permanent grassland and meadow	permanent crops
		ha		
Germany	16,578,460	11,663,800	4,489,010	198,170
France	27,364,630	17,039,400	7,768,520	1,032,480
Italy	12,041,230	7,197,650	1,456,400	2,177,860
Spain	23,913,680	11,714,690	1,778,380	4,662,880
Poland	14,749,240	11,147,160	2,777,770	379,970
Romania	12,762,830	8,570,730	2,922,020	343,930
Netherlands	1,817,900	1,008,180	694,440	37,310
Belgium	1,368,120	869,280	473,260	22,730
Czech Republic	3,492,570	2,476,710	647,900	37,640
Greece	2,822,890	1,501,060	154,450	839,290
Hungary	4,921,740	4,027,970	9,240	158,170
Portugal	3,963,940	1,036,680	585,910	860,660
Sweden	3,005,810	2,538,170	415,650	4,120
Israel	515,050	262,530	164,000	88,520
Austria	2,602,670	1,322,910	789,620	67,710
Bulgaria	4,564,150	3,318,400	734,710	101,310
Denmark	2,629,930	2,373,420	143,690	28,650
Slovenia	483,440	173,050	239,490	28,300
Slovakia	1,862,650	1,325,330	459,870	17,590
Finland	2,281,710	2,255,680	13,970	3,690
Ireland	4,498,990	1,209,770	2,837,510	1,750
Croatia	1,231,500	887,960	154,570	76,170
Lithuania	2,914,550	2,237,320	558,790	26,900
Latvia	1,968,960	1,333,290	230,750	7,580
Estonia	975,320	692,860	245,880	4,120
Cyprus	134,140	102,240	1,350	29,480
Luxembourg	132,140	62,310	68,080	1,570
Malta	9,800	7,780	0	950
Total EU	155,598,240	98,348,550	30,815,230	11,238,550

Source for EU countries: EUROSTAT, https://ec.europa.eu/eurostat/databrowser/view/ef_lus_allcrops__custom_8818851/default/table?lang=en Sources for Israel: for arable land and permanent crops: Israel Central Bureau of Statistics, census of agriculture 2017; https://www.cbs.gov.il/he/mediarelease/DocLib/2020/269/07_20_269b.pdf; source for permanent grassland and meadow: FAOSTAT "permanent meadows and pastures", 2021. There are some differences between the definitions of the EU and of Israel / the FAO, that should be considered.

REGACE develops a technology that will allow production of solar energy in greenhouses. Therefore, data on the use of greenhouses in agriculture in the partners' countries was summarized.
The following table presents data on the land size of "cropland under protective cover" / "under glass" (greenhouses, glasshouses, shade houses) in the REGACE

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partners' countries and other European countries (including non-EU members). The REGACE partner countries are highlighted. The table presents the most recent data that is available, for the years 2015-2021. The table present data from two main sources (FAOSTAT and EUROSTAT), which are mostly compatible with each other. The table presents the total area of cropland[3] in each country, and the ratio of cropland under protective cover of the total cropland area. The data is presented in order of the greenhouse' size in country (from large to small).

[3] Cropland is defined by the FAO as: Land used for cultivation of crops. The total of areas under "arable land" and "permanent crops". https://www.fao.org/faostat/en/#data/RL

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Table 4: Greenhouses in REGACE partner countries and selected European countries

Country	Cropland area under protective cover, Ha	year	source for cropland area under protective cover	Total agricultural area (cropland), ha, 2020, source: FAOSTAT	% Cropland area under protective cover of total cropland
Total European countries (for which data is available)	141,402	different years	different sources	276,037,348	0.05%
Spain	43,540	2016	EUROSTAT	16,646,395	0.26%
Italy	28,310	2016	EUROSTAT	9,384,570	0.30%
Israel	11,959	2023	GIS of the Israeli Ministry of Agriculture	406,743	2.94%
France	10,300	2016	EUROSTAT	18,970,540	0.05%
Netherlands	10,080	2020	FAOSTAT compatible with EUROSTAT	1,042,040	0.97%
Poland	7,000	2020	FAOSTAT compatible with EUROSTAT	11,530,000	0.06%
Ukraine	6,000	2021	FAOSTAT	33,777,000	0.02%
Germany	5,600	2020	FAOSTAT compatible with EUROSTAT	11,862,000	0.05%
Greece	5,250	2016	EUROSTAT compatible with FAOSTAT	3,220,160	0.16%
Romania	4,200	2021	FAOSTAT compatible with EUROSTAT	8,886,000	0.05%
Russian Federation	3,800	2021	FAOSTAT	123,442,000	0.00%
Portugal	2,310	2016	FAOSTAT	1,840,970	0.13%
United Kingdom	2,290	2016	EUROSTAT	6,023,596	0.04%

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Country	Cropland area under protective cover, Ha	year	source for cropland area under protective cover	Total agricultural area (cropland), ha, 2020, source: FAOSTAT	% Cropland area under protective cover of total cropland
Belgium	2,080	2016	EUROSTAT	888,490	0.23%
Hungary	2,000	2020	FAOSTAT compatible with EUROSTAT	4,184,136	0.05%
Albania	1,880	2021	FAOSTAT	687,555	0.27%
Bulgaria	1,600	2018	FAOSTAT compatible with EUROSTAT	3,644,000	0.04%
Switzerland	737	2021	FAOSTAT	425,037	0.17%
Lithuania	700	2021	FAOSTAT	2,284,800	0.03%
Croatia	620	2016	EUROSTAT	968,000	0.06%
Austria	590	2020	FAOSTAT compatible with EUROSTAT	1,392,685	0.04%
Finland	400	2020	FAOSTAT compatible with EUROSTAT	2,248,000	0.02%
Cyprus	370	2016	EUROSTAT	125,392	0.30%
Denmark	350	2020	FAOSTAT compatible with EUROSTAT	2,397,582	0.01%
Sweden	300	2020	FAOSTAT compatible with EUROSTAT	2,542,030	0.01%
Ireland	270	2016	EUROSTAT	445,000	0.06%
Slovenia	190	2021	FAOSTAT compatible with EUROSTAT	233,950	0.08%
Norway	181	2021	FAOSTAT	807,663	0.02%
Malta	110	2016	EUROSTAT	9,110	1.21%

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Country	Cropland area under protective cover, Ha	year	source for cropland area under protective cover	Total agricultural area (cropland), ha, 2020, source: FAOSTAT	% Cropland area under protective cover of total cropland
Estonia	107	2021	FAOSTAT compatible with EUROSTAT	699,000	0.02%
Latvia	100	2021	FAOSTAT compatible with EUROSTAT	1,343,000	0.01%
Slovakia	90	2016	EUROSTAT	1,364,000	0.01%
Iceland	15	2020	FAOSTAT	121,000	0.01%
Luxembourg	6	2021	FAOSTAT	63,685	0.01%

The data sources are: FAOSTAT (Item: "cropland area under protective cover") and EUROSTAT (dataset: Under glass by NUTS 2 regions [ef_lus_unglass__custom_7828380][4])
Some countries are presented only in one of the sources; when only one source is listed in the table – it means that the country is listed only in this source. When the data of the two sources were not compatible, the most recent information is presented. When the data of the sources was not compatible, and both relate to the same year – the information of the EUROSTAT is presented.
The source for Israel: greenhouses: Israeli Ministry of Agriculture GIS database, 2022. Total agricultural area: Israeli Ministry of Agriculture GIS database, 2024.

[4] The data in the table is a sum of the data for: Fresh vegetables (including melons) and strawberries - under glass or high accessible cover; flowers and ornamental plants (excluding nurseries) - under glass or high accessible cover; and permanent crops under glass or high accessible cover. Source: Under glass by NUTS 2 regions [ef_lus_unglass__custom_7828380]

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As can be seen, Spain and Italy are the leading European countries in absolute size of cropland under protective cover. Israel is third in line. For half of the countries in the database, the area of cropland under protective cover is small (under 1,000 ha). The average ratio of cropland under protective cover of the total cropland area is 0.05%. The leading European country in this parameter is The Netherlands, in which 0.97% of the cropland is under protected cover. In Israel the ratio is much higher than in the European countries: 2.94% of the cropland is under protected cover.
Analyzing the trends in the development of greenhouses over the years 2015-2021 allows us to assess the future development of greenhouses in REGACE partner countries and other European countries. The trends are detailed in the following 3 charts: the first chart details the European countries, and Israel, where greenhouse area increased in 2015-2021; the second chart details the European countries where greenhouse area decreased in 2015-2021; and the third chart details the European countries where greenhouse area was stable during that period. All the charts are based on the data of FAOSTAT.

Figure 2: European countries, and Israel, where greenhouse area increased in 2015-2021

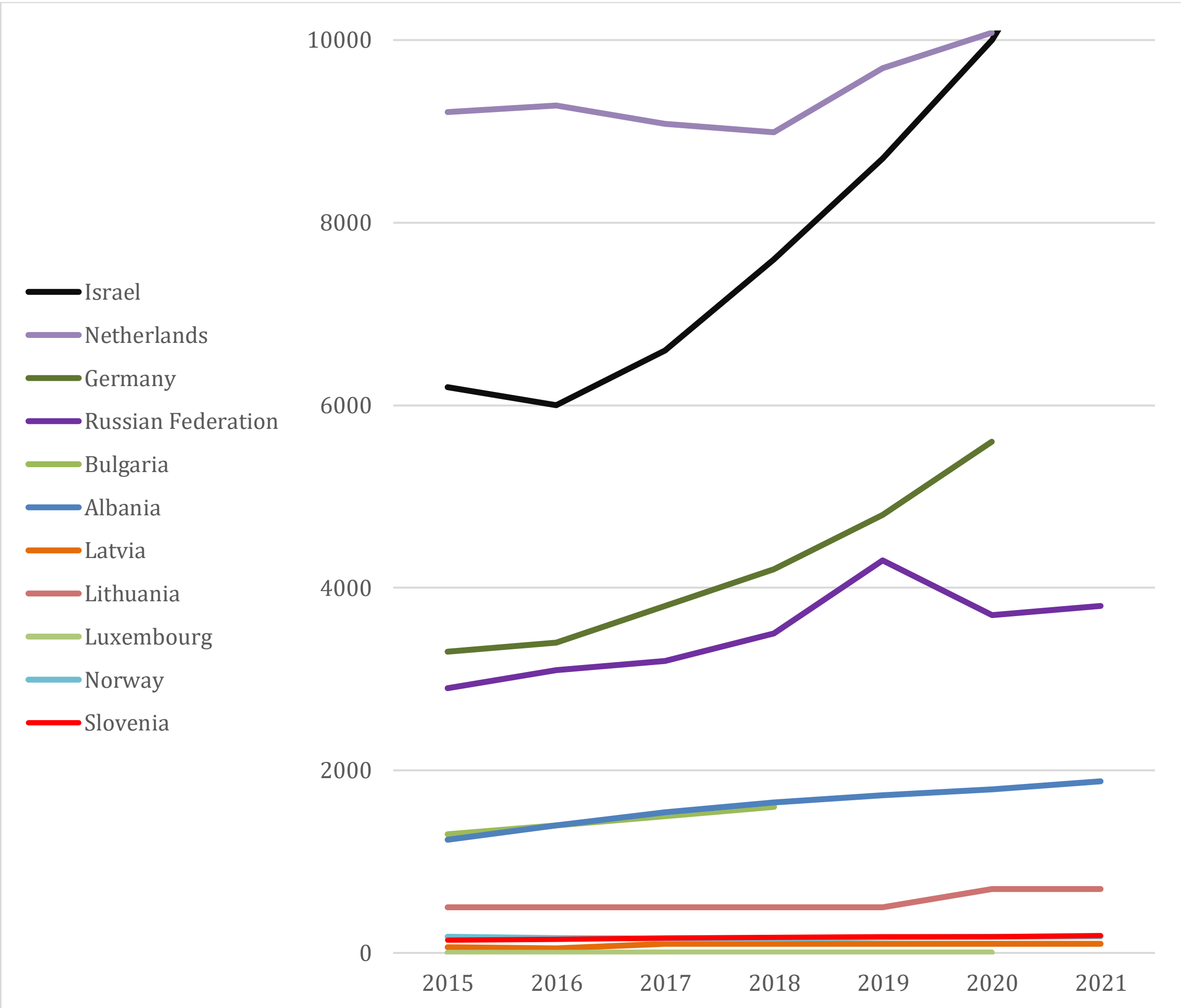

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Figure**3** : European countries where greenhouse area decreased in 2015-2021

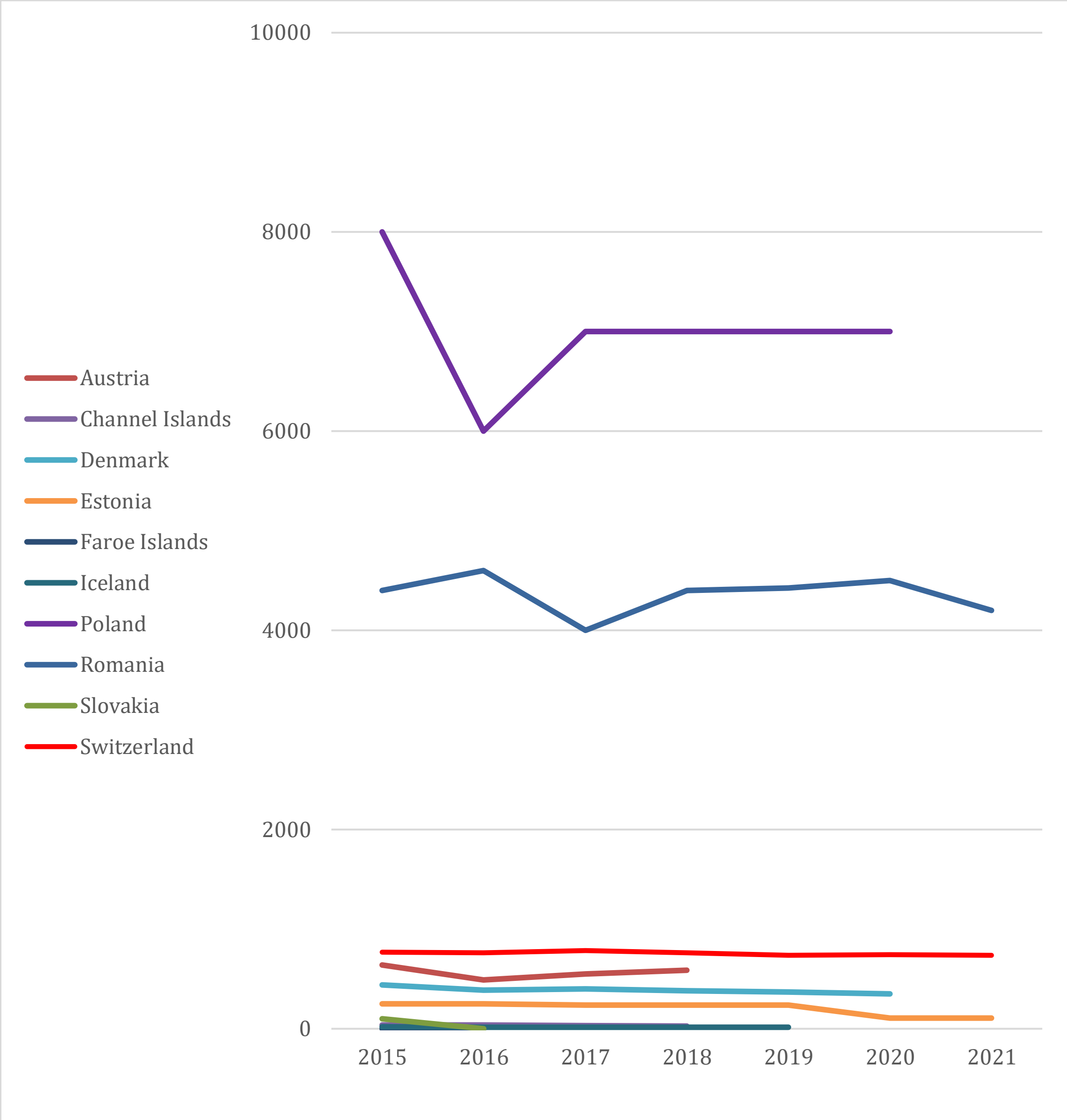

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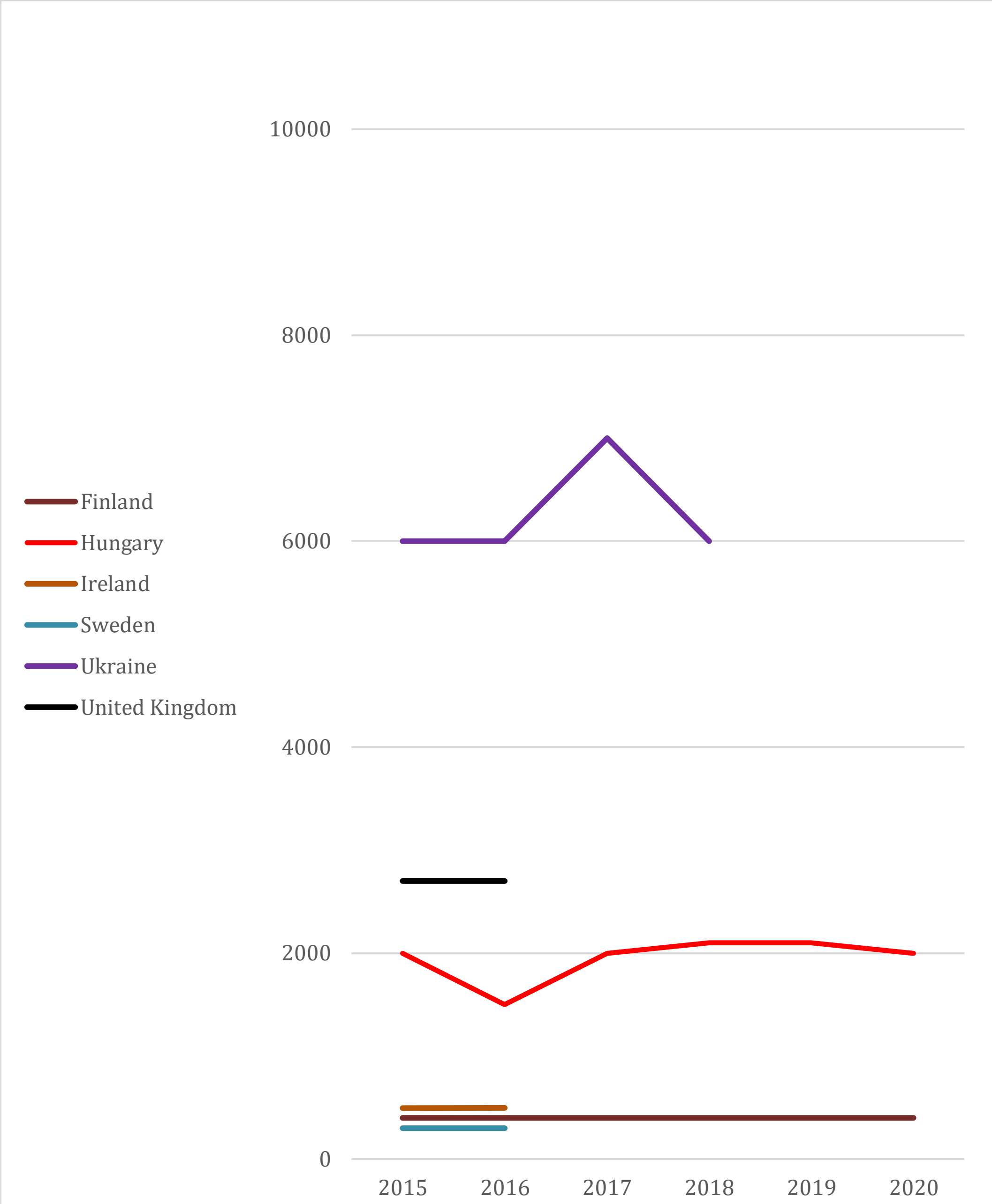
Figure**4** : European countries where greenhouse area didn't change between 2015 and 2021



As can be seen, in 10 European countries (the Netherlands, Germany, Russian Federation, Bulgaria, Albania, Latvia, Lithuania, Luxemburg, Norway and Slovenia), and in Israel, the total area of greenhouses increased during the years 2015-2021. In 10 European countries and areas, the total area of greenhouses decreased during the years 2015-2021 (although in 8 of them the decrease was not large). In 6 European countries the total area of greenhouses either did not change during the years 2015-2021 or increased and decreased so that the area in 2015 resembles that of 2021.

Use of farmland for solar energy production

The technologies harnessing renewable energy sources are characterized by a power density lower than fossil fuels. Therefore, the transition to these energy sources is

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expected to intensify the global competition for land, against goals such as food security (the need for farmland) and biodiversity protection (the need for conservation of land for nature reserves).

Farmland is becoming scarce all over the world. Due to housing, industrial and infrastructure development, as well as soil degradation and desertification, farmland is expected to decrease globally by between 50-650 million hectares by 2100 (Schindele et al., 2020). A recent study (van de Ven et. al. 2021) showed that in some cases, ground mounted solar expansion actually leads to more carbon emissions. For example, emissions related to vegetation loss if forest and scrubland makes place for solar-land, either directly through deforestation for the solar project, or through conversion of cropland into solar-land in one place which indirectly leads to clearing forests for farmland elsewhere, in order to compensate for the farmland and the food production that was lost.

As food security and sustainable energy are equally important goals, the potential for conflict between them should be addressed in detail. The following investigates the questions:

- What share of farmland in the partner countries might turn into solar energy plants, in the form of conventional ground-based systems, to fulfill their respective solar energy goals?
- And how might this land use change affect the respective country's food security?

As of 2023, existing utility-scale ground mounted PV systems use about 100,000 ha in the EU (Chatzipanagi et. al, 2023), which are about 0.064% of the Utilised Agricultural Area in the EU. In 2020, ground mounted PV systems covered 0.07% of Germany's arable land (about 11,000 ha), however the goal was to double the capacity and nearly double the use of arable land for ground mounted PV systems by 2021 (Schindele et al., 2020). In Israel, in 2021, about 2,700 ha were covered by ground mounted PV systems (analysis of GIS layers of Survey of Israel, 2023), which amounts to about 0.52% of the Utilised Agricultural Area in Israel (9 times more than in the EU, in relative terms to the total amount of farmland); the total size of solar-land in Israel can reach about 10,300 ha of ground mounted PV systems which will amount to about 2% of the Utilised Agricultural Area in Israel (Decision of Israel's National Council for Planning and Building of 6 June 2023). It should be considered that renewable energy in Israel is based mainly on solar systems, whereas in the EU there are additional renewable energy sources.

A recent study (van de Ven, 2021) point to 0.5- 5.2% of the total territory (not only farmland) of the EU that will need to be occupied by ground based solar systems by 2050[5]. The following table presents the estimated size of land that could be occupied by solar energy plants in Europe in 2050, according to this study. The estimations relate to different scenarios of solar penetration levels (% of solar production in the electricity mix) and solar modules efficiency.

[5] Note that this study is based on old estimations (from the years 2013 and 2017) of and land use efficiency. A recent study (Bolinger and Bolinger, 2022) showed that the actual power density is on average higher. This means that the land size necessary for ground based solar systems is probably smaller than presented in the table.

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Table 5: Estimated size of land that will be occupied by solar energy plants in the EU in 2050. Ranges show results for different future solar module efficiencies with left values representing 28% efficiency and right values 20%.

Scenarios of solar energy in the electricity mix by 2050	Occupation of land suitable for commercial purposes by 2050*	Relative solar land occupation by 2050	
% of total electricity produced by solar facilities	Solar energy, 1000 km^2	% of total land area	Compared to crop area in 2050 (%)
26%	21-28	0.5-0.7	1.9-2.5
53%	53-69	1.3-1.7	4.8-6.3
79%	85-111	2.1-2.8	7.7-10

Source: van de Ven et al. 2021.
*The "land suitable for commercial purposes" means cropland, pasture and commercial forests. Rooftop PV and land not suitable for commercial purposes (such as dry scrubland not suitable for cultivation) was excluded.

When looking into the potential conflict between solar energy systems and farmland, one should consider that a portion of the solar energy can be produced in urban areas, mainly on rooftops. The estimated share of solar energy that can be produced in urban areas differs between places and sources. van de Ven et. al. (2021) estimates it between 7.6% and 24.3% for the EU in 2025 (the larger the % of solar penetration in the electricity mix – the smaller is the estimated % of rooftop PV generation). Chatzipanagi et. al. (2023) estimates that approximately 50% of the nominal capacity goal of the EU in 2030 will be installed on roofs, in urban areas, on brownfield sites and on infrastructure; the rest will be deployed as ground mounted system in agricultural areas. As for Israel, the Ministry of Energy (2022) and the Ministry of Environmental Protection (2023) estimated that about 35% of the future capacity can be installed on rooftops. The Ministry of Environmental Protection (2023) estimated that 52% can be installed in non-farmland (on top of water reservoirs, and in areas that were designated for industrial development, that wasn't fulfilled).
To understand the potential for farmland occupation by solar plants, one should "translate" power density to land size. An assessment of ground mounted systems' power density gave an average of 0.87 MWp/ha for solar plants that were built in the USA between 2011-2019 (Bolinger and Bolinger, 2022). However, in other studies, a power density of 1.15 MWp/ha is considered characteristic for traditional ground-mounted PV (Chatzipanagi et. al, 2023). In a recent field study, a power density of 1.5 MWp/ha was reached (de Ruijter at al. 2023). It should be considered that the median energy density for utility scale PV plants in the USA increased by 25-33% from 2011 to 2019 (Bolinger and Bolinger, 2022), and further improvements in efficiency are possible; this means that in the future less land will be required to reach renewable energy goals.
The following table presents the estimates of the area needed to fulfill solar energy goals of the partner countries and EU countries, by using ground mounted PV. A ratio of 35% rooftop installation was deducted. The power density of ground mounted PV

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systems was calculated at 0.87, 1.15 and 1.5 MW/ha (according to Bolinger and Bolinger 2022; Chatzipanagi et al. 2023; and de Ruijter et al. 2023). The data is presented in order of the countries' population size (from large to small) the REGACE partner countries are highlighted in green.

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Table 6: Goals for solar energy, 2030, the REGACE partner countries and selected Eurpean countries, and the land size that will be needed to fulfil them using ground mounted solar systems (35% rooftop installation was deducted)

Country	Goal for solar energy GW, 2030		Area for ground mounted PV, 2030 (ha) power density 0.87 MW/ha		Area for ground mounted PV, 2030 (ha) power density 1.15 MW/ha		Area for ground mounted PV 2030, (ha) power density 1.5 MW/ha	
	National Energy and Climate Plans (NECP) 2019	New Policy Trends*	National Energy and Climate Plans (NECP) 2019	New Policy Trends	National Energy and Climate Plans (NECP) 2019	New Policy Trends	National Energy and Climate Plans (NECP) 2019	New Policy Trends
Germany	70.51	215.00	52,680	160,632	39,853	121,522	30,554	93,167
France	25.00	47.30	18,678	35,339	14,130	26,735	10,833	20,497
Italy	51.12	72.00	38,193	53,793	28,894	40,696	22,152	31,200
Spain	44.00	92.00	32,874	68,736	24,870	52,000	19,067	39,867
Poland	7.30	30.00	5,454	22,414	4,126	16,957	3,163	13,000
Romania	5.89		4,401		3,329		2,552	
Netherlands	36.00		26,897		20,348		15,600	
Belgium	11.00	22.00	8,218	16,437	6,217	12,435	4,767	9,533
Czech Republic	3.98		2,974		2,250		1,725	
Greece	8.00	13.00	5,977	9,713	4,522	7,348	3,467	5,633
Hungary	6.00	6.50	4,483	4,856	3,391	3,674	2,600	2,817
Portugal	9.00	10.00	6,724	7,471	5,087	5,652	3,900	4,333
Sweden	2.50	3.5	1,868	2,615	1,413	1,978	1,083	1,517
Israel	17.10		12,776		9,665		7,410	
Austria	12.00	13.00	8,966	9,713	6,783	7,348	5,200	5,633
Bulgaria	2.90	3.20	2,167	2,391	1,639	1,809	1,257	1,387
Denmark	7.84		5,857		4,431		3,397	
Slovakia	1.20		897		678		520	

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Finland	1.20		897		678		520	
Ireland	1.50		1,121		848		650	
Croatia	0.77		575		435		334	
Lithuania	1.53		1,143		865		663	
Slovenia	1.65		1,233		933		715	
Latvia	0.50		374		283		217	
Cyprus	0.80		598		452		347	
Estonia	0.42		314		237		182	
Luxembourg	1.11		829		627		481	
Malta	0.26		194		147		113	

Source for solar energy goals: EU countries: Chatzipanagi et al. 2023; Israel: Israel Ministry of Energy https://www.gov.il/he/departments/news/re_290522
* Targets that were announced by some countries, more recently than NECP.

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How might ground-mounted solar energy development impact food security?
The following table compares the area required for ground mounted PV systems to the size of farmland in the REGACE partner countries. Different agricultural land uses are considered. Note that the potential % of coverage of PV systems for different land area categories is calculated for each category for its own (e.g. as if all the solar systems are mounted only on cropland or only on grassland). That is because in some countries, the regulatory framework direct solar energy facilities to certain types of farmlands (for example, in Israel solar energy plants are usually directed to cropland, rather than to grassland).

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Table 7: Potential % coverage of ground mounted systems for different farmland categories, based on solar energy goals, REGACE partner countries

country	PV goal 2030 GW[1]	Area needed for ground mounted PV according to the PV goal ha[2]	Current size of farmland, ha			Potential coverage of ground mounted PV systems, % for different farmland categories		
			Utilised agricultural area ha[5]	cropland ha[3]	Permanent grassland and meadow ha[4]	Utilised agricultural area %	Cropland %	Permanent grassland and meadow %
Germany	215.0	160,632	16,699,580	11,862,000	4,620,980	1.0%	1.35%	3.5%
Italy	72.0	53,793	12,098,890	9,384,570	3,316,430	0.4%	0.57%	1.6%
Greece	13.0	9,713	4,856,780	2,811,203	2,102,380	0.2%	0.35%	0.5%
Israel	17.1	12,776	516,000	406,743	164,000	2.5%	3.14%	7.8%
Austria	13.0	9,713	2,726,890	1,392,685	1,296,270	0.4%	0.70%	0.7%

Source of data for European countries, for PV goals, size of Utilised Agricultural Area, cropland and permanent grassland and meadow: Chatzipanagi et al. 2023

1 Source: For EU countries: NECP PV 2030 or more recent goals (if existing). For Israel: Ministry of Energy https://www.gov.il/BlobFolder/news/re_290522/he/roadmap_reference_2030.pdf

2 Assumed installed capacity of 0.87 MW/ha; assumed 65% of ground mounted PV in electricity mix.

3 Source for European countries: FAOSTAT 2020 Source for Israel: Israel Central Bureau of Statistics, census of agriculture 2017; farmland includes field crops, permanent crops and greenhouses, https://www.cbs.gov.il/he/mediarelease/DocLib/2020/269/07_20_269b.pdf

4 Source for Israel: FAOSTAT "permanent meadows and pastures", 2021

5 for Israel: sum of cropland + Permanent grassland and meadow

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As can be seen, in Israel, ground mounted PV systems have the highest coverage potential: they could cover about 2.5% of the total utilized agricultural area. Given that the population growth rate in Israel is about 1.9% per year; that food imports amount for about 80% of the local food supply (Amdur, 2020); and that about 1,200 ha of farmland is lost each year for urbanization (Hamaarag, 2022) – this additional loss of farmland for solar systems can have a severe effect on food security.
In the European countries, the coverage potential is between 1% (in Germany) and 0.2% (in Greece) of utilized agricultural area. This could also have some effect on food security.
The impact of ground mounted solar plants on food security can also be estimated by assessing the number of people that that land could have fed. These can be calculated as the projected agricultural yield * the land size / the recommended consumption per person-year.
The yield of various types of crops is detailed in FAOSTAT (the database of the FAO). The average yields for the EU-27[6] are:

- Cereals: 5260 kg/ha
- Fruit: 12,279 kg/ha
- Vegetables: 32,546 kg/ha
-

The recommended amount of various types of foodstuffs that an adult person should consume per day was calculated by the United State Department of Agriculture (USDA, 2011) at:

- Cereals: 200 gr/day = 77.5 kg/year
- Fruit: 200 gr/day = 77.5 kg/year
- Vegetables: 300 gr/day = 109.5 kg/year

[6] For simplicity, the calculation will be done according to the average yields in the EU-27; note that the average yields in Israel are different.

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Table 8: production potential of land that could turn into solar plants and the number of people it could feed, based on solar energ y goals, REGACE partner countries

country	PV goal 2030 GW[1]	Land needed for ground mounted PV according to the PV goal ha[2]	The production potential (kg/year) of the land if it was used for[3]:			Number of people the land could have fed if it was used for production of[4]:		
			Cereals	Fruit	Vegetables	Cereals	Fruit	Vegetables
Germany	215.0	160,632	844,925,287	1,972,402,586	5,227,935,057	10,902,262	25,450,356	47,743,699
Italy	72.0	53,793	282,951,724	660,525,517	1,750,750,345	3,650,990	8,522,910	15,988,588
Greece	13.0	9,713	51,088,506	119,261,552	316,107,701	659,207	1,538,859	2,886,828
Israel	17.1	12,776	67,201,034	156,874,810	415,803,207	867,110	2,024,191	3,797,290
Austria	13.0	9,713	51,088,506	119,261,552	316,107,701	659,207	1,538,859	2,886,828

1 Source: For EU countries: NECP PV 2030 or more recent goals (if existing), Chatzipanagi et al. 2023. For Israel: Ministry of Energy https://www.gov.il/BlobFolder/news/re_290522/he/roadmap_reference_2030.pdf			
2 Assumed installed capacity of 0.87 MW/ha; assumed 65% of ground mounted PV in electricity mix.			
3 yields of cereals EU	5260	kg/ha	source: FAOSTAT
yields of fruit EU	12279	kg/ha	source: FAOSTAT
yields of vegetables EU	32546	kg/ha	source: FAOSTAT
4 recommended consumption of cereals	77.5	kg/person/year	
recommended consumption of fruit	77.5	kg/person/year	
recommended consumption vegetables	109.5	kg/person/year	

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As can be seen, the number of people that could have been fed, if land that might be used for solar plants would have stayed in its agricultural use, is substantial. In Germany, it is about 11 million people (if the land was used for cereals) to about 48 million (if the land was used for vegetables). This illustrates the impact solar plants development can have on food security.

The potential for agrivoltaics

Agrivoltaics constitute an alternative to ground-mounted solar systems. Agrivoltaics allow for both food and energy production on the same parcel of land ("dual land use"). On the same piece of land, solar energy as well as food and feed crops can be harvested at the same time, which reduces competition for arable land and contributes to more efficient land use (Fraunhofer ISE, 2021).

There are several forms for Agrivoltaics implementation: the most common is by building a construction over the farmland, where solar panels are installed over the crops. Another form is by installing vertical panels in agricultural fences, or fence-like constructions on fields.

In some countries, agrivoltaics is becoming a preferred alternative to ground mounted PV plants. For example, in Israel, Government Decision 456 of 25 October 2020 has instructed several ministries and authorities to examine steps that will encourage the establishment of renewable electricity production facilities in dual use of land (e.g. agrivoltaics).

What may be the effect of agrivoltaics on farmland? And can it reduce the conflict on land use between food and energy production?

A recent study (Chatzipanagi et. al, 2023) found that using 1% of the EU's Utilised Agricultural Area[7] for Agri-PV systems could allow 1 TW of PV capacity, well above the recent targets for solar energy of the EU. The same study found that the obtained range for the power density of a wide variety of realized Agri-PV projects is between 0.2-0.9 MW/ ha. The study assumed a value of 0.6 MW/ha.

The following table presents the goals for solar energy for the REGACE partner countries and other European countries, and estimates of the area needed to fulfill these goals by using ground mounted PV plants, and by using agri-voltaics. A ratio of 35% rooftop installation was deducted. The power density of ground mounted PV systems was calculated at 0.87 MW/ha (according to Bolinger and Bolinger 2022; and Chatzipanagi et al. 2023) and the power density of agri-viltaic systems at 0.6 MW/ha (in line with Chatzipanagi et al. 2023). The data is presented in order of the countries' population size (from large to small) the REGACE partner countries are highlighted in green.

[7] The Utilised Agricultural Area (UAA) describes the area used for farming. It includes the following categories: arable land; permanent grassland; permanent crops; other agricultural land such as kitchen gardens. The term does not include unused agricultural land, woodland and land occupied by buildings, farmyards, tracks, ponds, etc (data.europa.eu, 17.11.2023).

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Table 9: Goals for solar energy, 2030, the REGACE partner countries and selected Eurpean countries, and the land size that will be needed to fulfill them using ground mounted solar systems and agri-voltaic systems

Country	goal for solar energy GW	goal for solar energy GW	Area for ground mounted PV 2030 (ha), power density 0.87 MW/ha		Area for agri- PV 2030 (ha), power density 0.6 MW/ha	
	National Energy and Climate Plans (NECP) 2019	New Policy Trends (new targets that were announced by some countries, more recently than NECP)	National Energy and Climate Plans (NECP) 2019	New Policy Trends	National Energy and Climate Plans (NECP) 2019	New Policy Trends
Germany	70.51	215.00	52,680	160,632	76,386	232,917
France	25.00	47.30	18,678	35,339	27,083	51,242
Italy	51.12	72.00	38,193	53,793	55,380	78,000
Spain	44.00	92.00	32,874	68,736	47,667	99,667
Poland	7.30	30.00	5,454	22,414	7,908	32,500
Romania	5.89		4,401		6,381	
Netherlands	36.00		26,897		39,000	
Belgium	11.00	22.00	8,218	16,437	11,917	23,833
Czech Republic	3.98		2,974		4,312	
Greece	8.00	13.00	5,977	9,713	8,667	14,083
Hungary	6.00	6.50	4,483	4,856	6,500	7,042
Portugal	9.00	10.00	6,724	7,471	9,750	10,833
Sweden	2.50	3.5	1,868	2,615	2,708	3,792
Israel	17.1		12,776		18,525	
Austria	12.00	13.00	8,966	9,713	13,000	14,083
Bulgaria	2.90	3.20	2,167	2,391	3,142	3,467
Denmark	7.84		5,857		8,493	
Slovakia	1.20		897		1,300	

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Finland	1.20		897		1,300	
Ireland	1.50		1,121		1,625	
Croatia	0.77		575		834	
Lithuania	1.53		1,143		1,658	
Slovenia	1.65		1,233		1,788	
Latvia	0.50		374		542	
Cyprus	0.80		598		867	
Estonia	0.42		314		455	
Luxembourg	1.11		829		1,203	
Malta	0.26		194		282	

Source for solar energy goals: EU countries: Chatzipanagi et al. 2023; Israel: Israel Ministry of Energy https://www.gov.il/he/departments/news/re_290522

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The following table compares the area required for agri- PV systems to the size of farmland in the REGACE partner countries. Different agricultural land uses are considered. Note that the potential % of coverage of agri-PV systems for different land area categories are calculated for each category for its own (as if all the solar systems are mounted only on cropland or only on grassland). As stated before, in some countries some land uses are preferred for the conversation to solar (for example, in Israel usually cropland is converted to solar, not grassland).
Although the land size of agri-voltaic systems is about 45% larger than that of ground mounted solar systems, one should consider that a substantial proportion of the agricultural production can be sustained under agri-voltaic systems, whereas in areas of ground-mounted solar systems – there is no agricultural production. This reduces the impact that solar energy can have on food security, although it does not eliminate it altogether.
The impact of agrivoltaics on food security arises from the fact that agricultural yields are lower under agrivoltaics in comparison to standard fields or plantation without agrivoltaics. This is due to higher amount of shade that is created by the solar panels over the plants, and a portion of the farmland that is used for the solar facility, for example the foundations of the structure that holds the panels over the agricultural plants.

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Table 10: Potential area percentage coverage of Agri-PV systems for different land area categories with regards to solar energy goals with assumed installed capacity of 0.6 MW/ha ; and comparison to ground mounted systems

			potential % of coverage of Agri-PV systems for different land area categories			Potential coverage of ground mounted PV systems, % for different farmland categories		
country	PV goal 2030 GW[1]	Area for agri-PV according to the PV goal ha[2]	utilised agricultural area %	Cropland %	Permanent grassland and meadow %	utilised agricultural area %	Cropland %	Permanent grassland and meadow %
Germany	215	232,916	1.4%	2.0%	5.0%	1.0%	1.4%	3.5%
Italy	72	78,000	0.6%	1.2%	2.4%	0.4%	0.8%	1.6%
Greece	13	14,084	0.3%	0.8%	0.7%	0.2%	0.5%	0.5%
Israel	17.1	18,525	3.6%	5.3%	11.3%	2.5%	3.6%	7.8%
Austria	13	14,084	0.5%	1.0%	1.1%	0.4%	0.7%	0.7%

1 Source: For EU countries: NECP PV 2030 or more recent goals (if existing), Chatzipanagi et al. 2023. For Israel: Ministry of Energy https://www.gov.il/BlobFolder/news/re_290522/he/roadmap_reference_2030.pdf

2 Assumed installed capacity of 0.6 MW/ha; assumed 65% of Agri PV in electricity mix (35% rooftop solar installations).

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The potential for agrivoltaics in greenhouses

REGACE project develops technology of integrating solar panels into greenhouses. The panels are hung over the agricultural plants inside the greenhouse. Energy production on greenhouse rooftops, or inside greenhouses, does not consume any ground space, as it is the greenhouse itself that occupies farmland (Carreño-Ortega, 2017).

Integrating solar panels over the roof top of a greenhouse, using a separate frame structure or integrating the panels directly into the roof surface, is an established technology (although not yet practiced widely in some countries; for example, there are only 2 greenhouse agri-PV sites out of 383 sites in the USA, in the NREL database for 2023; Staie, 2023). The innovation of REGACE lies, among other things, in installing the panels inside the greenhouses, which allows us to use the structure of the greenhouse itself as a structural frame for the panels.

Like agrivoltaics, PV facilities in greenhouses mitigate the competition over land between energy and crop production. The REGACE technology for agrivoltaics in greenhouses is expected to mitigate this competition to larger degree than other agrivoltaics technologies, as it avoids the need to use a portion of the farmland for the foundations of the solar frame structure.

However, as seen in a previous chapter, in many countries, greenhouses occupy a small fraction of the farmland. This brings about the question: can greenhouses contribute to achieving solar energy goals in a substantial way? What share of the country's renewable energy goals can be fulfilled using agrivoltaics in greenhouses?

The average power density of the REGACE installations is 0. 396 MW/ha, as detailed in the following table. The ground cover rate is around 30%.

Table 11: Power density in REGACE installations

Site	**System size m2**	**System size kW**	**System power density kw / 1,000 m2**
Italy, Fattoria Solidale del Circeo farm	100	4.8	53
Germany, Bio-Gärtnerei Watzkendorf GmbH	384	16	32
Israel, Triangle Research and Development Center	280	12.4	44.3
Austria, University of Natural Resources and Life Sciences, Vienna	42	1.32	43.2
Germany, Humboldt University	151.2	3.78	25.3
Greece, University of Thessaly	400	16	40
Average			**39.63**

A survey of greenhouses in Israel where solar systems are installed found that such systems can be installed at a power density of 0.5 MW/ha.

The following table presents the goals for solar energy for the REGACE partner countries and other European countries, and estimates of the area needed to fulfill these goals by using agrivoltaics in greenhouses. A ratio of 35% rooftop installation was deducted. The power density of agri-PV systems in greenhouses was calculated at 0.365

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MW/ha and 0.5 MW/ha. The total area of greenhouses in each country is given, the source is as detailed in table 4 in sub-section 1.2 above. The % of area needed for solar energy that could be covered by agri PV in greenhouses is calculated, and the data is presented according to this parameter, from large to small. The REGACE partner countries are highlighted in green.

As can be seen, the range of the potential for agri-PV in greenhouses to contribute to countries' renewable energy goals is large. It comes up to as much as 62% in Croatia, and to as little as 0.4% in Luxemburg. It depends on the ambition of the country's renewable goals and the prevalence of greenhouses. On average, for the countries considered here, agri-PV in greenhouses can cover about 23% of the PV energy goals.

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Table 12: Goals for solar energy, 2030, the REGACE partner countries and selected Eurpean countries, the land size needed to fulfill them using agri-voltaic systems in greenhouses, and the % that could be covered by agri PV in greenhouses. Power density of 0.365 MW/ha, as in the average of REGACE installations

country	PV goal 2030 GW[1]	Area needed for agri-PV in greenhouses (REGACE technology) to fulfil the PV goal ha[2]	greenhouse area, ha[3]	% of area needed for agri PV that could be covered by agri PV in greenhouses
Croatia	0.77	1,263	620	49.09%
Romania	5.89	9,661	4,200	43.48%
Israel	17.1	28,047	11,959	42.64%
Bulgaria	3.2	5,249	1,600	30.48%
Spain	92	150,896	43,540	28.85%
Cyprus	0.8	1,312	370	28.20%
Lithuania	1.53	2,509	700	27.89%
Malta	0.26	426	110	25.79%
Greece	13	21,322	5,250	24.62%
Italy	72	118,092	28,310	23.97%
Finland	1.2	1,968	400	20.32%
Hungary	6.5	10,661	2,000	18.76%
Netherlands	36	59,046	10,080	17.07%
Estonia	0.42	689	107	15.53%
Poland	30	49,205	7,000	14.23%
Portugal	10	16,402	2,310	14.08%
France	47.3	77,580	10,300	13.28%
Latvia	0.5	820	100	12.19%
Ireland	1.5	2,460	270	10.97%
Slovenia	1.65	2,706	190	7.02%
Belgium	22	36,084	2,080	5.76%
Sweden	3.5	5,741	300	5.23%
Slovakia	1.2	1,968	90	4.57%
Austria	13	21,322	590	2.77%
Denmark	7.84	12,859	350	2.72%
Germany	215	352,637	5,600	1.59%
Luxembourg	1.11	1,821	6	0.33%
Average for the countries considered				18.20%

1 source: for EU countries: NECP PV 2030 or more recent goals (if existing) Chatzipanagi et al. 2023 1 for Israel: Ministry of Energy https://www.gov.il/BlobFolder/news/re_290522/he/roadmap_reference_2030.pdf
2 assumed installed capacity of 0.396 MW/ha; source: average of REGACE installations. Assumed % of agri PV in electricity mix (versus rooftop PV) 65%
3 sources: As detailed in table 4 in sub-section 1.2 of this report; the data is for the most recent year available

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Table 13: Goals for solar energy, 2030, the REGACE partner countries and selected Eurpean countries, the land size needed to fulfill them using agri-voltaic systems in greenhouses, and the % that could be covered by agri PV in greenhouses. Power density of 0.5 MW/ha, as is potentially attainable for greenhouses

Country	PV goal 2030 GW[1]	Area needed for agri-PV in greenhouses according to the PV goal ha[2]	greenhouse area, ha[3]	% of area needed for agri PV that could be covered by agri PV in greenhouses
Croatia	0.77	1,001	620	61.94%
Romania	5.89	7,657	4,200	54.85%
Israel	17.1	22,230	11,959	53.80%
Bulgaria	3.2	4,160	1,600	38.46%
Spain	92	119,600	43,540	36.40%
Cyprus	0.8	1,040	370	35.58%
Lithuania	1.53	1,989	700	35.19%
Malta	0.26	338	110	32.54%
Greece	13	16,900	5,250	31.07%
Italy	72	93,600	28,310	30.25%
Finland	1.2	1,560	400	25.64%
Hungary	6.5	8,450	2,000	23.67%
Netherlands	36	46,800	10,080	21.54%
Estonia	0.42	546	107	19.60%
Poland	30	39,000	7,000	17.95%
Portugal	10	13,000	2,310	17.77%
France	47.3	61,490	10,300	16.75%
Latvia	0.5	650	100	15.38%
Ireland	1.5	1,950	270	13.85%
Slovenia	1.65	2,145	190	8.86%
Belgium	22	28,600	2,080	7.27%
Sweden	3.5	4,550	300	6.59%
Slovakia	1.2	1,560	90	5.77%
Austria	13	16,900	590	3.49%
Denmark	7.84	10,192	350	3.43%
Germany	215	279,500	5,600	2.00%
Luxembourg	1.11	1,443	6	0.42%
Average for the countries considered				22.97%

1 source: for EU countries: NECP PV 2030 or more recent goals (if existing) Chatzipanagi et al. 2023 1 for Israel: Ministry of Energy https://www.gov.il/BlobFolder/news/re_290522/he/roadmap_reference_2030.pdf
2 assumed installed capacity of 0.5 MW/ha; source: survey of Israeli greenhouses with solar panel. Assumed % of agri PV in electricity mix (versus rooftop PV) 65%
3 source: As detailed in table 4 in sub-section 1.2 of this report; the data is for the most recent year available

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One should consider that in some countries, the local regulations do not allow using the REGACE technology. For example, in Israel the regulation allows for maximum of 15% cover of solar panels in greenhouses, (Israel Ministry of Agriculture and Rural Development, 2023) whereas the REGACE technology is based on 30% coverage. In Israel, solar panels can be integrated only on top of the greenhouses (Israel Ministry of Agriculture and Rural Development, 2023), whereas the REGACE technology integrates the panels inside the greenhouses. Therefore, the fulfillment of the above presented potential for solar energy production in greenhouses depends on several conditions, including change in the regulatory framework.

Comparison of Ground mounted PV, Agri-PV in open fields and Agri-PV in greenhouses

The following table compares the area that is needed to fulfil the solar energy goals in various countries, using ground mounted systems, agri-PV in open fields, and agri-PV in greenhouses. As can be seen, the ground-mounted systems consume the least land, however their impact on food security is the largest, because no crops can be grown on the land that is designated for ground mounted PV plants.

Agri-PV in open fields consume the largest land size as result of lower power density. However, the impact on food security can be lower than that of ground mounted PV, as crops can be grown under or between the panels. The agricultural yields under agri-PV can be lower than in standard fields or plantations. The damage to the yields depends on the crop, the PV technology, panel density, etc.

Agri-PV in greenhouses takes an intermediate place: the land consumption is higher than in ground mounted PV and lower than in agri-PV in open fields. This is due to the relatively high power density that is expected of the REGACE technology, and the fact that the panels are hung on the structure of the greenhouse, without using additional farmland for foundations. In agri-PV in greenhouses, just like for agri-PV in open fields, some damage to the agricultural yield is expected.

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Table 14: The land size that will be needed to fulfill solar energy goals for year 2030 using ground mounted PV, open field agri -PV and greenhouse agri-PV

Country	Area for ground mounted PV (ha), power density 0.87 MW/ha	Area for open field agri- PV (ha), power density 0.6 MW/ha	Area needed for agri-PV in greenhouses (Trisolar-REGACE technology) (ha), power density 0.7 MW/ha [2]
Germany	160,632	232,917	199,643
France	35,339	51,242	43,921
Italy	53,793	78,000	66,857
Spain	68,736	99,667	85,429
Poland	22,414	32,500	27,857
Romania	4,401	6,381	5,469
Netherlands	26,897	39,000	33,429
Belgium	16,437	23,833	20,429
Czech Republic	2,974	4,312	n.d.
Greece	9,713	14,083	12,071
Hungary	4,856	7,042	6,036
Portugal	7,471	10,833	9,286
Sweden	2,615	3,792	3,250
Israel	12,776	18,525	15,879
Austria	9,713	14,083	12,071
Bulgaria	2,391	3,467	2,971
Denmark	5,857	8,493	7,280
Slovakia	897	1,300	1,114
Finland	897	1,300	1,114
Ireland	1,121	1,625	1,393
Croatia	575	834	715
Lithuania	1,143	1,658	1,421
Slovenia	1,233	1,788	1,532
Latvia	374	542	464
Cyprus	598	867	743
Estonia	314	455	390
Luxembourg	829	1,203	1,031
Malta	194	282	241

Source for solar energy goals: EU countries NECP PV 2030 or more recent goals (if existing) (Chatzipanagi et al. 2023); Israel: Israel Ministry of Energy https://www.gov.il/he/departments/news/re_290522

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Chapter 3 - Resource Efficiency Analysis

Resource Efficiency Analysis - Comparing an agri-voltaic greenhouse to a regular greenhouse, with the same crop, according to agricultural production parameters; Comparing an agri-voltaic greenhouse to open field agri-voltaic systems.

The chapter aims to calculate and demonstrate the efficiency gains of the REGACE solar technology on various resources of agricultural and energy production.

The chapter investigates the environmental impacts of various solar technologies and compares them to the technology of the REGACE project, to identify technologies with relatively low environmental impact.

This will take 2 phases:

1: Comparing an agri-voltaic greenhouse to a control greenhouse without panels, with the same crop, according to agricultural production parameters.

The parameters for comparison will be:

1.1 Water usage per unit of produce. It is projected that in agri-voltaic greenhouses the use of water will be lower, therefore raising the resource efficiency of the system.

1.2 Yields: this comparison will demonstrate whether the agri-voltaic system impacts the agricultural yields.

1.3 Arthropods: pests and beneficials. The manipulation of shade / light in the agri-voltaic greenhouse can influence the population and number of pests, leading to different usage of pesticides. It might also impact pollinators and therefore have an impact on agricultural yields.

2 : Comparing an agri-voltaic greenhouse to open-field agrivoltaics.

The parameters for comparison are detailed in the following chapters, and include, among others:

2.1 Construction materials for the agrivoltaics system: concrete foundation, metal poles etc. How much material is needed for the construction of the system, and its cost.

2.2 Labor (working hours) in setting up the system and in its maintenance.

In addition to a quantitative index for each parameter, an economic index will be calculated (how much money will be saved / added by using the agri-voltaic in greenhouses, versus other technologies).

Methodology

The analysis of the findings of the field studies in the 6 partners' sites where field research in greenhouses was conducted.

Arthropods' survey conducted in the greenhouses of TRDC in Kfar Kara, Israel.

Analysis of the following sources:

- Literature survey and analysis of findings of studies that looked into the investment costs of constructing agri-PV facilities in open fields and plantations.
- Data collection from existing agri-PV facilities in open fields and plantations in Israel.
- Data collection from existing agri-PV facilities in greenhouses in Israel. See Annex 2 for more information on the methodology of the survey.
- Data collection and analysis of agri-PV installations that were constructed in the 6 field-research sites of REGACE project.

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Results

Comparing an agri-voltaic greenhouse to a greenhouse without PV

Monitoring for the impact of the PV system on yields was conducted in 6 sites. In 5 sites data on irrigation was collected, and in 5 sites experiments with CO2 enrichment were conducted.

The following table shows the locations, number of trials, seasons, crops, treatments and controlled parameters in the greenhouses' trial sites.

Table 15: Characrtistics of REGACE crop trials

Site	No of trials	Season	Crop	Treatments	Control for irrigation?
TRDC, Israel	2	Spring 2024	Cucumber	PV, Control	Yes
		Winter 2025	Cucumber	PV, Control, PV+CO2	no
BOKU, Austria	10	Spring 2023	Basil, lettuce, bell pepper	PV, Control, PV+NH_4HCO_3	Yes
		Spring 2024	Basil, cucumber, radish*2	PV, Control, PV+NH_4HCO_3	Yes
		Summer 2024	Bell pepper	PV, Control, PV+ NH_4HCO_3	Yes
		Spring 2025	Basil, radish	PV, Control, PV+CO2	Yes
UTH, Greece	3	Autumn 2024	Cucumber	PV, Control, PV+CO2, CO2 no PV	Yes
		Winter 2025	Cucumber	PV, Control, PV+CO2, CO2 no PV	Yes
		Summer 2025	Cucumber	PV, Control, PV+CO2, CO2 no PV	Yes
HU, Germany	3	Autumn 2024	Lettuce	PV heavy, medium, light shade; Control	No
		Winter 2025	Lettuce	PV heavy, medium, light shade; Control	No
		Spring 2025	Tomato	PV heavy, medium, light shade; Control*2	No
BW, Germany	2	Summer 2024	Tomato	PV, Control	Yes
		Summer 2025	Cucumber	PV, Control	No
FSC, Italy	4	Winter 2025	Lettuce	PV, Control	Yes
		Winter 2025	Zucchini	PV, Control	Yes
		Summer 2025	Eggplant	PV, Control	Yes
		Summer 2025	Tomato	PV, Control	Yes
Total	**24**				

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The trials included 8 different crops, of which cucumber was the most frequent (8 trials) followed by tomato and lettuce (4 trials each).

Table 16: the crops of REGACE trials

No	Crop	Number of trials
1	Cucumber	7
2	Tomato	3
4	lettuce	4
3	Basil	3
6	radish	3
5	bell pepper	2
7	Zucchini	1
8	Eggplant	1
	Total	24

Irrigation was monitored in 19 trials (76% of all trials). CO2 enrichment was performed in 8 trials (32% of all trials); in 7 trials NH_4HCO_3 was used (each cultivar represents a single trial, i.e. 7 trials with NH4HCO3).
In one site (HU) 3 levels of shade were tested; the results in this report relate to the medium shade level (15%).
In two trials (in BOKU) additional light was used in some greenhouses.
In one trial (in UTH) reverse tracking was preformed (programming the tracking so that panels move away from the sun). The results of this trial are not considered here.

Water use efficiency

The impact on irrigation was measured as "water use efficiency", meaning the amount of water (m3) that was needed to produce 1 kg of the crop[8]. The presence of PV panels is supposed to lower the need for irrigation. Lowering the irrigation in the PV greenhouses is considered a positive impact of the PV system. However, since in some cases yield is reduced under PV panels, it could be that the amount of water needed to reach a certain yield under PV is higher than without PV.
The following table presents the results of the water efficiency in the trials.

[8] Note that in D.3.2 water efficiency is considered as the amount of produce (kg) produced per water unit (m3). This is the reversed measurement and does not change the results in essence.

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Table 17: Results- Impact of PV system on water use efficiency (m3 water / kg produce[9]), general trend and % change due to PV. Comparison of PV and control greenhouses (without PV). (-) when water use efficiency in PV is lower than control

			Impact on yields PV / control	
Site	**Season**	**Crop**	**trend of water use efficiency with PV versus control**	**%.** (-) when water use efficiency of PV is lower than control
TRDC, Israel	Spring 2024	Cucumber	Lower	12.65%
BOKU, Austria	Spring 2023	Basil	Higher	-3.72%
	Summer 2023	Bell pepper	Lower	246.59%
	Summer 2023	Lettuce	Higher	-23.04%
	Winter 2024	Basil	Higher	-7.91%
	Spring 2024	Radish-1	Lower	8,633%*
	Spring 2024	Bell pepper	Lower	234.87%
	Spring 2024	Radish-2	Higher	-14.40%
	Spring 2024	Cucumber	Lower	823.93%
	Spring 2025	Basil	Lower	38.44%
	Spring 2025	Radish	Lower	320.89%
UTH, Greece	Autumn 2024	Cucumber	Lower	7.41%
	Winter 2025	Cucumber	Higher	-0.85%
	Spring 2025	Cucumber	Lower	5.15%
BW, Germany	Summer 2024	Tomato	Lower	-12.73%
FSC, Italy	Spring 2025	Zucchini	Higher	-0.62%
	Summer 2025	Eggplant	Lower	44.43%
	Summer 2025	Tomato	Higher	-49.71%

* There was hardly any produce under PV in this trial.

[9] In Deliverable D 3.2 the results for irrigation are given in the reverse term (produce / water use), however the trend is the same.

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On average, the water use efficiency (M3 water / kg produce) is about 48% higher in the control greenhouses than in PV greenhouses, probably due to the lower yields in PV greenhouses (see the next paragraph).

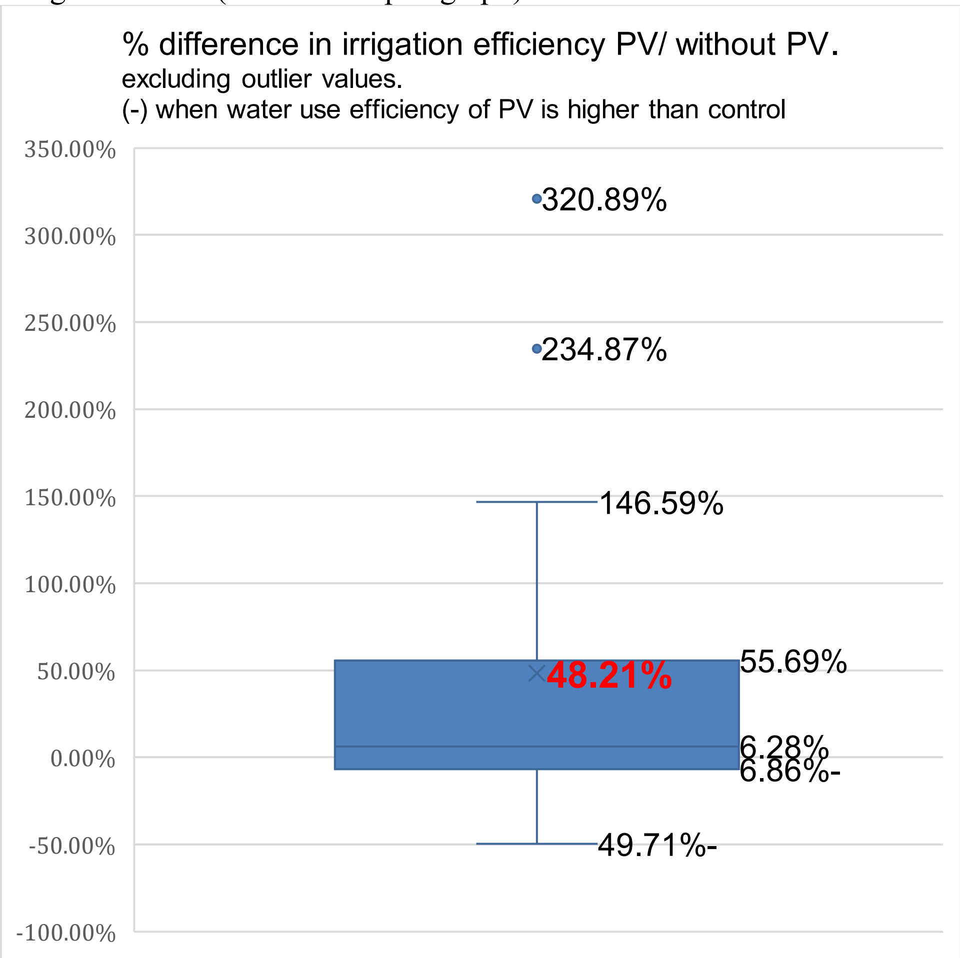

Figure 5: PV impact on water use efficiency (m3 water / kg produce), % change in water use efficiency with PV compared to control. results of crops' trials. box plot. N=14

Two outlier results, where water use efficiency was about 8 and 86 times higher in the control greenhouse than in the PV greenhouse, were excluded from the figure, to make in graphically readable.

Yields

The following table details the impact of PV on crops' yield. The comparison relates to the yield in the greenhouse with PV compared to the control greenhouse. (-) means that the yield in the PV greenhouse is lower than the yield in the control greenhouse.

Table 18: Results- Impact of the PV system on yields, general trend and % change in yields due to PV. Comparison of yields of PV and control greenhouses. (-) when yield of PV is lower than control

Site	Season	Crop	Yields: PV / control	% difference
TRDC, Israel	Spring 2024	Cucumber	PV yield lower than control	-18.56%
	Winter 2025	Cucumber	PV yield lower than control	-15.51%
BOKU, Austria	Spring 2023	Basil	PV yield higher than control	3.86%
	Summer 2023	Red pepper	PV yield lower than control	-59.45%
	Summer 2023	Lettuce	PV yield lower than control	-21.31%
	Winter 2024	Basil	PV yield lower than control	-25.68%
	Spring 2024	Radish-1	PV yield lower than control	-99.10%
	Spring 2024	Radish-2	PV yield lower than control	-41.38%
	Spring 2024	Cucumber	PV yield lower than control	-94.07%
	Spring 2024	Bell pepper	PV yield lower than control	-69.49%
	Winter 2025	Basil	PV yield lower than control	-27.77%
	Spring 2025	Radish	PV yield lower than control	-73.47%
UTH, Greece	Autumn 2024	Cucumber	PV yield lower than control	-3.49%
	Winter 2025	Cucumber	PV yield equals control/ not significantly different	0.00%
	Spring 2025	Cucumber	PV yield lower than control	-6.78%
HU, Germany	Autumn 2024	Lettuce	PV yield equals control/ not significantly different	0.22%
	Winter 2025	Lettuce	PV yield higher than control	7.64%
	Spring 2025	Tomato	PV yield lower than control	-17.49%
BW, Germany	Summer 2024	Tomato	PV yield lower than control	-12.73%
	Summer 2025	Cucumber	PV yield lower than control	-10.12%
FSC, Italy	Winter 2025	Lettuce	PV yield lower than control	-12.67%
	Winter 2025	Zucchini	PV yield lower than control	-18.86%
	Summer 2025	Tomato	PV yield lower than control	-9.27%
	Summer 2025	Eggplant	PV yield lower than control	-18.58%

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In 83% of the trials (21 trials) the yield under PV was lower than in the control (without PV).

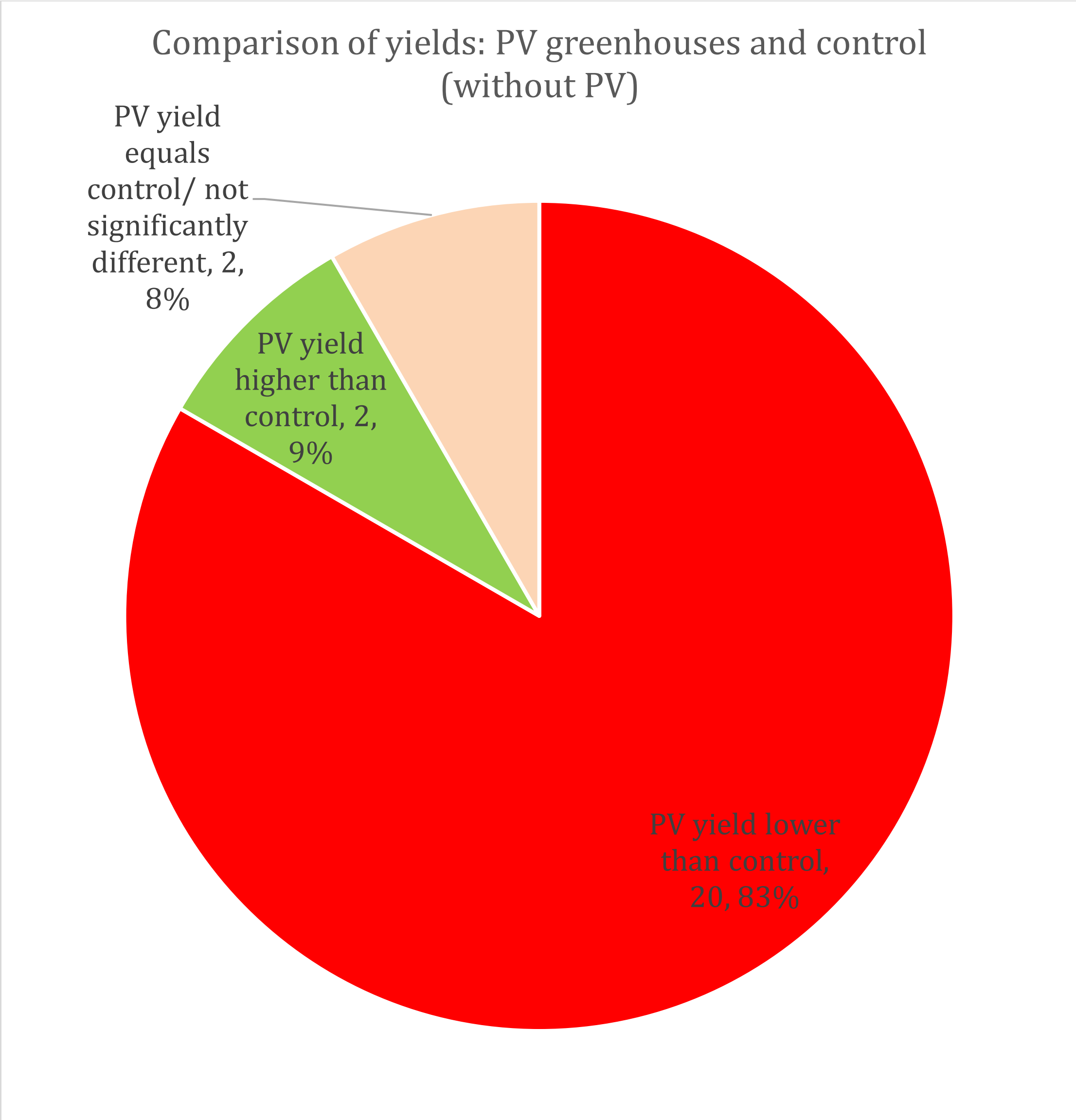

figure 6: Results- Impact of PV system on yields, general trend. Pie chart.

On average, the PV system lowers the yield by 26.83% compared to the control greenhouse.

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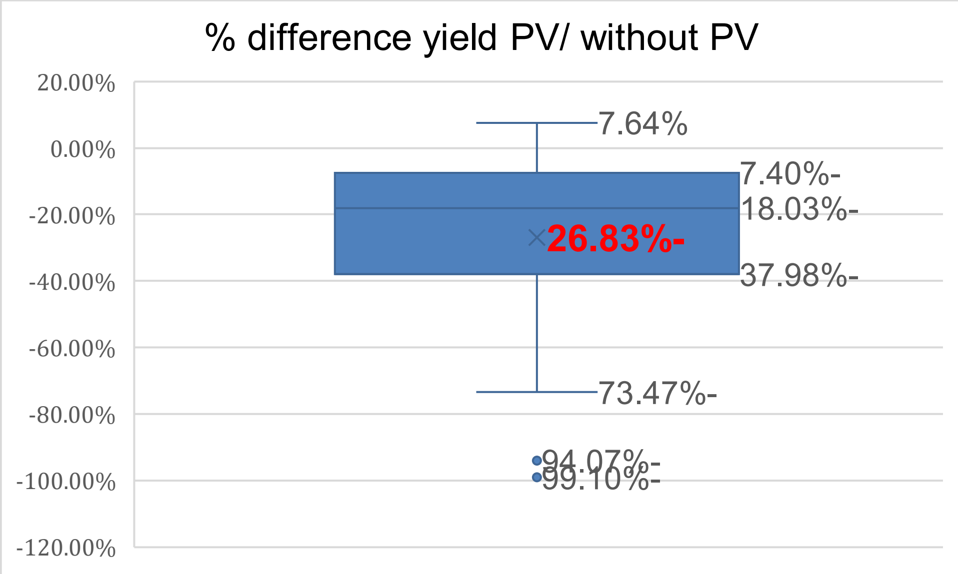

Figure 7 results of crops' trials. PV impact on yields, % change in yields with PV compared to control. box plot. N=25.

Possible interpretations of the results:
Looking into the impact of the season of cultivation, the data may be interpreted as follows[10]:
In summer (6 trials) the result is always "PV yield lower than control". One could argue that only cultivars that can deal with the summer climate in the greenhouse were planted. Hence, a negative aspect of shading may be expected.
In autumn (3 trials) there is at least one result where "PV yield equals control" (in Germany). This result contradicts those in Israel and Greece where "PV yield lower than control". It may be that the conditions in Greece and Israel are more summer-like when compared with Germany. Hence, light might not have been the limiting factor in Germany.
In winter (7 trials) the data are more abundant:
- "PV yield lower than control" in Israel, BOKU, Italy (2x)
- "PV yield equals control" in Greece
- "PV yield higher than control" in Germany

The German result is unexpected.
In spring (9 trials):
- "PV yield lower than control" in Israel, BOKU (5x), Greece, Germany.
- "PV yield higher than control" in BOKU

The contradicting results come from BOKU. The difference could reflect weather conditions (temperature, humidity, the position of the sun).
In summary: "PV yield lower than control" is the common result. Other results may be the consequence of local weather conditions, statistic effects related to sampling, or other reasons.

Looking into the impact on different crops, the following observations can be made[11]:
<u>CUCUMBER</u>

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[10] The following insights were written by Dr. Norbert Keutgen.
[11] The following insights were written by Dr. Chrysoula Papaionnou.

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Cucumber plants were cultivated in total 8 times in 4 countries: Israel (3 times), Austria (1 time), Greece (3 times) and Germany (once).

It was found that in almost all these locations, regardless of the season (spring-autumn-winter in Israel, autumn -spring in Greece, spring in Austria, summer in Germany) the yield of cucumber plants was suppressed under PV panels. There is one exception in Greece on winter, where the yield of the cucumber plants was not affected significantly by presence of PV panels, but no conclusions can be made without any replications in the same location and the same season.

LETTUCE

Lettuce was cultivated in total 4 times in 3 different countries: Germany (2 times: autumn-winter), Italy (1 time: winter) and Austria (1 time: summer).

The effect of PVs on lettuce yield can't be attributed to decreased light under PV panels, because in the same season (winter) in Germany (a northern location with less light) yield was higher under PV panels than in the control greenhouse without PVs, while in Italy (a southern location with more light) the yield under PVs was lower than in the control.

The fact that in Germany in the autumn, the yield didn't differ between plants grown under PV panels or without PV could be attributed to better cultivation conditions between the 2 locations (such as better aerial environmental condition except light, CO_2 concentration, air temperature and relative humidity etc.).

Discussion:

It is impossible to compare a leafy vegetable (lettuce) with a fruity one (cucumber). The duration of the cultivation season of lettuce is almost 1 month while the duration of the cultivation season of cucumbers exceeds 3 months.

The purpose of the research performed within REGACE project was to collect data about the effect of PV panels on yield of typical plant species of each country with different climate and different cultivation methods. It is well known that in order to exclude results concerning plant behaviour on a parameter that affects its growth and development, all the other parameters (cultivar, nutrition uptake, irrigation, environmental conditions etc.) must be the same between tested plants, and repetitions of at least 3 years should be made.

Statistical analysis

A statistical analysis was conducted to test the effects of agri-PV on crop yield for two dependent variables: yield per plant (g/plant) and yield per land area (kg/dunam). Each variable was analyzed separately using paired t-tests and ANCOVA for covariate effects.

For each variable, the study analyzed 22 paired trials across five countries, four seasons, and multiple crop types, yielding two key findings:

1. Panels significantly reduce crop yield by approximately 283 g/plant (17.3% reduction) and 928 kg/ 1000m2 (25.6% reduction)
2. All examined covariates (site, season, crop type, cultivation duration) demonstrate statistically significant effects on yield

Paired T-Test Results

Primary Finding: Panels Reduce Yield Significantly

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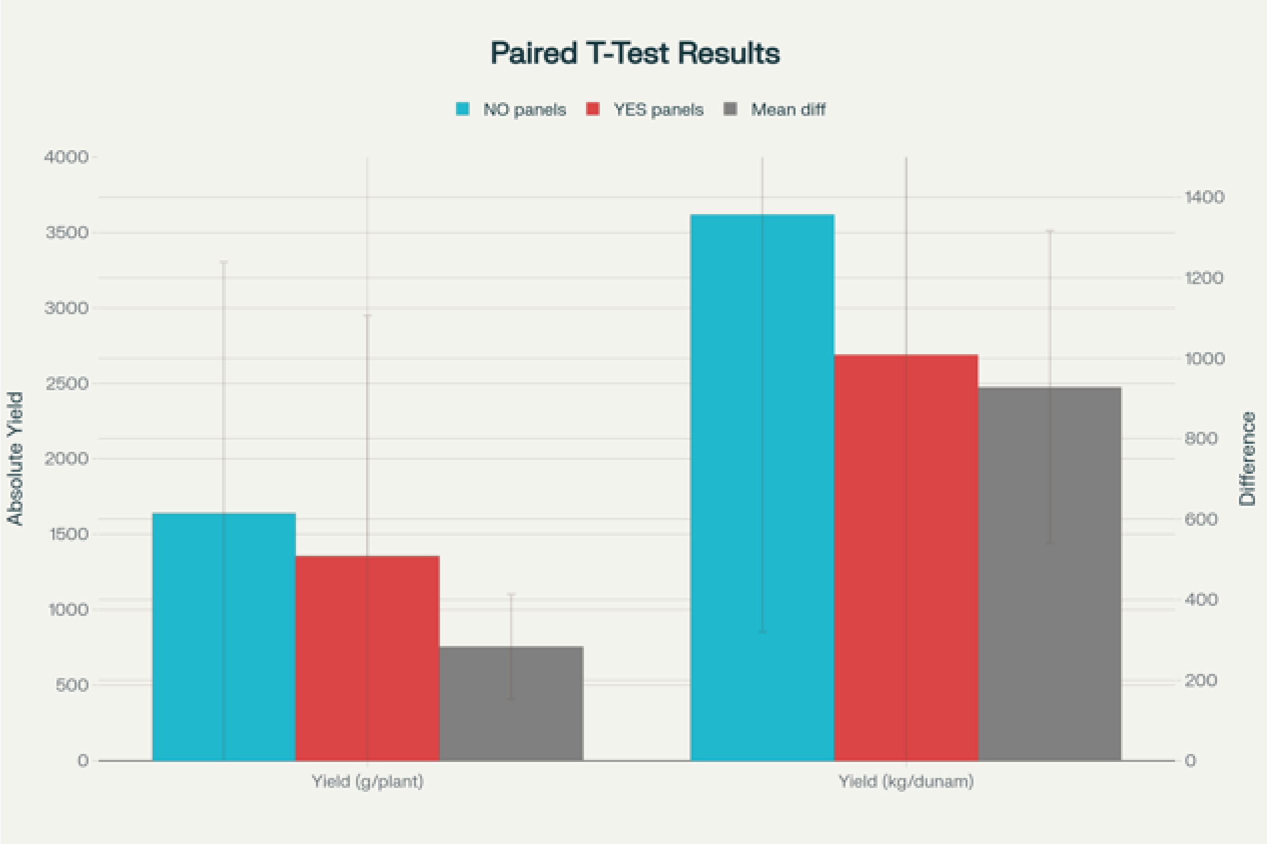

figure 8: Paired T-Test Results: Effect of Panels on Crop Yield (Both Measures)

The paired t-test analysis reveals a **highly significant effect** of panels on both yield measures:

Yield (g/plant):

- Number of paired trials: 22
- Mean yield (NO panels): 1638.95 g/plant
- Mean yield (YES panels): 1355.67 g/plant
- Mean difference: 283.28 g/plant (95% CI: 152.91 to 413.65)
- Paired t-test significance: $p = 0.00047$ (highly significant)
- Wilcoxon signed-rank test confirmation: $p = 0.00020$ (highly significant)
- Effect size (Cohen's d): 0.98 (very large)

Yield (kg/1000 m2):

- Number of paired trials: 22
- Mean yield (NO panels): 3619.07 kg/dunam
- Mean yield (YES panels): 2690.70 kg/dunam
- Mean difference: 928.38 kg/dunam (95% CI: 539.59 to 1317.17)
- Paired t-test significance: $p = 0.00019$ (highly significant)
- Wilcoxon signed-rank test confirmation: $p = 0.00020$ (highly significant)
- Effect size (Cohen's d): 1.07 (very large)

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Covariate Analysis
Covariate Effects on Yield (g/plant)

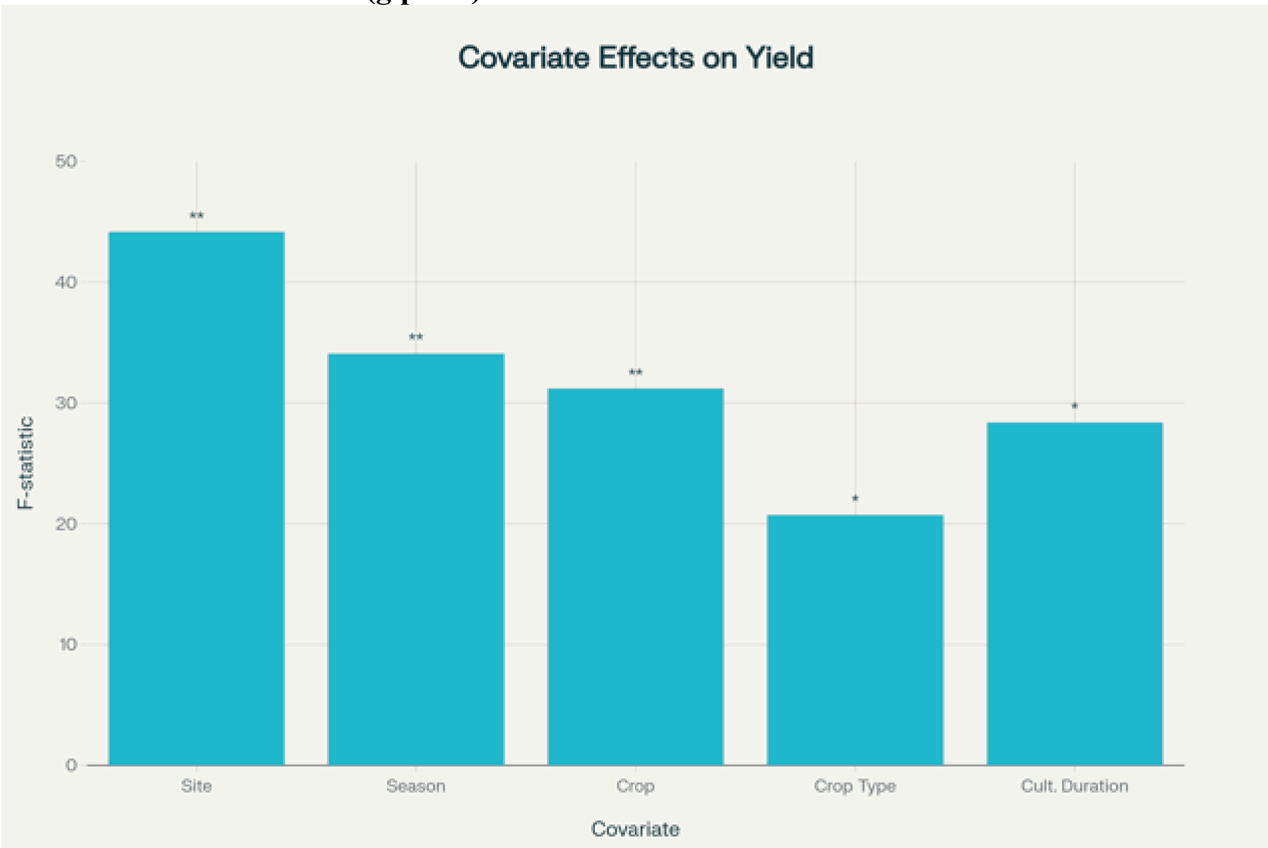

figure 9: Covariate Effects on Yield (g/plant): ANOVA F-Statistics

ANOVA Results (Model $R^2 = 0.9961$):

Covariate	F-statistic	p-value	Significance
Site	**44.15**	0.0053	**
Season	**34.07**	0.0081	**
Crop	**31.18**	0.0084	**
Type of Crop	**20.71**	0.0176	*
Cultivation Duration	**28.37**	0.0129	*

Significance Notation: *** p<0.001 (highly significant); ** p<0.01 (very significant); * p<0.05 (significant)

Interpretation: All five covariates show statistically significant effects. Site has the strongest effect (F=44.15), indicating that environmental and management factors vary substantially across locations. Season (F=34.07) and Crop type (F=31.18) are nearly as important, suggesting timing and crop selection are critical production factors.

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Covariate Effects on Yield (kg/1000 m2)

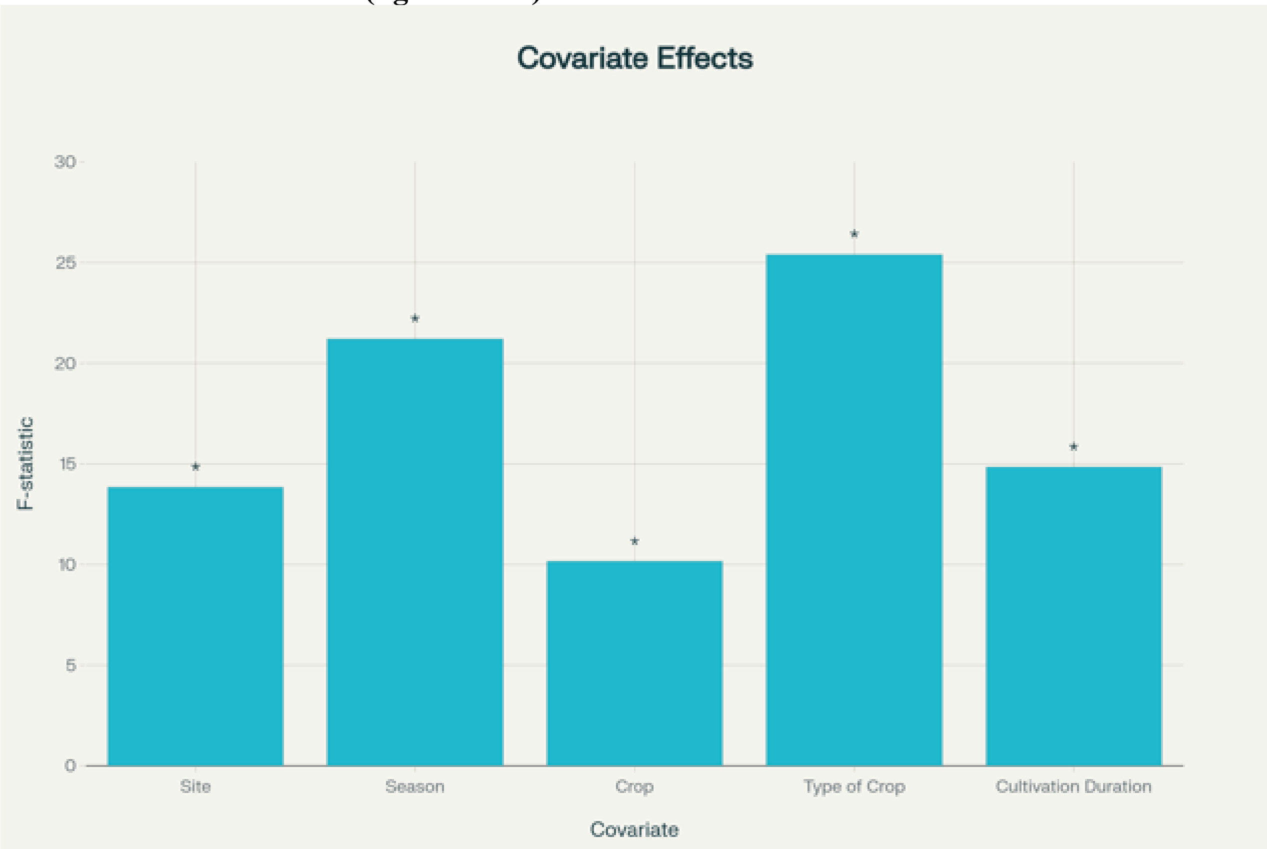

figure 10: Covariate Effects on Yield (kg/1000 m2): ANOVA F-Statistics

ANOVA Results (Model $R^2 = 0.9865$):

Covariate	F-statistic	p-value	Significance
Type of Crop	**25.40**	0.0132	*
Season	**21.21**	0.0160	*
Cultivation Duration	**14.84**	0.0309	*
Site	**13.84**	0.0282	*
Crop	**10.16**	0.0416	*

Interpretation: For area-based yield, Type of Crop has the strongest effect (F=25.40), emphasizing that crop category (fruty, leafy, tuber) is particularly important for production planning. All covariates remain statistically significant ($p<0.05$).

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Seasonal Effects on Panels Impact

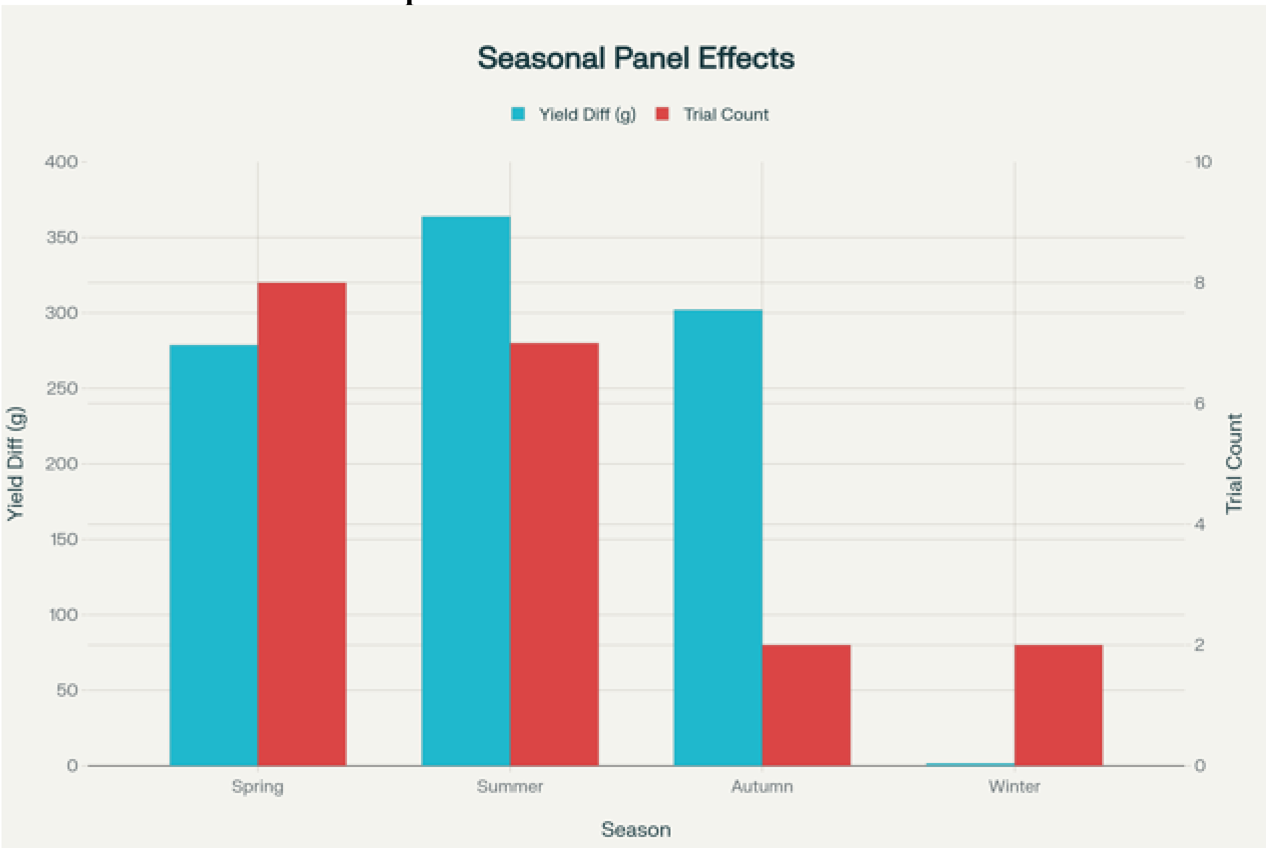

figure 11: Seasonal Variation in Panels Effect (Yield g/plant Reduction)

Mean yield reduction by season (NO - YES panels):

- Summer: +363.77 g/plant (strongest seasonal effect, n=7 trials)
- Autumn: +302.03 g/plant (n=2 trials)
- Spring: +278.63 g/plant (n=8 trials)
- Winter: +1.46 g/plant (minimal effect, n=2 trials)

The substantially larger effect in warmer seasons (summer/autumn) versus minimal effect in winter suggests that panels' impact is moderated by environmental conditions.

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Crop Type Variation in Panels Effect

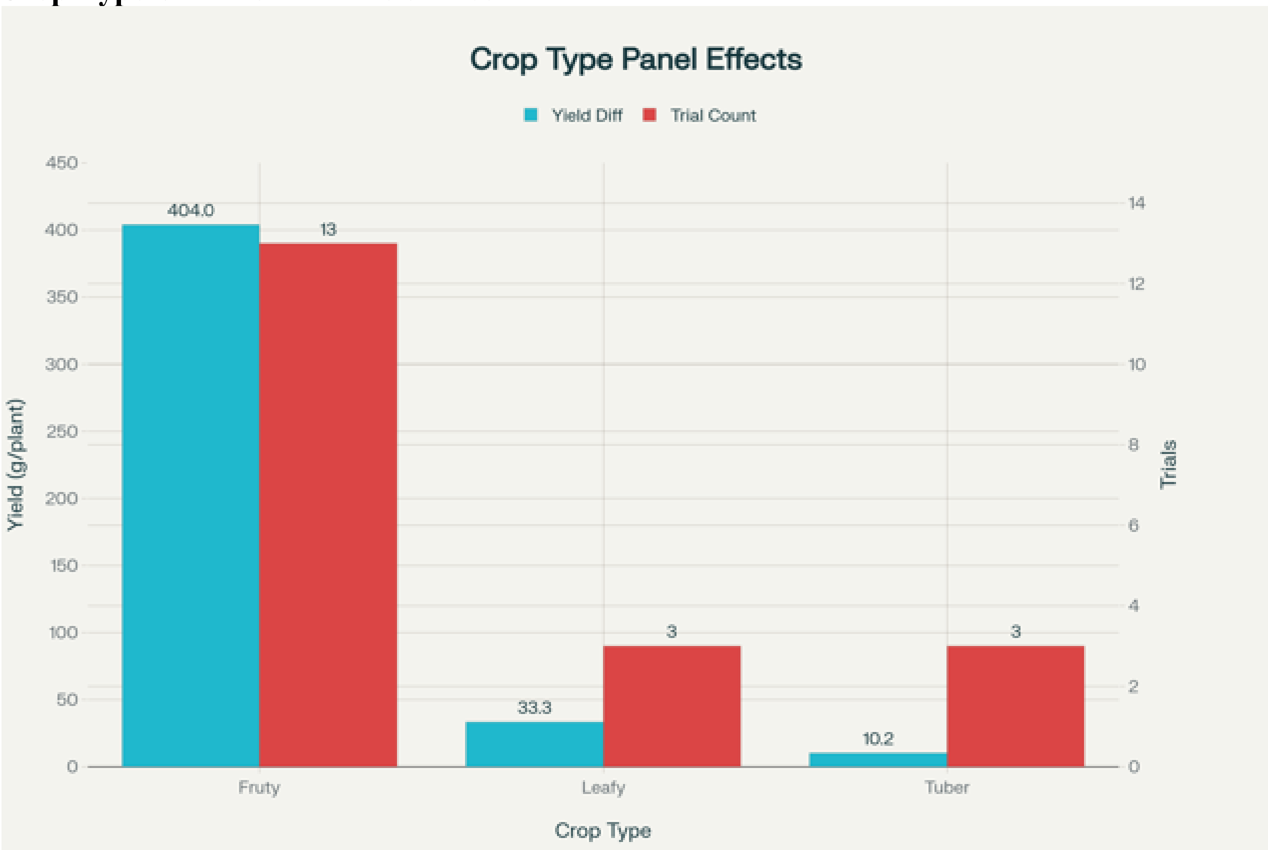

figure 12: Crop Type Variation in Panels Effect (Yield g/plant Reduction)

Mean yield reduction by crop type (NO - YES panels):

- Fruty crops: +403.99 g/plant (strong effect, n=13 trials)
- Leafy crops: +33.32 g/plant (minimal effect, n=3 trials)
- Tuber crops: +10.20 g/plant (minimal effect, n=3 trials)

Fruty crops (cucumber, pepper, tomato, etc.) show approximately 12 times larger yield reduction than leafy crops when panels are used. This suggests crop-specific responses to panel presence, with fruity crop production particularly sensitive to panels.

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CO2 enrichment partly compensates for the impact of PV on yields. CO2 enrichment improves the yields in some cases, but on average the yields are still about 16% lower in the PV + CO2 enrichment greenhouses than in the control greenhouses without PV or CO2 enrichment.

Table 19: Results- Impact of PV system + CO2 enrichment on yields, general trend and % change in yields. Comparison of yields of PV+ CO2 enrichment and control

			Impact on yields PV / control	
Site	**Season**	**Crop**	**trend**	**%.** (-) when yield of PV is lower than control
TRDC, Israel	Winter 2025	Cucumber	PV+CO2 yield higher than control	11.39%
UTH, Greece	Automn 2024	Cucumber	PV+CO2 yield higher than control	3.49%
	Winter 2025	Cucumber	PV+CO2 yield higher than control	11.76%
BOKU, Austria	Winter 2025	Basil	PV+CO2 yield lower than control	-25.73%
	Winter 2025	radish	PV+CO2 yield lower than control	-81.92

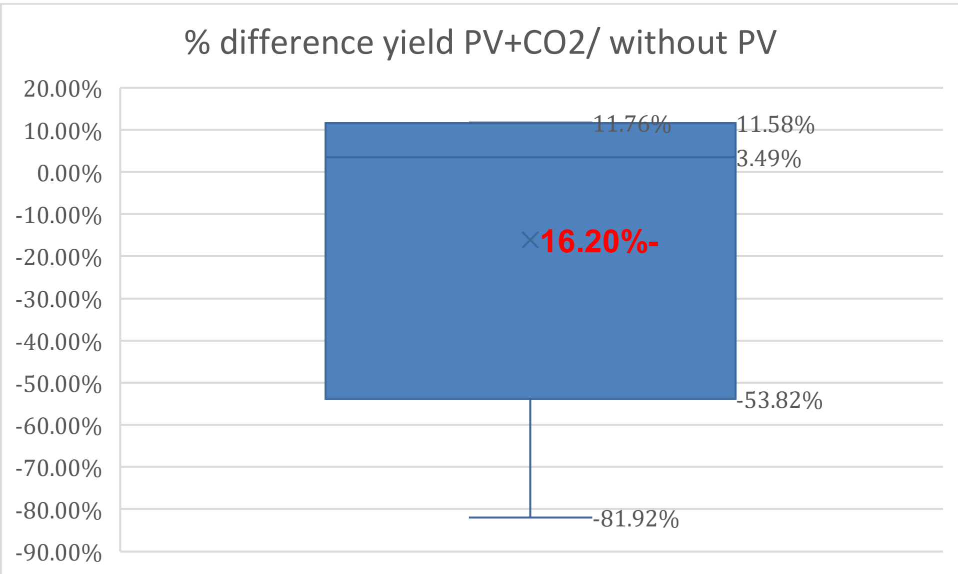

Figure 13: results of crops' trials. PV+CO2 enrichmnet impact on yields, % change in yields with PV+CO2 compared to control. box plot.

Two trials, both carried out in BOKU in winter 2025, included adding light in the PV and control greenhouses, either separately or in addition to CO2. The results:

- When the crop was radish – adding light improved the yield of the PV greenhouse, and it exceeded the yield of the control greenhouse (without panels,

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CO2 or additional light) by 14.57%. When CO2 and additional light were used, the yield of the PV greenhouse was 4.25% lower than the control greenhouse.

- When the crop was basil – adding CO2 and light improved the yield of the PV greenhouse, and it exceeded the yield of the control greenhouse (without panels, CO2 or additional light) by 11.32%. When additional light alone was used, the yield of the PV greenhouse was 9.03% lower than the control greenhouse.

Arthropods: pests and beneficials

The research was conducted, and the report was written by Gilad Ben Zvi, Adi Ramot and Ya'ara Arazi, Entomology Laboratory for Applied Ecology, Steinhardt Museum of Natural History, Tel Aviv University

Methodology

The purpose of the monitoring is to examine the effect of PV panels shading in the greenhouses on arthropods. This is achieved by examining the presence and impact of a variety of arthropods in an agri-voltaic greenhouse versus a control greenhouse without panels, in different growing seasons. The monitoring focuses on arthropods that are typical for cultivated tomatoes and cucumbers - pests and their natural enemies. Monitoring of the arthropods was conducted in four greenhouses of 140 square meters in Kafr Qara, two with solar panels and two without panels (control).
The planting of cucumbers in the summer cycle was carried out in April 2024. The two monitoring of this growth cycle were conducted on June 3-5, 2024 (the beginning of fruit ripening) and on July 15-17, 2024 (about a week before the end of the growing season). The planting of cucumbers in the winter cycle was carried out in October 2024. The third monitoring was conducted on November 5-7, 2024 (before the fruit ripen).
We implemented methods aimed at examining the presence and abundance of a number of key pests for cucumbers in particular and for greenhouses in general.
A. Red mite (*Tetranychus urticae*).
B. Thrips, especially the tobacco thrips (*Thrips tabaci*) and California thrips (*Frankliniella occidentalis*). We didn't differentiate between the species in the ER.
C. Tobacco moth aphid (*Bemisia tabaci*).
D. Species of tunnels, especially the greenhouse tunnel (*Liriomyza trifoli*).
E. The Little Fire Ant (*Wasmannia auropunctata*).
We also examined the presence and influence of two natural enemy species to the above pests:
F. Carnivorous mites (*Phytoseiulus persimillis*).
G. Carnivorous fly (*Coenosia attenuata*).
The four sampling methods we used are:
1. Leaf sampling: In each greenhouse, 5 samples were sampled, each with 5 leaves from a single growing row that were harvested and taken to the laboratory for identification and counting (Fig. 4).

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Figure 14 Leaves collected as part of the sampling.

2. Beating – an active method designed to capture all natural pests and enemies: thrips, tunnels, fire ants, web mites, tobacco moth aphids and other aphids. In each greenhouse, 5 beating samples were performed – gently beating 10 plants in a row growing with a stick and dropping the insects adjacent to them to a collection bucket. The sampled insects were taken to the laboratory, where they were identified and counted.

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Figure 15: beating sampling in a greenhouse

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3. Transparent glue traps: Designed to monitor liriomyza trifoli, predatory flies, thrips and mites. Sixteen traps were placed in each greenhouse for two days. Afterwards, the various pests and natural enemies trapped were identified and counted in the laboratory.

Figure 16: Transparent glue traps in a greenhouse

4. The Little Fire Ant: Bamba baits impaled with pennants embedded in the ground is a method designed to test the presence of the fire ant, which in recent years has become a major pest due to the difficulty of carrying out agricultural work in its presence. 30 such baits were scattered in each greenhouse at distances of about 5 meters from each other and collected 45 minutes later. This monitoring was conducted only once, on June 3, 2024, the peak of the ant's activity season. The ants were categorically counted in each bait (none/unity/tens/hundreds).

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Figure17 : Flag marking a Bamba dispersed to monitor the small fire ant

The effect of the panels on the presence of the different target species in the different models were examined using generalized linear models with the Poisson distribution.

Figure 18 :Identification box for the insects collected in TRDC, June 2024

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Results

Results:

A. Red hyphae mite:

Leaf sampling: On June 3, 2024, few mites were found in the leaves. On July 15, 2024, there were already large numbers, and the greenhouses with the panels had significantly higher numbers than the control greenhouses (Z=36.754, p<2e-16). In the autumn sample, almost no mites were found (Fig. 9).

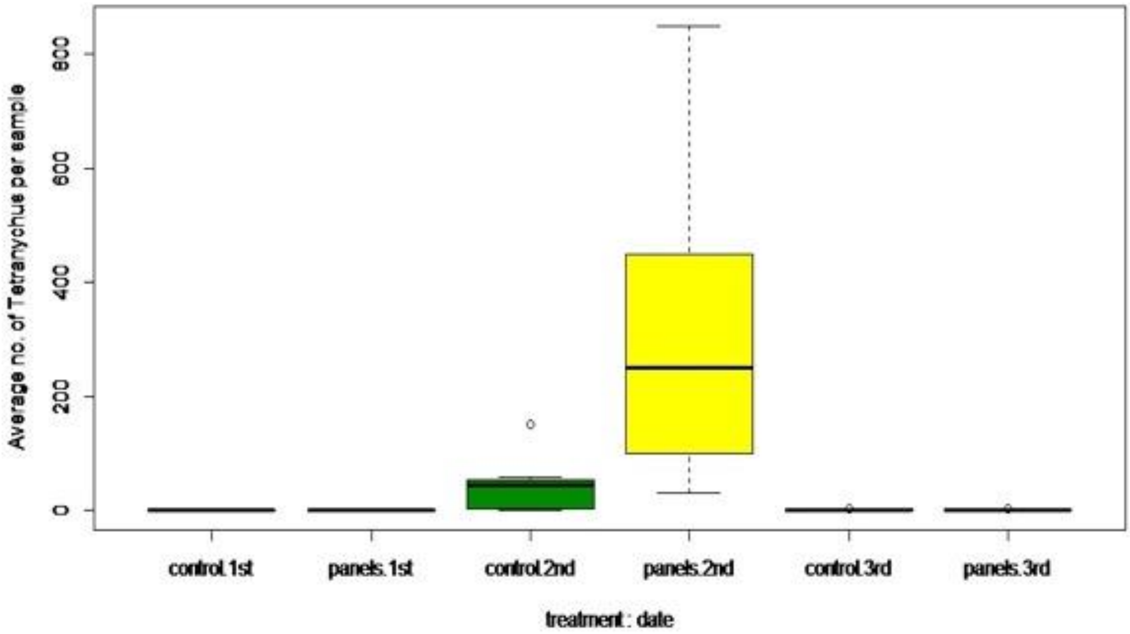

Figure 19: Mites on the leaves.1st – Sampling in 3.6.2nd – Sampling on July 15th.3rd – Sampling on 5.11.

On June 3, 2024, a few mites eggs were found in the leaves. On July 15, 2024, there were already large numbers, and the incubators with the panels had significantly higher numbers than the control incubators (Z=26.038, p<2e-16). In the autumn sample, no mite eggs were found at all.

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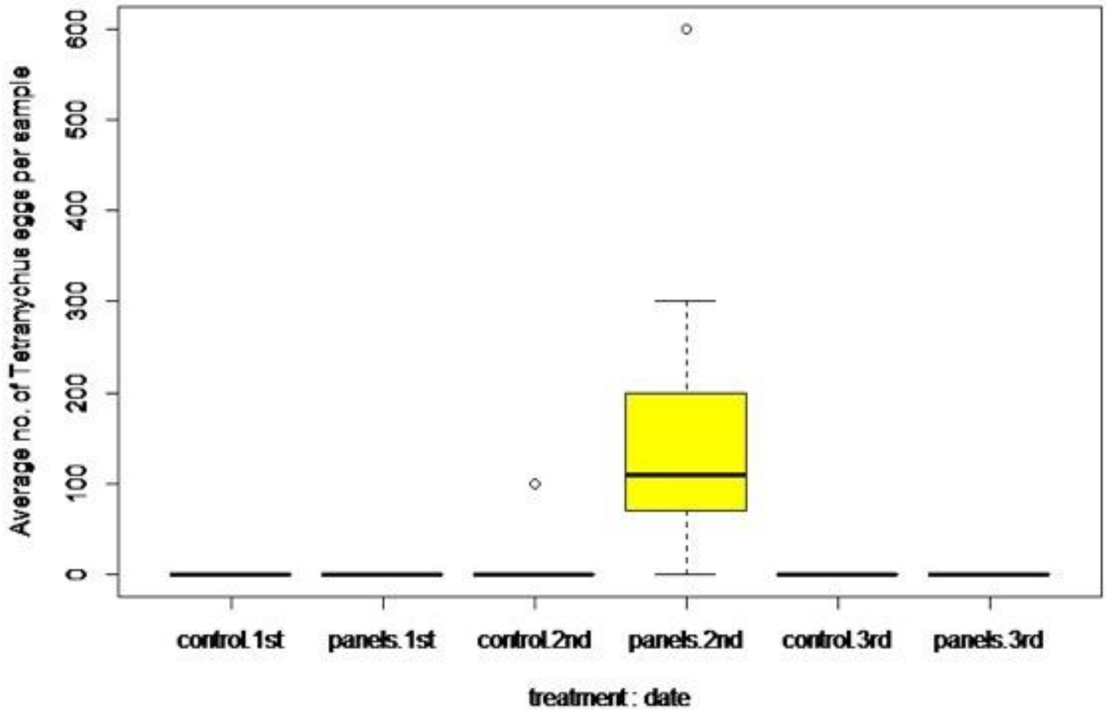

Figure 20: Mite eggs on the leaves.

Biting sampling: On June 3, 2024, some mites were found in biting. On July 15, 2024, there were already large numbers, and in the greenhouses with the panels there were significantly higher numbers than in the control greenhouses ($Z=14.292$, $p<2e-16$). In the autumn sample, almost no mites were found (Fig. 11).

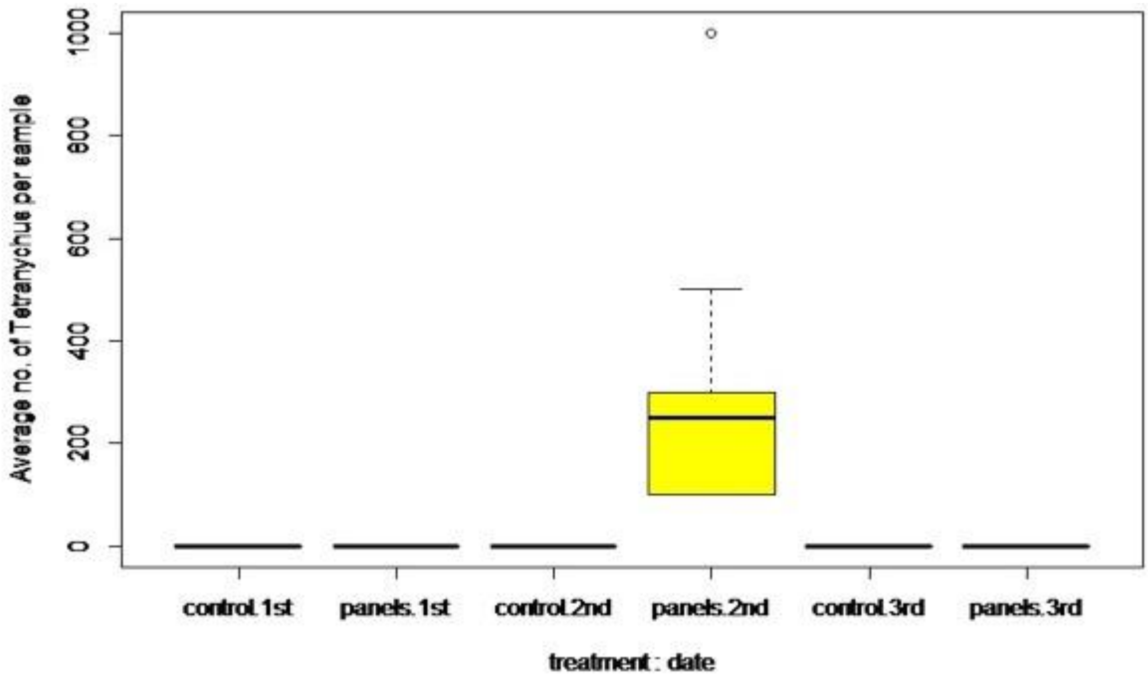

Figure 21: Mites in biting sampling.

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Glue traps: On June 3, 2024, some mites were found in the glue traps. On July 15, 2024, there were already large numbers of mites, and in the greenhouses with the panels, there were significantly higher numbers than in the control greenhouses (Z=6.984, p=2.87e-12). In the autumn samples, almost no mites were found (Fig. 12).

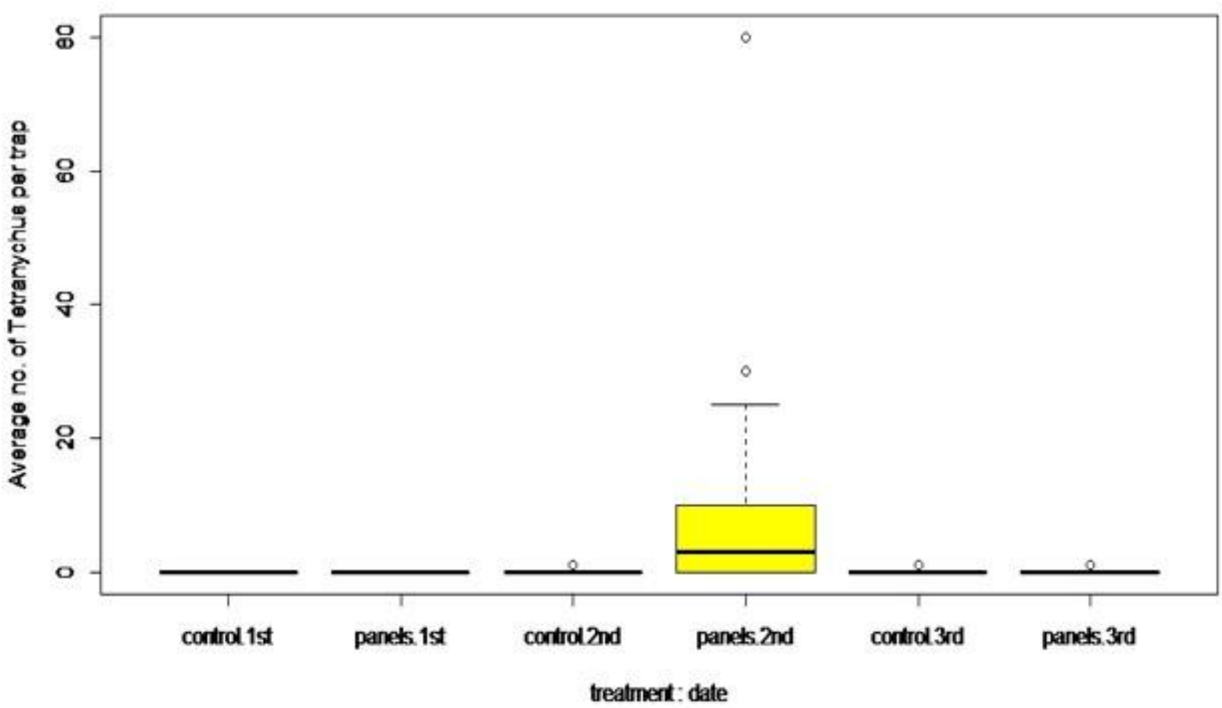

Figure 22: Mites in the glue traps.

<u>B. Thrips:</u>

Leaf sampling: On June 3, 2024, a few thrips were found on the leaves. On July 15, 2024, there were already large numbers, and no significant differences were found between the treatments. In the autumn sample, a few thrips were again found, but more than on June 3 (Fig. 13).

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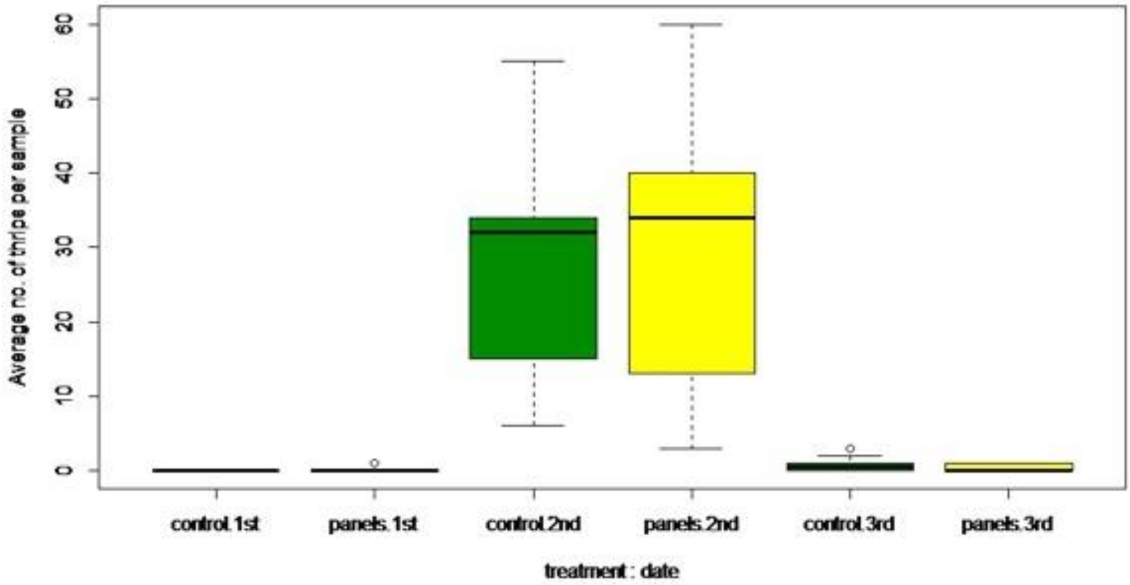

Figure 23: Thrips on the leaves.

Biting sampling: On 3 June 2024, a few thrips were found in biting. On 15 July 2024, there were already large numbers, and the incubators with the panels had significantly lower numbers than in the control greenhouses (Z=-4.078, p=4.53e-05). On 5 November 2024, a few thrips were found again (Fig. 14).

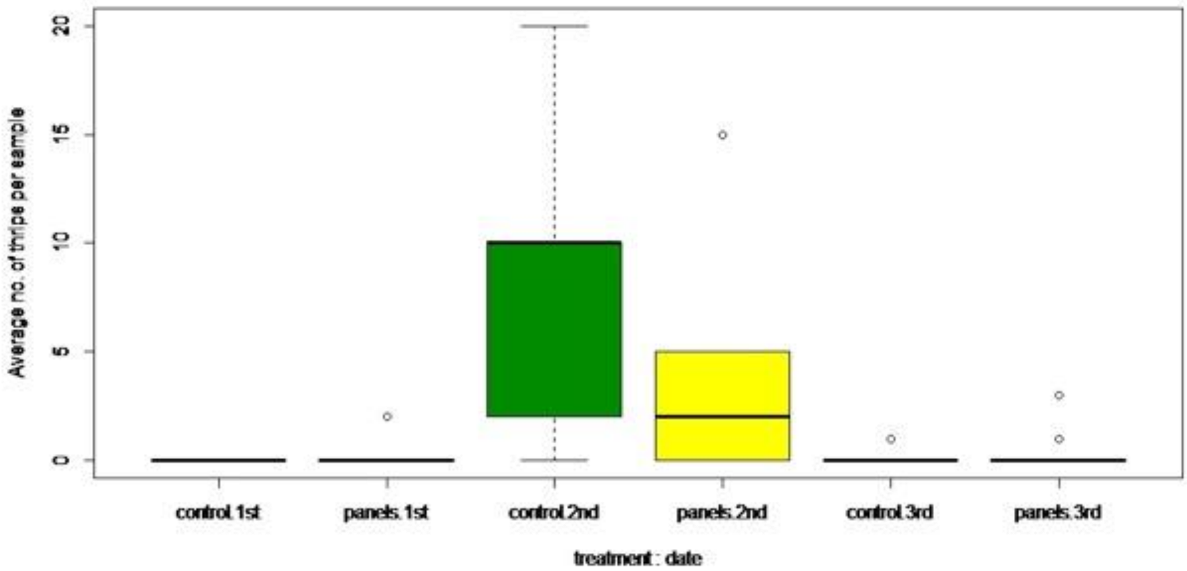

Figure 24: Thrips in the biting sample.

Glue traps: A few thrips were found on all dates, but on July 15, 2024 the highest numbers were found. No significant differences were found in any of the samples between the treatments, but most notably in the early season samples there were more thrips in the control greenhouse and in the end-of-season samples there were more thrips in the greenhouse with panels. When examined in the totality of the data, it was

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found that the effect of thrips in the control greenhouse was marginally higher (Z=1.818, p=0.069).

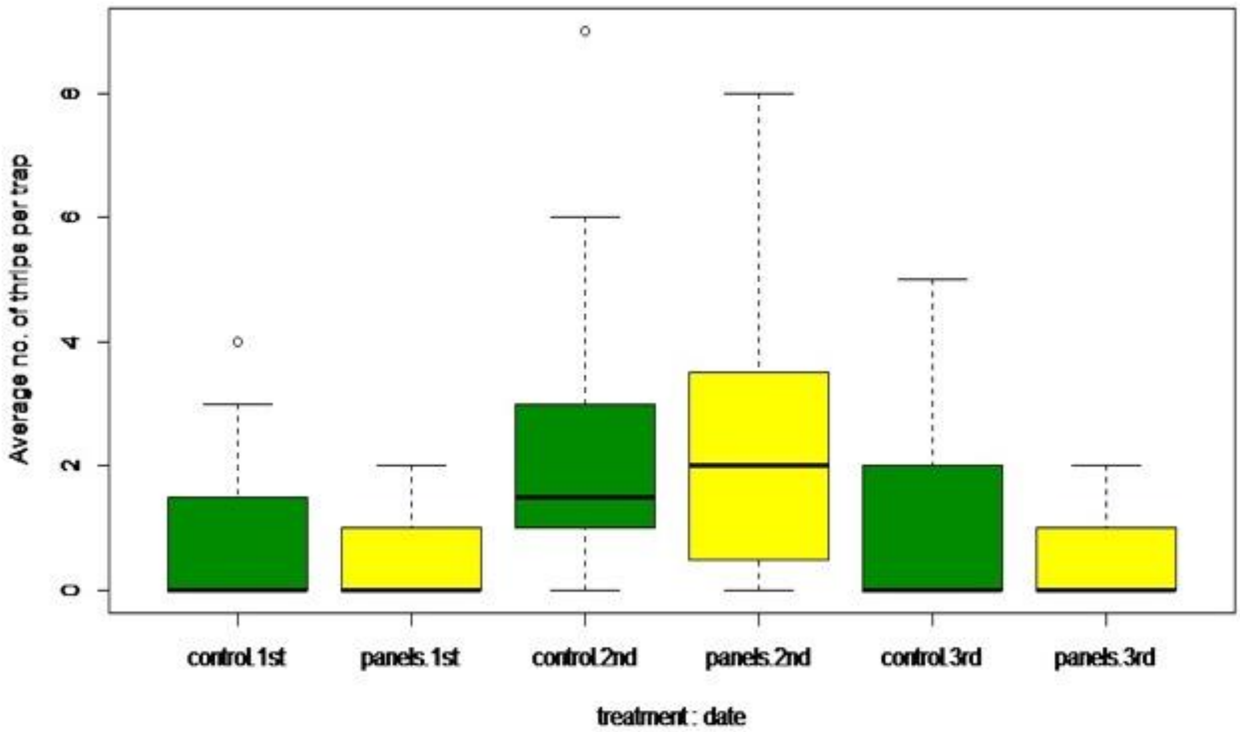

Figure 25: Thrips in the glue traps.

<u>C. Tobacco moth aphid:</u>

In all three types of samples, almost no aphids were found on June 3rd, more aphids were found on July 15th , with a higher effect in the control (in the biting sampling it was also significant: Z=--1.961, p=0.049), and on November 5th, very few aphids were again found (Fig. 12).

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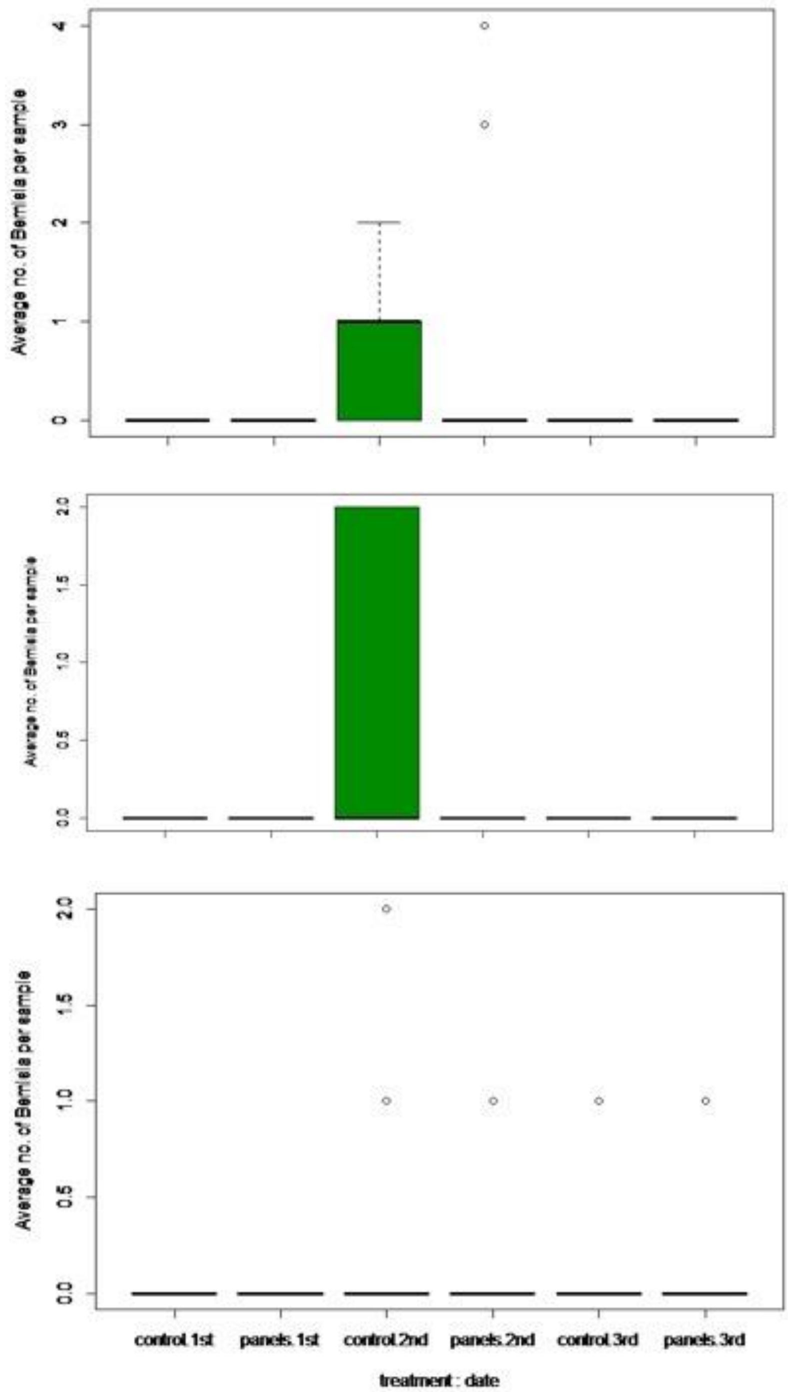

Figure 26: Tobacco moth aphids sampling the leaves (top), biting (center) and glue traps (bottom).

<u>D. Liriomyza trifoli:</u>
No Liriomyza trifoli were found in the greenhouses.
E. <u>The Little Fire Ant:</u>
No fire ants were found in the greenhouses in the designated monitoring conducted on 3 June 2024. But on November 5, 2024, one ant was found in the biting sampling, in one of the greenhouses with panels.

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F. Predatory mite:
No predatory mites were found in the greenhouses.
G. The carnivorous Fly Coenosia:
In contrast to the pest species, there was a decrease in numbers in coenosia with the growth of plants during the summer growth cycle. In addition, on 3.6.24 more flies were found in the panels (Z=2.006, p=0.044862), but on 15.7.24 there were significantly more flies in the control (Z=3.356, p=0.000789), and the same was true in 5.11 (Z=2.123, p=0033746; Fig. 13).

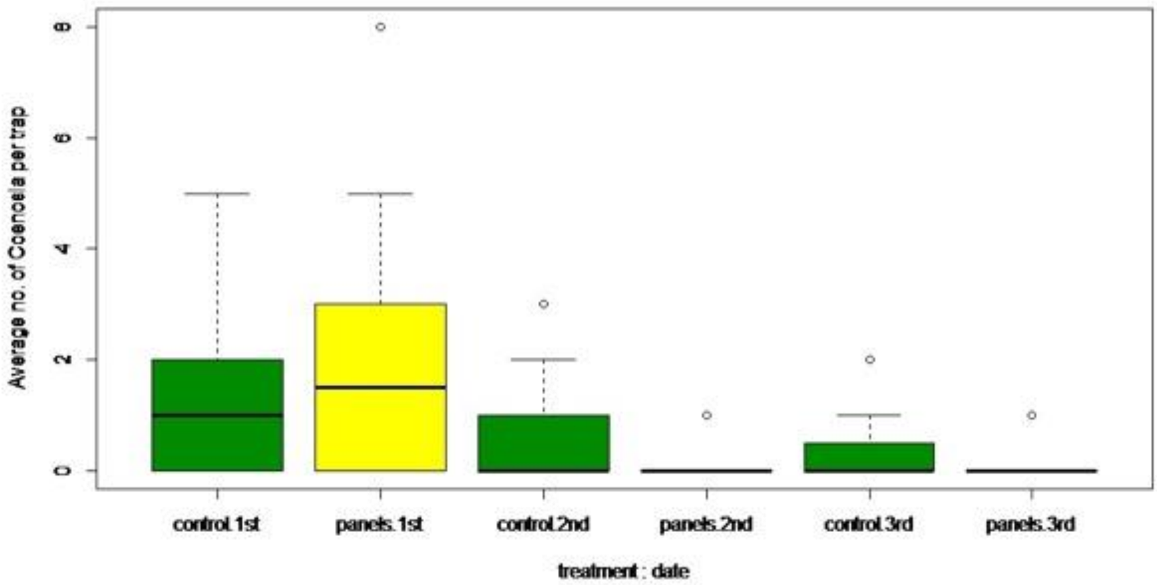

Figure 27: Coenosia flies preying in the glue traps.

Conclusions:
The shade and moisture-loving red hyphae mites benefited from the amplification of these by the panels and appeared there with a much higher incidence than in the control, a trend that was evident in all three relevant sampling methods. This happened only in adult plants—in the young plants, the numbers were still very small in both treatments.
In thrips, the differences were smaller. The only significant difference was found in 15.7 in the beating sample, where the trend was the opposite: the panels led to a decrease in the number of thrips. However, the other two samples on the same date (the leaves and the glue traps) had more thrips in the panels, although not significantly. In conclusion, it is difficult to point to a clear trend in thrips.
The tobacco moth aphid was found in all types of samples in higher numbers in the control greenhouse, but only in beating was the difference significant.
These three pest species showed a much higher effect in developed plants, towards the end of the growth cycle.
The carnivorous fly coenosia, which specializes in *Liriomyza trifoli* predation, showed changes in trends: on June 3, 2024, there were large numbers, especially in the greenhouse with panels; on July 15, 2024, the numbers were already lower, especially in the control, and the same was true on November 5, 2024. It is possible that the abundance of the carnivorous fly should be viewed as an indicator of the lack of *Liriomyza trifoli*.
No *Liriomyza trifoli* were found in greenhouses, nor were predatory mites.

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In the first monitoring, no fire ants were found in the greenhouses, but infestations were detected around the TRDC offices, about 50 meters away from the control greenhouses. However, in the third monitoring, the fire ant was found in one of the PV greenhouses. It is unclear whether this happened because of an invasion from an infected area nearby or because of the introduction of infected seedlings. It is also unclear whether the increased shading and humidity, which are expected to benefit the ant, helped the ant to establish itself in the panel greenhouse. In any case, it is advisable to exterminate the ants in the greenhouse and in the area as soon as spring arrives to prevent them from establishing themselves in the experimental area, which will make it very difficult for the workers in the greenhouses. At the same time, the plant material introduced into the greenhouses must be carefully examined to prevent further invasion.
In conclusion, it can be said with certainty that the panels, apparently due to the increased shading and humidity, lead to a significant increase in the number of mites in the advanced stages of the growth cycle. They may also facilitate the invasion of the fire ant. Their effect on thrips is variable and inconsistent, as is their effect on tunnel-carnivorous flies. They reduce the numbers of tobacco moth aphids to a certain extent, sometimes significantly.

Comparing an agri-voltaic greenhouse to open field agri-voltaic system

Conceptual framework

The unique challenge of agri-PV is the high capital and environmental costs associated with the mounting structure.

A major barrier to implementation of PV plants is their high up-front capital cost. A recent European Commission analysis indicates that under the recent European policy REPowerEU (2022) the additional investments in solar PVs would amount to EUR 26 billion between 2022 and 2027, on top of the investments needed to realize the objectives of the "Fit for 55" (the EU plan for a green transition) proposals (European Commission, 2022).
Directive EU 2018-2001 on the promotion of the use of energy from renewable sources, states that the European Commission should focus the allocation of funds on the reduction of the cost of capital of renewable energy projects since such cost has a material impact on the cost of the projects and on their competitiveness, as well as on the development of essential infrastructure for an enhanced technically feasible and economically affordable uptake of renewable energy (paragraph (13), EU, 2018).
Agri-PV has even higher initial capital expenditure than ground mounted PV projects, which makes agrivoltaics even less attractive economically. This is mainly due to the expenditures associated with the mounting structure for elevating the panels over the crops (Jung et al., 2021).
Schindele et al. (2020) found that the Levelized Cost of Electricity (LCOE) of agri-PV is 38% higher than ground-mounted PV plants. Most of this gap is attributed to capital expenditure (CAPEX). Schindele et al. (2020) estimated that CAPEX is 63% higher for agri-PV than for ground-mounted PV.
On the other hand, the operation expenditure (OPEX) of agri-PV is 18% lower than for ground-mounted PV. Schindele et al. (2020) estimated that the labor cost associated with operating agri-PV is like that of ground-mounted PV (for surveillance, monitoring, commercial management, repair services) or much lower for agri-PV (for maintenance / mowing).

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Schindele et al (2020) found that of the various components of capital expenditure the ones in which the gap is substantial are mounting structures and hardware (the expenditure for agri-PV is 6.2 times higher than that for ground mounted PV) and site preparation and installation (the expenditure for agri-PV is 2 times higher than that for ground mounted PV). For the other expenditure components – agri-PV and ground-mounted PV have similar or even identical values.

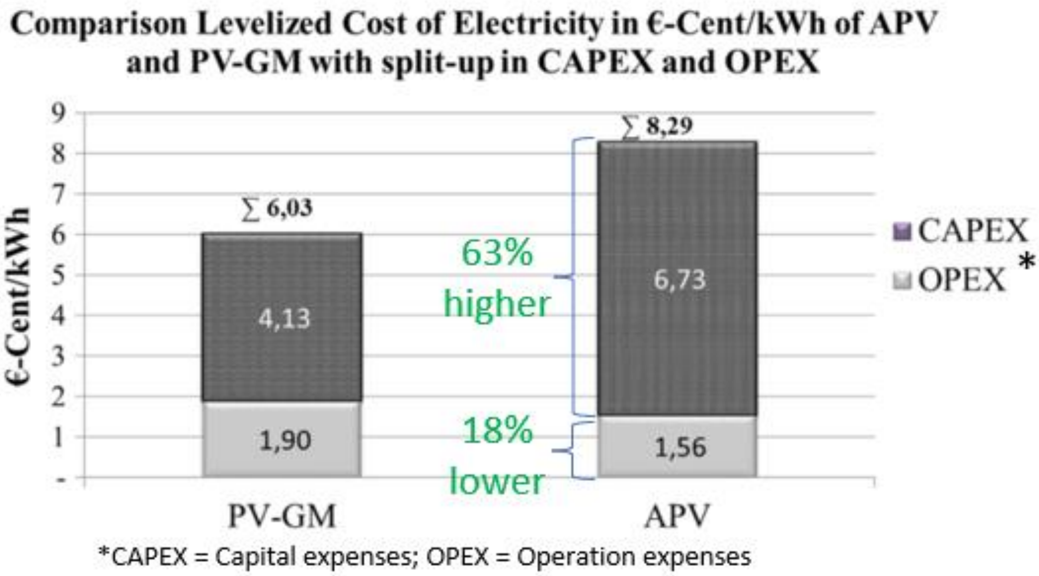

Figure 28: Comparison of capital cost (CAPEX) and operation cost (OPEX), ground mounted PV (PV-GM) and agri-PV (APV). Source: Schindele at al., 2020

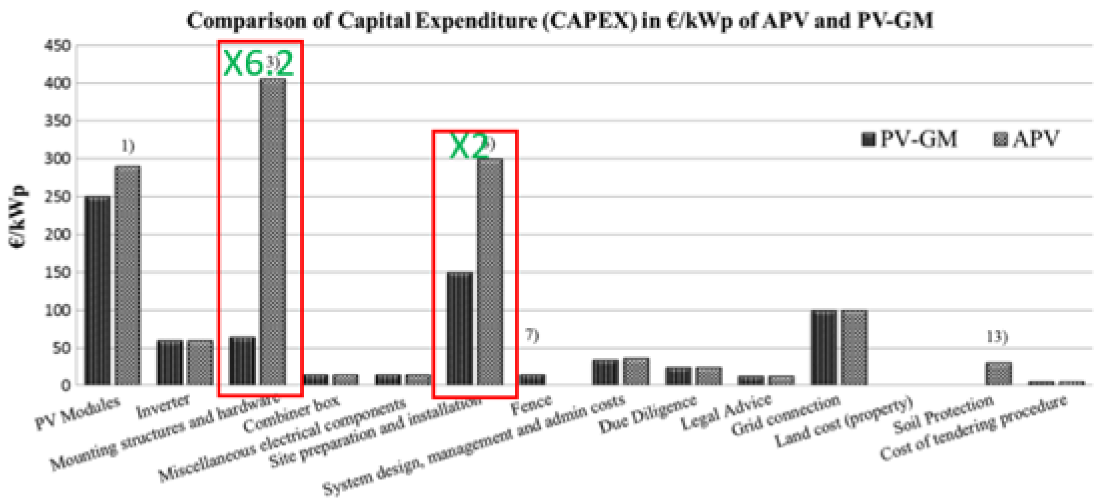

Figure29 : Comparison of components of capital cost (CAPEX), ground mounted PV (PV-GM) and agri-PV (APV). Source: Schindele at al., 2020

Horowitz et al. (2020) also found that the dual use of PV and crop adds costs to PV installation, in comparison to ground mounted PV. That is due to the use of modified PV mounting structures and site investigation costs, because of the additional effort

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needed to plan and design for these more complex installations and to coordinate across farmers.
In addition to economic costs, there is a substantial environmental cost associated with the mounting structures of agri-PV: the vast use of concrete for foundations and steel poles for the panel's mounting structure, leads to intensive GHG emissions (Agostini et al., 2021). The mounting structure consumes natural resources (minerals and metals) and energy in their production, thus negatively impacting climate change (the environmental challenge that agri-PV was meant to mitigate).
All the above justify the need to develop and identify the technologies that reduce the capital cost of agri-PV, by making the structure and installation cost as low as possible. Reducing the capital cost associated with agri-PV is crucial for making them more attractive, versus ground-mounted PV. Since a large part of the cost gap between ground-based and agri-PV stems from the cost of the mounting structure – we will focus below on its examination and what technologies can reduce the cost of its construction. The mounting structure is also the cause of the substantial environmental cost of agri-PV, reinforcing the need to investigate technologies for making it as lean as possible.
Schindele at al. (2020), suggested that "The largest cost-reducing potential for the CAPEX is, when possible, techno-ecological synergies and double functions are considered, for instance when the APV structure substitutes an existing supplementary growing structure such as hail protection nets used in fruit growing". Especially when the crops on the agricultural land need to be protected in any case, there are potential savings to be made when investing in an agri-PV system (Fraunhofer ISE, 2022). This calls for the integration of agri-PV with existing agricultural structures, such as greenhouses.

Parameters for comparison between agri-PV technologies

Agri-PV systems are characterized by a large combination of technical solutions (type of modules, mounting structures, tilt of the panels, fixed or tracking systems etc.).
There is also a variety of agricultural sectors that can be combined with PV (field crops, plantations, horticulture etc.); all of which make the comparison between agri-PV projects challenging (Di Francia and Cupo, 2023).
The analysis will relate to the various techniques of agri-PV in open fields. The more conventional agri-PV technique uses massive concrete foundations and large steel poles for mounting the PV panels over the crops. A more recent technique uses tensile structures, built on suspended structures (stilts), thus saving on materials (steel and concrete) (Agostini et al., 2021). Other techniques include integrating the panels into fences (vertical mount).

Figure 30: Technologies of open fields agri-PV. Source: Horowitz et al. 2020.

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Several parameters are relevant for the comparison of environmental impacts of different solar energy technologies (Pimentel Da Silva and Castelo Branco, 2018)[12]. The following table makes use of Pimentel Da Silva and Castelo Branco's conceptual framework to compare between three agri-PV technologies:

1. Open field agri-PV, where mounting structures are constructed to elevate panels above crops or place them vertically between crops.
2. Agri-PV on top of greenhouses, where the panels are placed outside the greenhouse, on top of its roof.
3. REGACE's technology, where the panels are placed inside the greenhouse, under its roof and above the crops.

The table presents the parameters for comparison and hypotheses regarding their impact, and points out the parameters that are investigated in our study (marked in green).

Table 20: Conceptual parameters for comparing impacts of agri-PV technologies

Parameter*	Open field agri-PV	Agri-PV on top of greenhouses	REGACE technology: Agri-PV inside greenhouses	Comments
Deforestation during set up and construction	Not relevant	Not relevant	Not relevant	The installation is on farmland
Farmland occupation by PV structure	8-20% of farmland is occupied by PV structures	Small share of the farmland is occupied by the PV structure	No farmland is occupied by PV structure	A comparison will be made between the technologies
Foundation and mounting structure	Major structural frame, with ground foundation	Medium-size structural frame, leans against the structure of the greenhouse	Minimal frame, panels are hung on the greenhouse' structure, no ground foundation	A comparison will be made between the technologies
Employment/ labour[13] in construction	Occur	Occur	Occur	A comparison will be made between the technologies

[12] Pimentel Da Silva and Castelo Branco (2018) compare conventional ground-based PV to floating PV on lacks and water reservoirs. The analysis here will make use of their conceptual framework to compare different technologies of agri-PV.

[13] Employment/ labour has both positive and negative impact: positive from the point of view of policy makers that want to create job opportunities, especially in distant rural areas. Negative from the point of view of the framer or energy firm, that need to pay its costs.

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Parameter*	Open field agri-PV	Agri-PV on top of greenhouses	REGACE technology: Agri-PV inside greenhouses	Comments
impacts during construction: traffic, noise, waste generation	Large, as there is need for major mounting structure	Medium, as the mounting structure is medium size	Small, as the mounting structure is minimal, with no ground foundation	
Bird collusion with panels	Might occur	Might occur	Does not occur, the panels are inside the greenhouse	
Attraction of insects	Might occur	Might occur	Might occur	Studied only for REGACE technology (see previous chapter)
Visual pollutions	Large, high structures in open fields	Minimal, the panels are visually absorbed in the greenhouse	No visual impact, the panels are inside the greenhouse	
Sunlight blocking	Might occur	Might occur	Might occur	
Water consumption for cleaning	Needed	Needed	Minimal, as the panels are inside the greenhouse the exposure to dust is small	A comparison will be made between the technologies
Application of chemicals for cleaning and dust suppression	Chemicals can impact the produce	The chemicals don't impact the produce, since the greenhouse' plastic sheets separate between the panels and the produce	Minimal, as the panels are inside the greenhouse the exposure to dust is small	A comparison will be made between the technologies

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Parameter*	Open field agri-PV	Agri-PV on top of greenhouses	REGACE technology: Agri-PV inside greenhouses	Comments
Employment/ Labour in maintenance of solar systems	Large, as panels are high and special equipment is needed to reach them	Large, as panels are high and special equipment is needed to reach them	Minimal, as the panels are inside the greenhouse and more protected from damage	A comparison will be made between the technologies
Employment/ Labour in farm operation	More labour is needed than in farm without PV	Might occur	Might occur	A comparison will be made between the technologies

*Source for conceptual framework: Pimentel Da Silva and Castelo Branco (2018), and additional relevant parameters.

The following relates to the parameters that are marked in green on the table.
The rest of the chapter is organized as follows:

a. Short conceptual description of the parameters studied.
b. Analysis of different agri-PV technologies. For each technology, the research methodology and results will be presented. Open fields agri-PV will be presented using 2 methodologies: literature survey; and survey of existing projects in Israel.
c. Comparison between REGACE technology and other agri-PV technologies, according to the parameters presented in the table above.

Conceptual description of the studied parameters

Capital costs and labor in installation

The expenditures that are included in capital expenditures (CAPEX) are the cost of the modules, combiners, switch gears, fuses, ground fault detectors, charge controllers, batteries, transformers, and grid connection equipment. Additional costs relate to system design, test, and start-up, as well as the installation and any other administrative or financial costs (Di Francia and Cupo, 2023).
Most of these items are capital costs (expenses for purchase of tangible or intangible goods such as equipment or permit for grid connection). Whereas, design, project management, testing, safety measures, site preparation and installation– are mainly labor costs. Fencing has components of both capital costs and labor costs.

Farmland occupation by the mounting structure of the agri-PV system

Agri-PV in open fields occupies a share of the farmland, although to a much smaller degree than ground-mounted systems. A portion of the farmland is occupied by the foundations of the mounting structure that holds the panels above or besides the crops. Different systems occupy different share of the farmland, and the more massive the structure is – the larger the portion of farmland its foundation occupy.
Perennial row crops (plantations) provide advantages, because the posts of the agri-PV mounting structure can be integrated into the crops' rows with no appreciable loss of farmland (Fraunhofer ISE, 2022). Hanging the panels on greenhouses roofs or inside the greenhouses eliminates the use of farmland by agri-PV mounting structures.

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Maintenance of the solar system

The maintenance of agri-PV system includes 2 major components: cleaning of the panels and technical maintenance of the energy system.

A major part of maintenance of agri-PV systems is cleaning the panels (Hajiahmadi et al., 2023). In some of the areas that are ideal for solar energy harvesting, such as the Middle East, there is also a lot of sand and dust, that lowers solar panels' efficiency. Energy losses can be 7% in some parts of the USA and up to 50% in the Middle East (Dutta et al., 2022). Agricultural activities increase dust accumulation (Jung et al., 2022) and agri-PV systems need to be cleaned more often than ground-mounted PV (Hajiahmadi et al., 2023).

Panels must be cleaned on a regular basis. However, cleaning is challenging due to the scarcity of water in the same regions where sunlight is abundant. The use of water in cleaning panels is therefore a highly pressing environmental challenge.

Cleaning of panels can be done in many ways, some of which don't consume a lot of water: dry brushing, dry wiping, compressed air, vacuum cleaning etc. The dust on the PV surface decreases with an increased tilt angel and solar tracking systems lower the dust effect by 50% (Al Mamun et al., 2022). Panels can be "self-cleaned" by rain (Jung et al., 2022), or cleaning robots can be used, that consume little water (Dutta et al., 2022). However, the use of cleaning robots in agrivoltaics plants is challenging as the panels can be scattered, and it is not economical for each panel to have a dedicated cleaning robot. Cleaning can be done manually, by heavy machinery or by small robots (Hajiahmadi et al., 2023). An automatic washing machine, using sprinklers, can be placed on the panels (Hadas, 2023).

In many agri-PV sites in the developing world, rainwater is collected to be used for cleaning the panels and irrigating the crops under them (Dutta et al., 2022; Al Mamun et al., 2022, Neupane Bhandari et al. 2021; Giri et al. 2022).

The costs of cleaning the PV modules or repairing the energy system are likely to be higher for agri-PV than for ground-mounted PV systems, as this work needs to be done at a greater height, using lifting platforms. This is particularly significant in regions with long dry summers (for example Mediterranean climate areas or arid areas), whereas in temperate climates, where rain is abundant all year round, the difference might be minor (Fraunhofer ISE, 2022). Placing the panels inside greenhouses might lower the need for cleaning, as the panels' exposure to dust is lower.

Additional labor in farm operation

The mounting structure which elevates the panels truncates the fields, which may lead to additional agricultural labor, especially when operating heavy machinery, in comparison to fields without panels. Some agricultural machinery, for example vineyards' harvesters, cannot be used when the plantation includes agri-PV structures. The matrix of shadow and light creates rows and areas where flowering and ripening come at different times, making it difficult to mechanically harvest the field at a specified time.

Analysis of different agri-PV technologies

Data collection for economic and structural components of agri-PV projects is challenging. Many commercial companies are reluctant to expose their economic data. Therefore, a literature review was used to analyze economic data, while an on-site survey of agri-PV projects was focused more on the structural dimensions of the mounting structures and additional parameters that are necessary for the sustainability analysis.

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Agri-PV in open fields – literature survey

Methodology

A literature survey was conducted, regarding the economics of agri-PV systems, focusing on investment costs. The survey included academic publications in peer-reviewed journals, publications of governmental agencies (such as the NREL in the USA and the Ministry of Agriculture in Israel), publications of research institutes (such as the Fraunhofer Institute for Solar Energy Systems or Wageningen University)) and presentations from recent academic conferences (such as the 2nd Annual Agri-Voltaics Europe conference, Amsterdam or the Agrivoltaics Industry Forum Europe, Strasbourg, both held on November 2023).

Altogether 56 relevant publications were scanned, but only 18 publications were proved to contain data about relevant economic parameters (investment cost and its components). However, as many of these publications describe more than one system, there are altogether 44 systems in the database. One publication (Horowitz et al., 2020) presents average modeled costs for eight states in the USA. The earliest publication in the database is from 2020, and the latest is from 2023. The publications relate to 18 countries, as detailed in the following Figure.

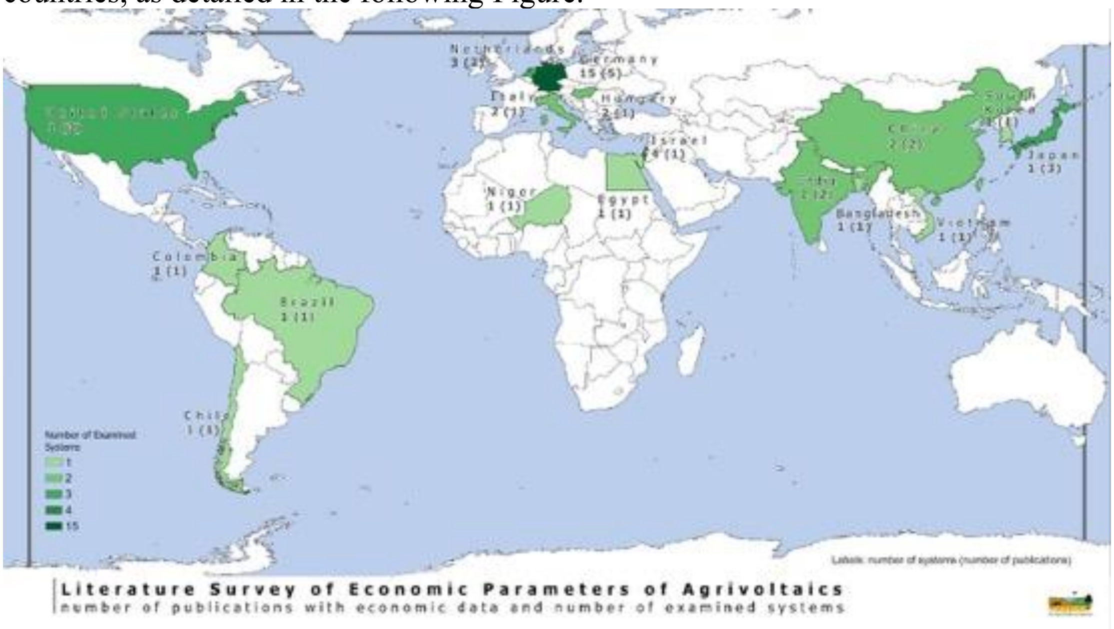

Figure 31: Literature survey of economic parameters of agrivoltaics

For each publication and system, the following data was collected: year of publication; country; agri-PV technology; crop. Costs of the following investment items: total investment cost; total capital cost, total labor cost; cost of modules, inverter, structure for modules mounting, electrical components; design, management, testing ("soft costs"); preparation and installation, fencing, network connection and other costs. Design, management, testing, preparation and installation were considered labor cost, whereas all the other items were considered capital cost.

For each publication a short system description was prepared, including pictures of the system, when available.

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Results

Mounting structure

There is very little information in the research literature regarding the materials used for the mounting structure of agri-PV systems[14]. Agostini et al. (2021) found that the amount of material in 3 different designs of agri-PV systems is as detailed in the following table.

Table 21: Materials for support structure and auxiliaries' foundations, aggregated value, kg per kW. Source: Agostini et al, 2021

agri-PV technology	**crop**	concrete (total)	steel (total)	aluminum
Static panels, concrete foundation and steel poles	arable crops	717	1075	not applicable
Tensile structure 1 axis tracker	arable crops	13	171	11
Tensile structure 2 axis tracker	arable crops	13	222	12

Data regarding the materials used for the mounting structure was collected in a survey of Israeli open-fields agrivoltaics projects (presented in the next chapter).

Capital costs and labor in installations

The following charts present the analysis of the literature survey in box plots. The average total investment of an open fields agri-PV project in is 1,200 Euro / kW. The average capital cost is 989 Euro / kW, and the average cost of labor in preparation and installation is 350 Euro / kW. The average cost of design, management and testing is 94 Euro / kW, which can be considered as part of the labor cost, or as a separate cost category.

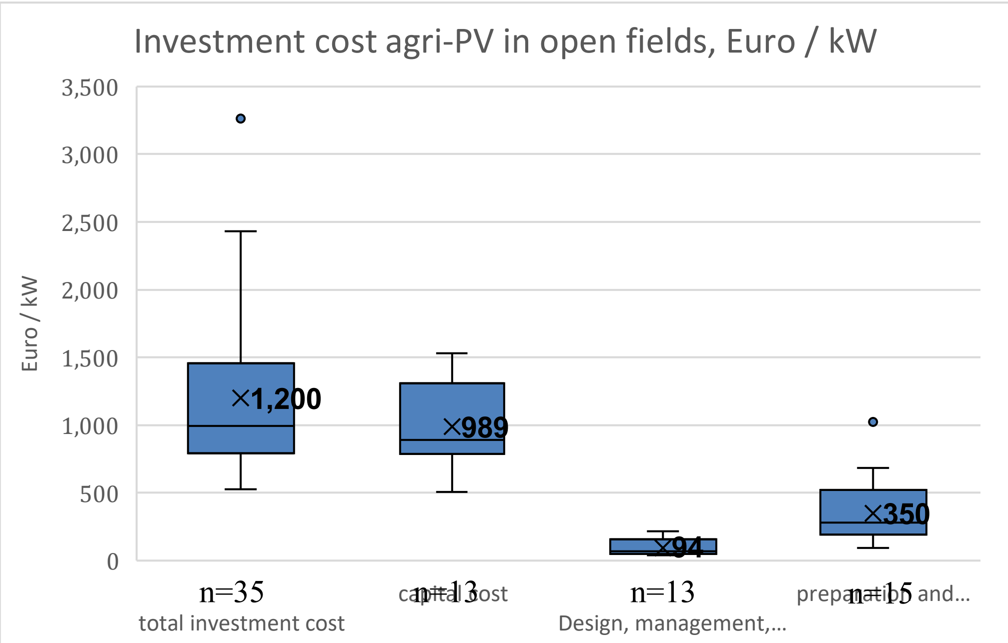

Figure 32: Investment cost in agri-PV in open fields, Euro / kW. Source: analysis of literature survey

[14] In order to bridge this information gap,tThe survey of open-fields agri-PV and greenhouse agri-PV, that are detailed in the following chapters, will focus mainly on estimating the amount of materials in the mounting structure.

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As for the components of capital cost, the most expensive one is the modules costing on average 456 Euro / kW. The mounting structure is the second most expensive component, costing on average 339 Euro / kW. The range of results for the cost of the mounting structure is wide (minimum cost: 50 Euro / kW; maximum cost: 683 Euro / kW) reflecting the different mounting technologies (reinforced regular mount, tracker stilt mount, vertical mount etc.).

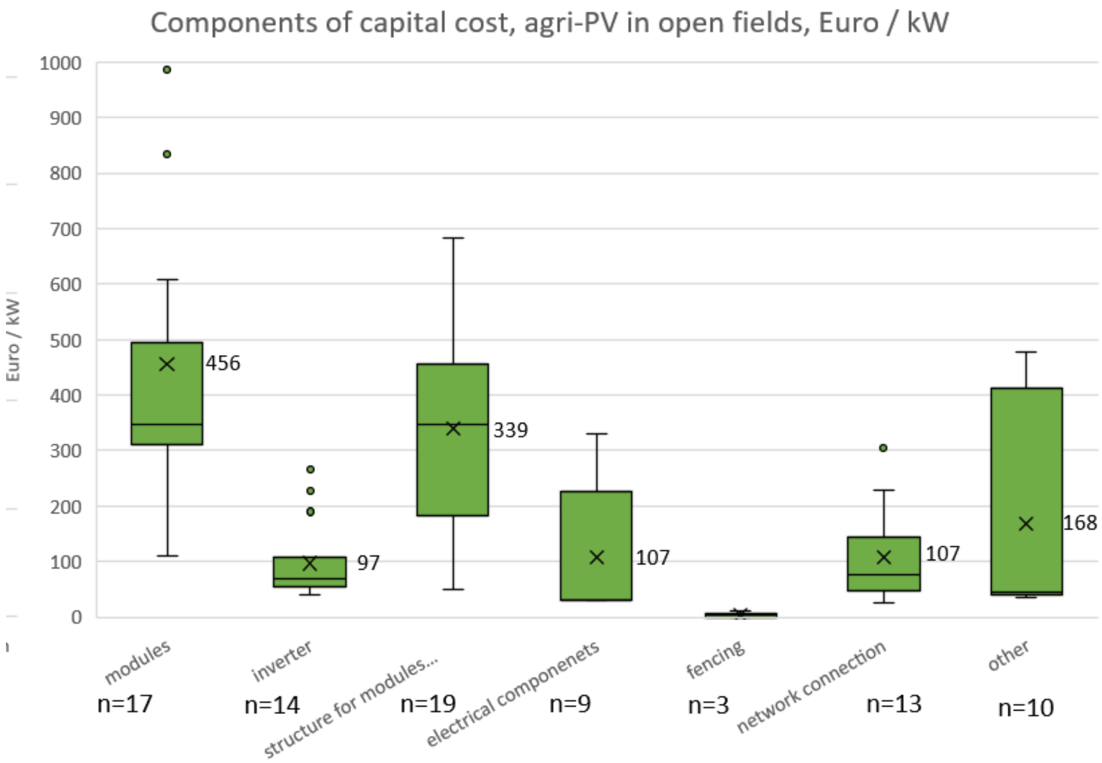

Figure33 : Components of capital cost, agri-PV in open fileds, Euro / kW. Source: analysis of literature survey.

The following Figure details the share of the different components of the total investment cost. The modules account, on average, for 27% of the total investment cost; while the mounting structure and preparation and installation each account for 20% of the total investment cost.

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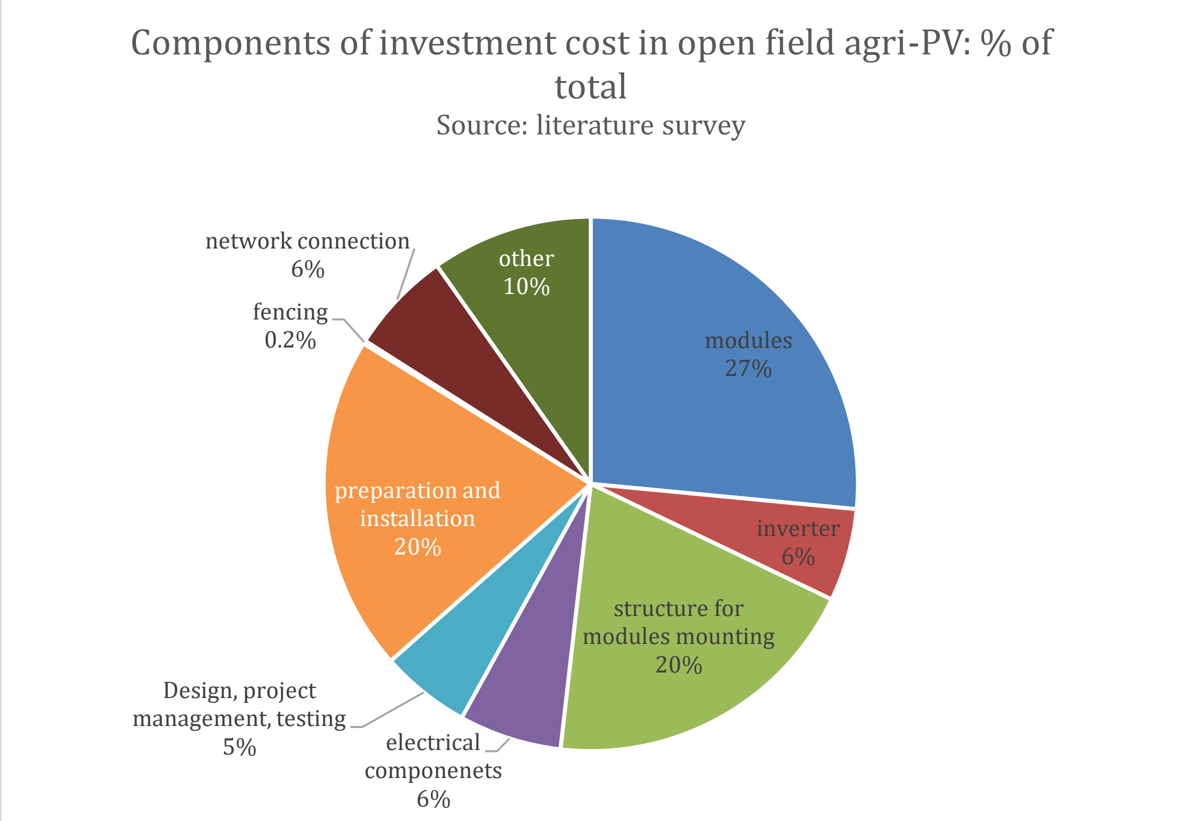

Figure 34:Components of investment cost in open-field agri-PV: % of total. Source: analysis of literature survey.

Farmland occupation by the mounting structure of the agri-PV system

Very little was published regarding the occupation of farmland by the mounting structure of agri-PV systems. Agostini et al. (2021) found that about 10-20% of the farmland is used for foundations of the mounting structure or is occupied in a way that impedes the use of large agricultural machinery (Agostini et al., 2021).
In a research site in Germany, an innovative mounting structure was used, based on concrete-free foundations; the supports are secured by a sort of corkscrew bolt (spider anchor) in the ground. Using this technique reduces the toll on farmland: the share of area lost within the agrivoltaic system is only approximately 8.3%. The researchers also maintain that the system can be dismantled without leaving residue behind (Feuerbacher et al. 2022, Trommsdorff et al. 2021).

Maintenance of the solar system: water, chemicals and labor

There is little reference to the amount of water used for panel cleaning in the research literature. The necessary frequency of cleaning depends on the conditions of the site, its climate, the type of agricultural activity and crop (Dutta et al., 2022; Hajiahmadi et al., 2023). The only evidence that was found in the literature for the amount of water used for cleaning is from a 3 MW agrivoltaics solar plant in India, that occupies 7.08 hectares of land and where vegetables are grown under the panels. Annually, 7,800,000 liters of water were used for cleaning the panels (2,600 liter / kW). The water used for cleaning the solar panels was reused for irrigation of the crops cultivated under the panels (Patel et al. 2019).

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Additional labor in farm operation

Feuerbacher et al (2022, 2021) found that under agri-PV, farm inputs are increased (in comparison to farms without agri-PV), especially labour (by 5%) and machinery use (by 10%). The intensity of other inputs (seeds, agrochemicals, etc.) remains unaffected.

Agri-PV in open fields – survey of existing projects in Israel

Methodology

A survey was conducted to identify all the agri-PV projects in Israel, in February-May 2023. Two projects were identified, both operating at research institutions. One project, at the Arava Institute for Environmental Studies, was visited on 23 April 2023.

The survey was conducted again on June-July 2024, this time additional 4 projects were identified, projects that started operating at the end of 2023 or the beginning of 2024. These projects were visited in August-September 2024. In one site (Ma'ale Gilboa) there are 9 plots using different agri-PV technologies, of which 4 are active and 5 are not yet constructed. Considering only the active plots, the database contains all together 9 data entries.

The following table gives background information on the agri-PV sites in the survey.

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Table 22: Characteristics of the agri-PV sites in the survey

no	site	category	date of visit	year of establish-ment	status of operation
1	Arava	experimental	23.04.2023	2019	Built and produces energy
2	Gvat	commercial demo plot	01.08.2024	2023	Built and produces energy
3	Revadim	commercial	23.09.2024	2023	Built and produces energy
4.1	Maale Gilboa	commercial	22.8.2024	2023	not constructed
4.2	Maale Gilboa	commercial	22.8.2024	2023	Partly constructed, not yet connected to the grid
4.3	Maale Gilboa	commercial	22.8.2024	2023	Partly constructed, not yet connected to the grid
4.4E	Maale Gilboa	commercial	22.8.2024	2023	Partly constructed, not yet connected to the grid
4.4W	Maale Gilboa	commercial	22.8.2024	2023	Partly constructed, not yet connected to the grid
4.5	Maale Gilboa	commercial	22.8.2024	planned for the end of 2024	not constructed
4.6	Maale Gilboa	commercial	22.8.2024	planned for the end of 2024	not constructed
4.7S	Maale Gilboa	commercial	22.8.2024	planned for the end of 2024	not constructed
4.7N	Maale Gilboa	commercial	22.8.2024	planned for the end of 2024	not constructed
5	Ramat Negev	experimental	4.8.2024	2024	built but does not produce energy
6	Bar Ilan	experimental	11.8.2024	2021	Built and produces energy

The managers of the agri-PV projects were interviewed on each site, using a semi-structured questionnaire (see annex 1 for the questionnaire). The questions related to

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the following: background information on the site (size, year of establishment, crops, technology); construction materials (ground foundations, above-ground supporting structure); height and number of pillars, span between pillars; investment cost in constructing the system; work hours in constructing the system; system's maintenance. The interviewees were also asked to specify, to their opinion, what are the factors that distinguish between solar systems in open fields and solar systems in greenhouses.

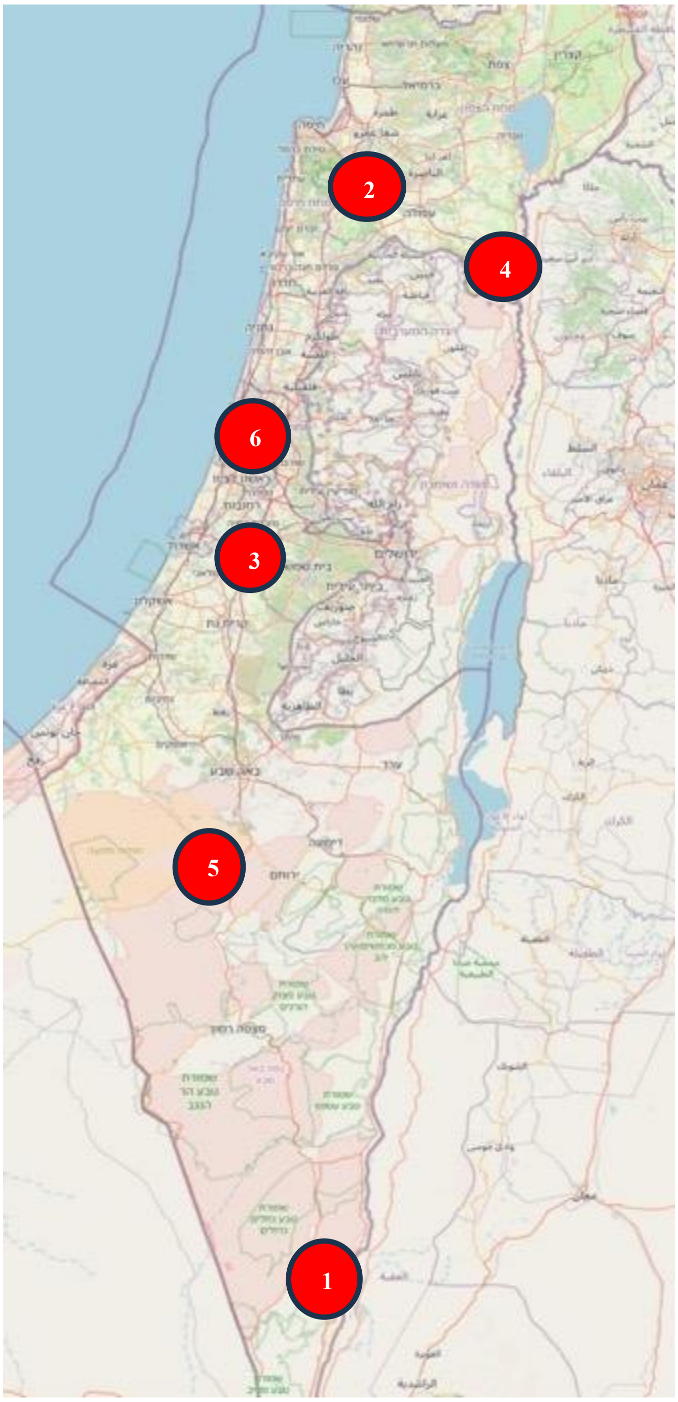

Figure 35: Location of the agri-PV projects in the survey

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Results

General characteristics

Half of the projects are experimental – located in universities or regional R&D centres. 2 projects are commercial, and one is a demo plot of a future commercial site.

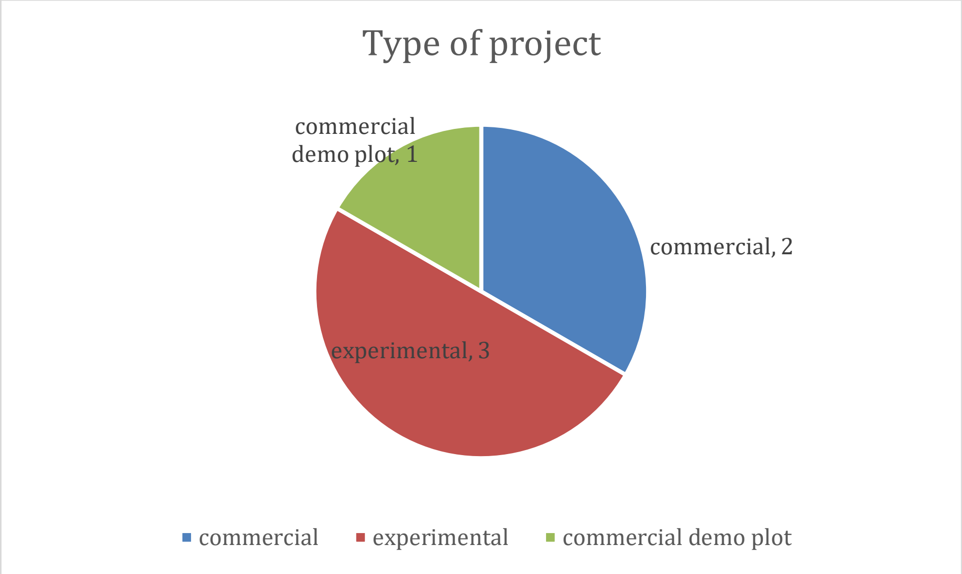

Figure 36: Type of agri-PV projects in the survey

Year of establishment

The projects were established recently, the earliest was established in 2019. 3 were established in 2023 (one of which is not yet fully built).

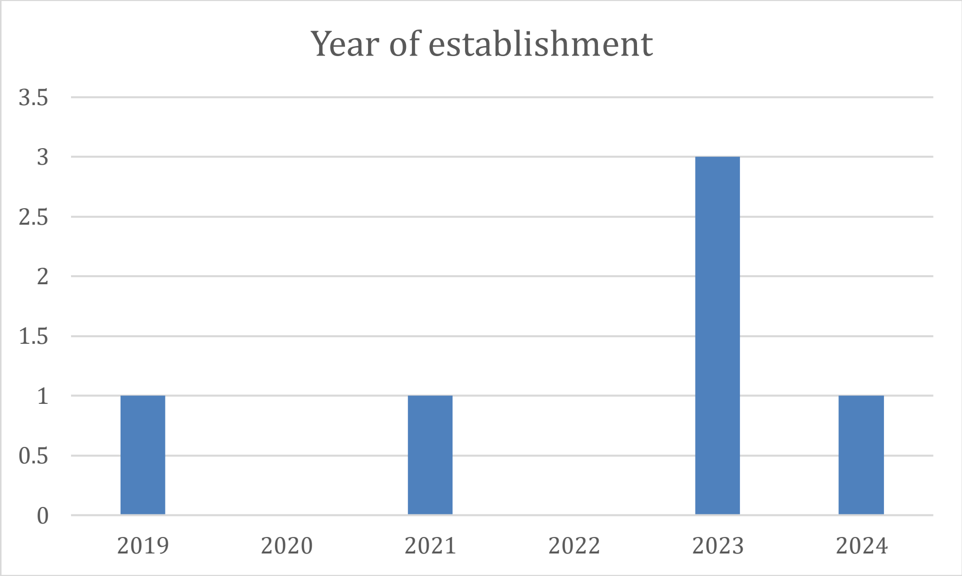

Figure 37: Year of establishment of the agri-PV projects in the survey

Status of operation

4 projects are fully built and produce energy. One project is partly constructed, and one project is fully constructed but does not produce energy due to regulation challenges.

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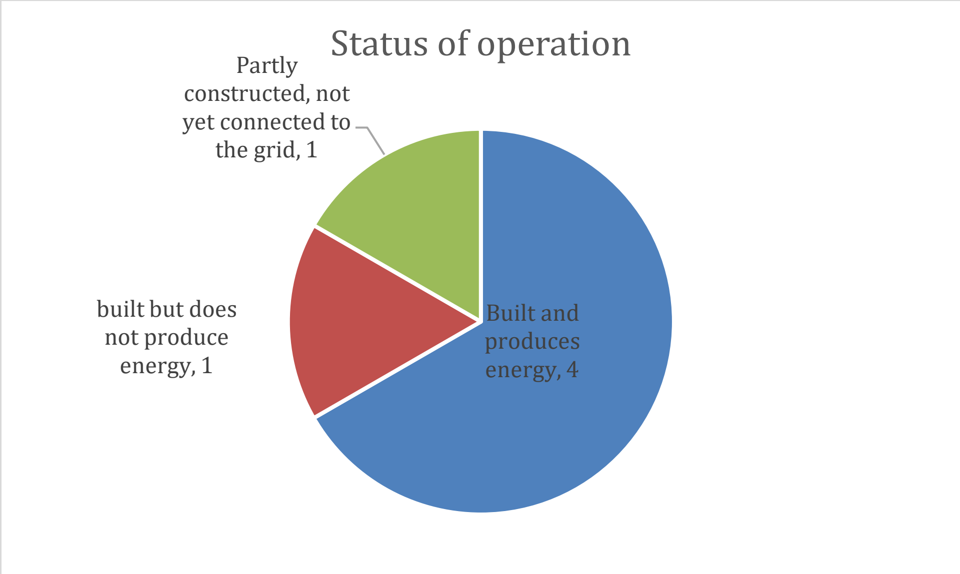

Figure 38: Status of operation of the agri-PV projects in the survey

<u>Size of agri-PV installation</u>

The range of the projects' installation size is extensive: from 100 m2 (the smallest project, located in an R&D center) to 100,000m2 (the largest commercial project).

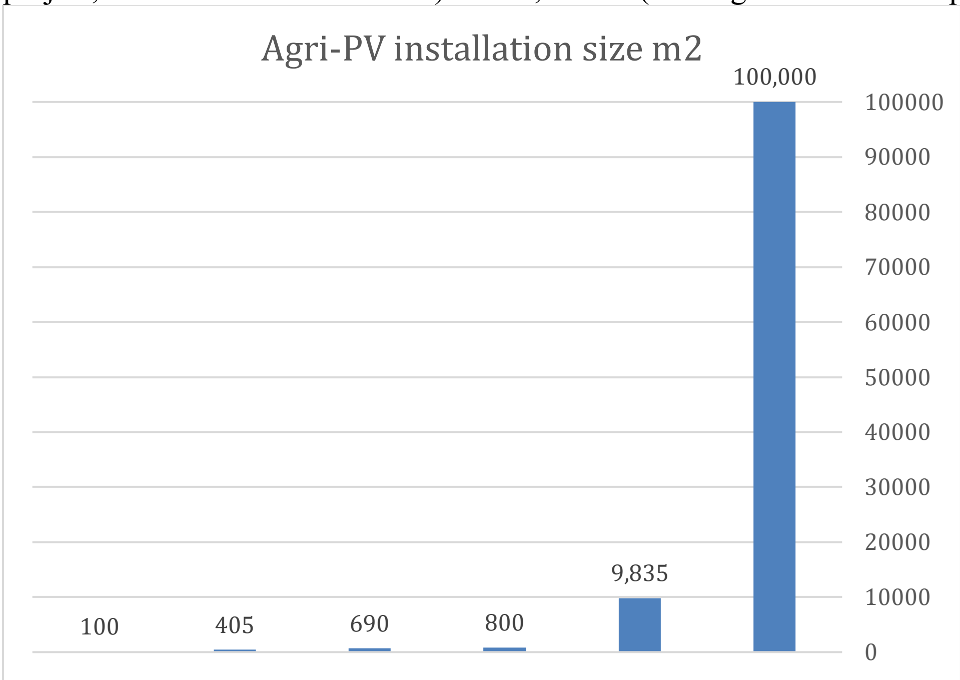

Figure 39: size of agri-PV installations in the survey, m2

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Coverage rate of the panels

The average coverage rate of all the plots[15] is 27%. However, the range is extensive: from 9% (a plot of field crops with free standing poles holding the panels) to 50% (a small installation at an R&D center).

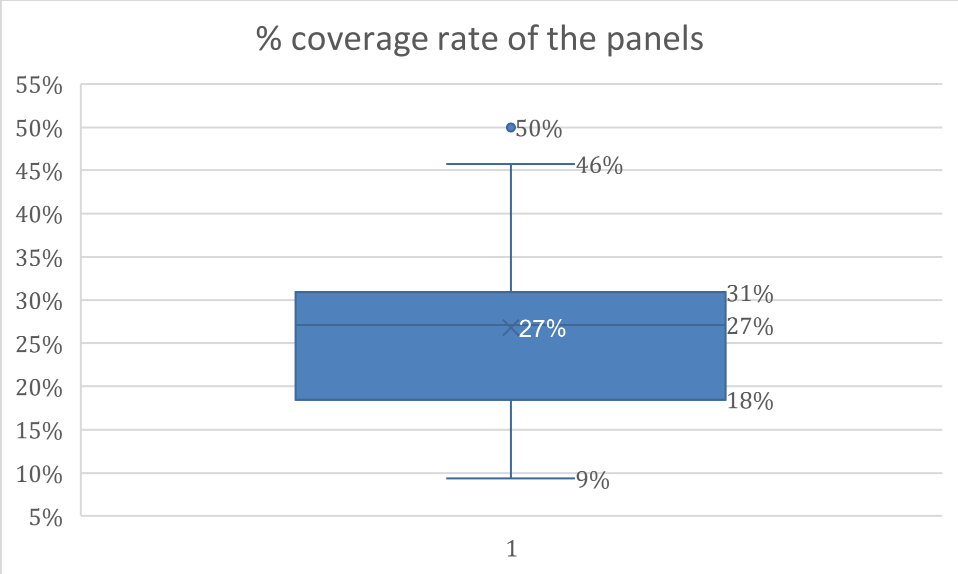

Figure 40: % coverage rate of the panels, plots of projects in the survey

Installed power density

The range of installed power is extensive: from 8 kW on a small experimental project to 10 MW on a large commercial project.

On average the installed power density is 60.6 kW / 1,000 m2, which is in line with the agri-PV projects in the EU (see Chatzipanagi et al. 2023).

[15] All projects' plots are counted hare, as there are different coverage rate in different plots of the same project. There are 14 different plots in the 6 projects, including plots that are not yet operational.

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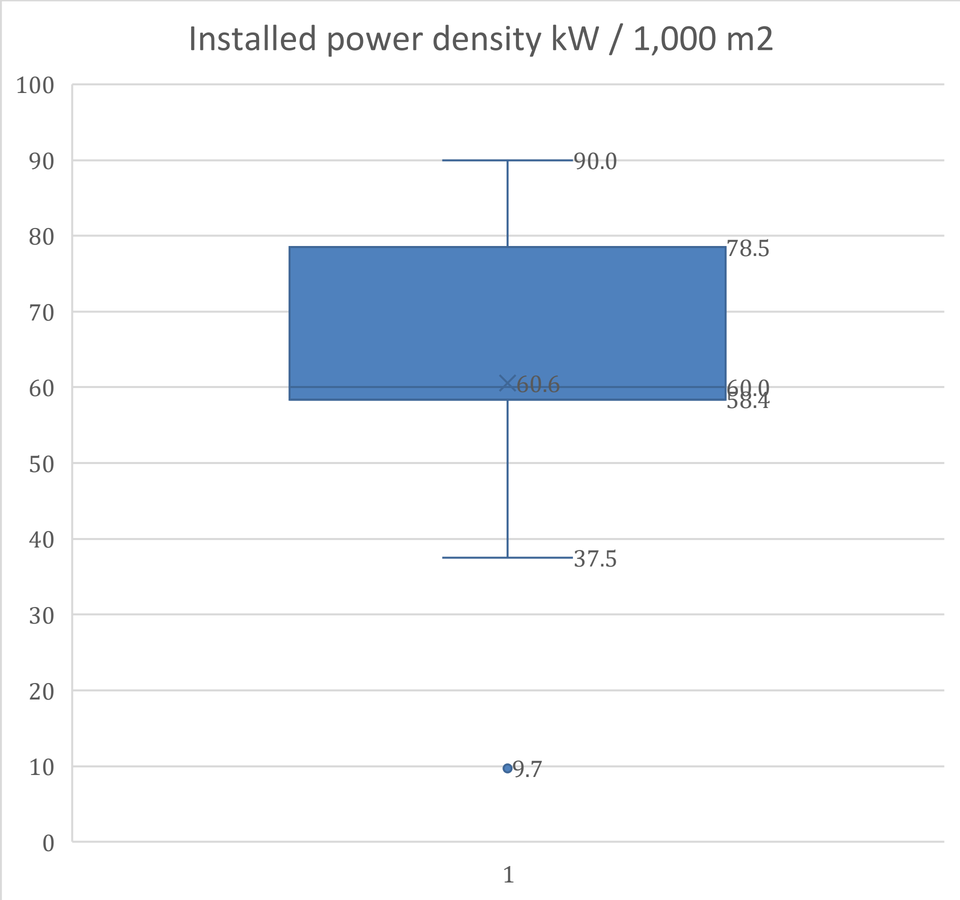

Figure 41: Installed power density kW/ 1,000 m2, plots of projects in the survey

Crops

In 6 plots[16] the crop is vineyards, either for table grapes (5 plots) or wine grapes (1 plot). In 3 plots the crop is field crops in rotation. In 3 plots there are fruit plantations: Avocado (1 plot) and Mango / Lychee (2 plots).

[16] All projects' plots are counted here, as there are different crops in different plots of the same project.

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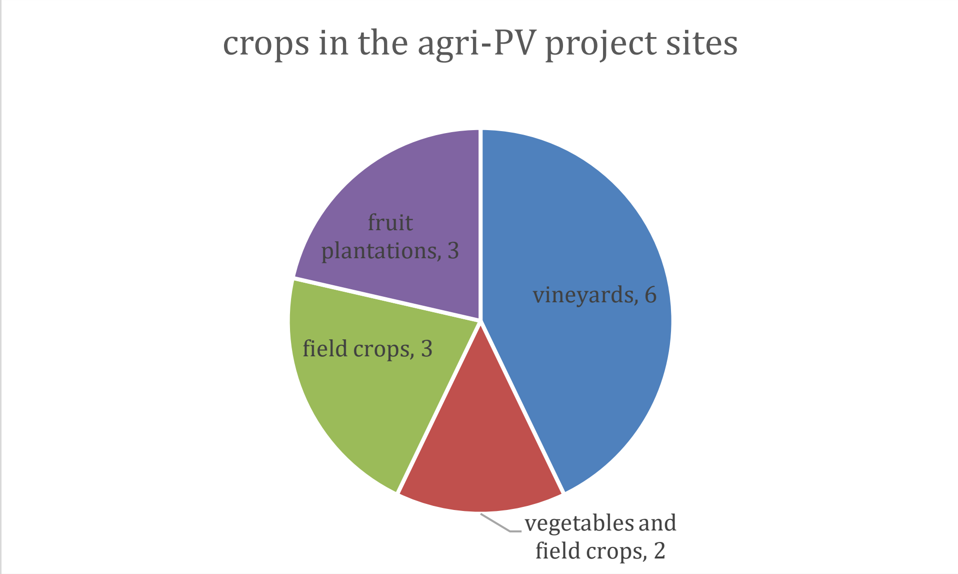

Figure 42: Crops in the plots of the agri-PV projects in the survey (14 plots in 6 projects)

Panel technology

6 plots[17] have single-axis tracker, while 4 plots have fixed panels and 3 have dual-axis tracker. One plot has a unique panel technology in which the panels move on horizontal rails, so that the panels track the sun while remaining parallel to the ground.

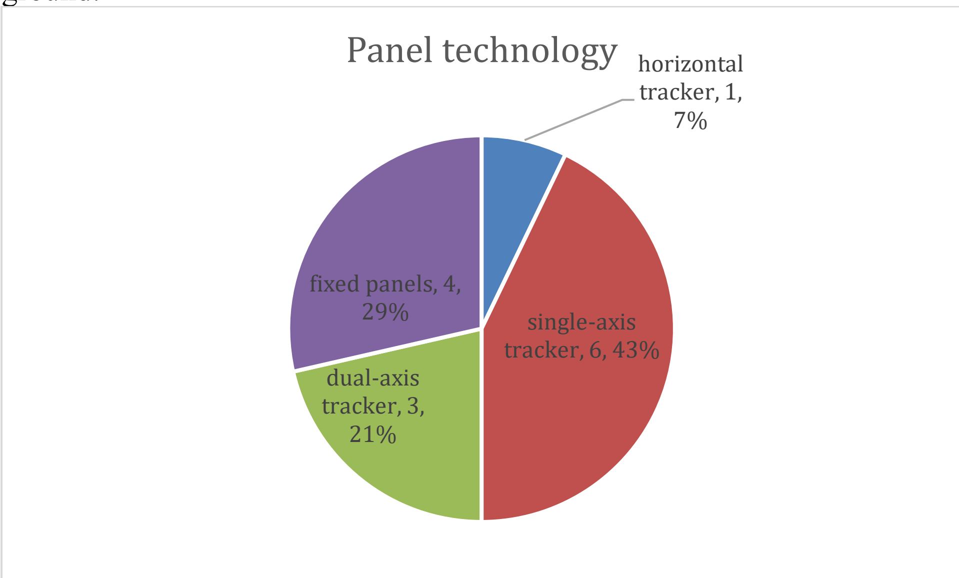

Figure 43: Panel technology in the agri-PV projects in the survey (14 plots in 6 projects)

Mounting structure

Foundations technology and materials

The dominant technology for foundations is ground screw foundations: inserting a galvanized-iron screw 2 m into the ground. This technology is practiced in 4 of the

[17] All projects' plots are counted here, as there are different panel technologies in different plots of the same project.

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studied sites[18], whereas the other 2 sites use reinforced concrete foundations. Using ground screw foundations is probably the only option when constructing an agri-PV facility over an existing plantation, as its impact on the trees' roots is minimal.
The sites' managers could not specify the amount of iron that is used for each screw foundation, as it is an off-the-shelf product, widely used in the agri-PV industry.
In the sites where concrete foundations are used, the amount of concrete is 0.25-0.5 m3 / single foundation.

Above the ground structure

There are many arrays and techniques for designing the mounting structure, and each plot has its own unique design.
All the sites use conventional reinforced regular mounting structure. Other techniques, such as vertical mount or tracker stilt mount, are not used. In one site the panels tracking system allow the panels to reach a vertical state, which is used when working in the field with heavy machinery, to allow the agricultural machines to move between the rows of panels. However, the panels are not held in vertical position on normal conditions.
All the sites use galvanized iron as the main material of the mounting structure.
On average, the pillars of the mounting structure are 3.3 m high, the range of pillars' height spans from 1.5 m (at an experimental plot of different field crops) to 4.5 m (at a plot of mango/lychee plantation, that is not yet constructed).

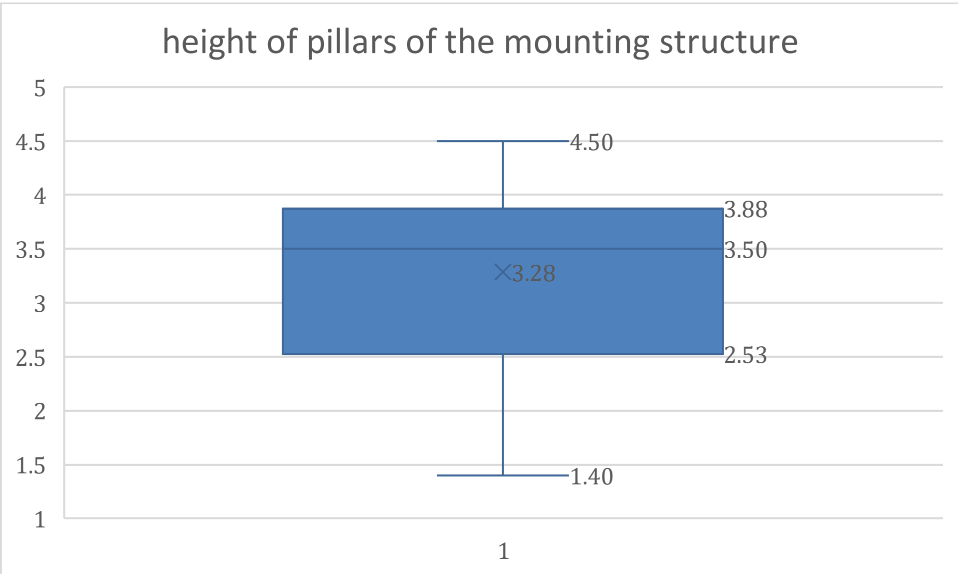

Figure 44: Height of pillars of the mounting structure in the agri-PV projects in the survey (14 plots in 6 projects)

On average, the mounting structure has 66 pillars / 1,000 m2. However, the range of pillars' number is extensive: from only 3 / 1000 m2 at a plot of field crops with single free-standing pillars, to 162 / 1000 m2 at a plot of vineyards with fixed panels.

[18] In one of the sites – concrete foundations are used under the pillars that support the tracker, whereas under the pillars that support the panels – ground screw foundations are used.

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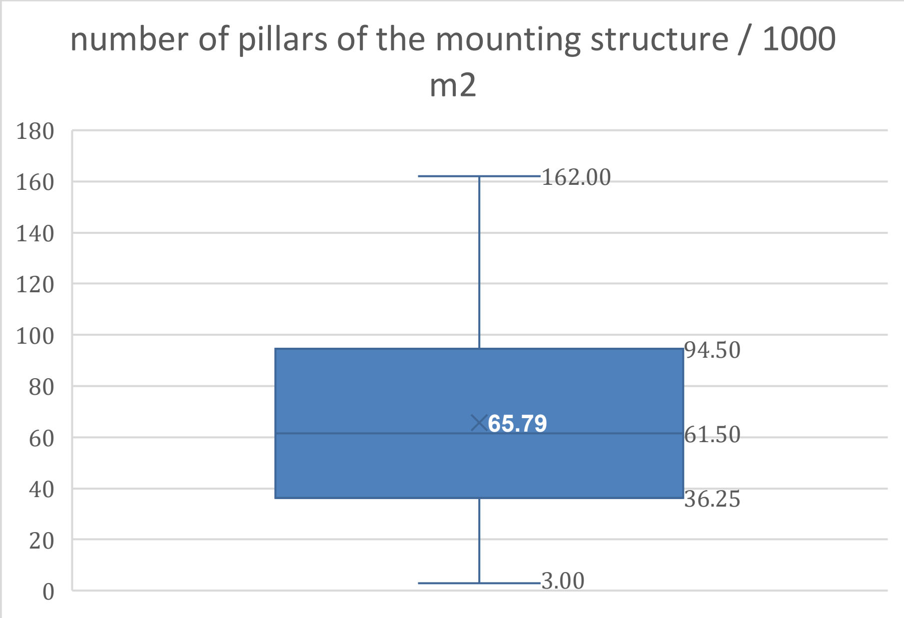

Figure 45: Number of pillars of the mounting structure / 1000 m2 in the agri-PV projects in the survey (14 plots in 6 projects)

On average, the span between rows of pillars of the mounting structure is 7.25 m. The range is from 3.5 m, at a densely planted vineyard, to 16 m at a commercial demo plot of field crops.

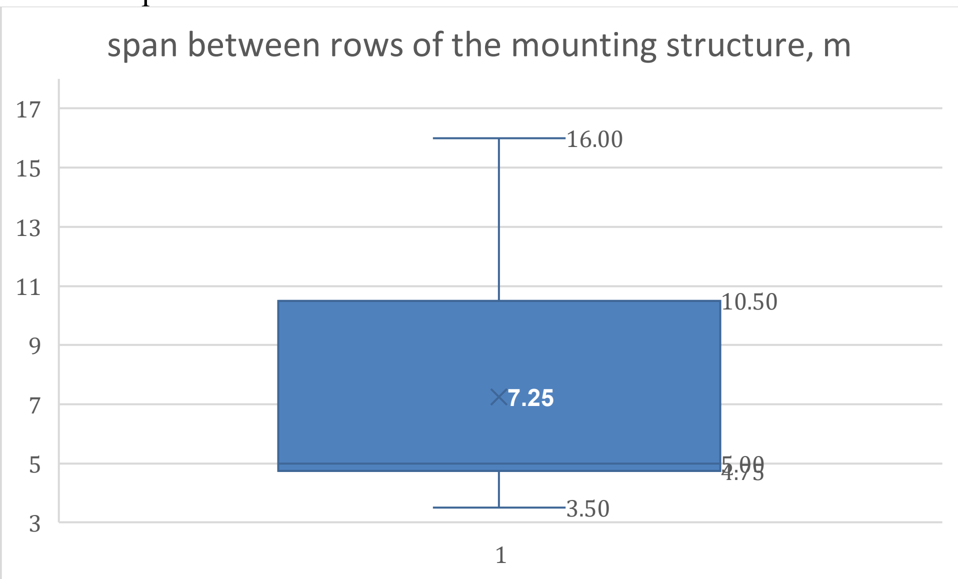

Figure 46: Span between rows of the mounting structure (m) in the agri-PV projects in the survey (14 plots in 6 projects)

On average, the span between pillars in a row is 4.7 m. The range is from 3 m at a commercial demo plot of field crops, to 6 m in plantation of avocado and vineyard.

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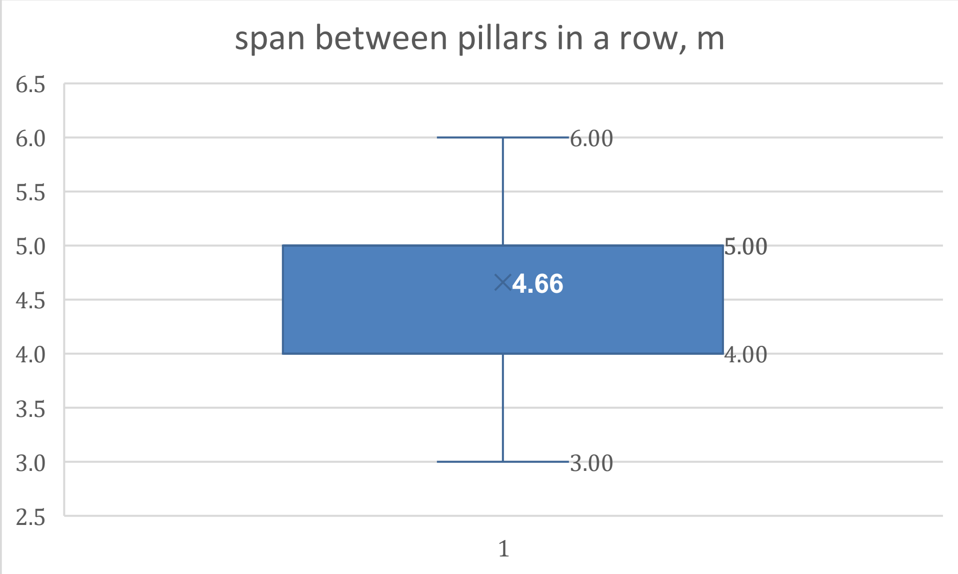

Figure 47: Span between pillars in a row (m) in the agri-PV projects in the survey (14 plots in 6 projects)

In 7 plots (out of total 14 plots in 6 sites) there are no connecting beams between the rows. In 6 plots connecting beams exist. In one project the design is mixed: in certain areas, the solar panels are above the plantation trees, and there are no connecting beams between rows of the mounting structure. In other parts of the project, the solar panels are located between the rows, in which case there are connecting beams between rows and the panels are mounted on the connecting beams.

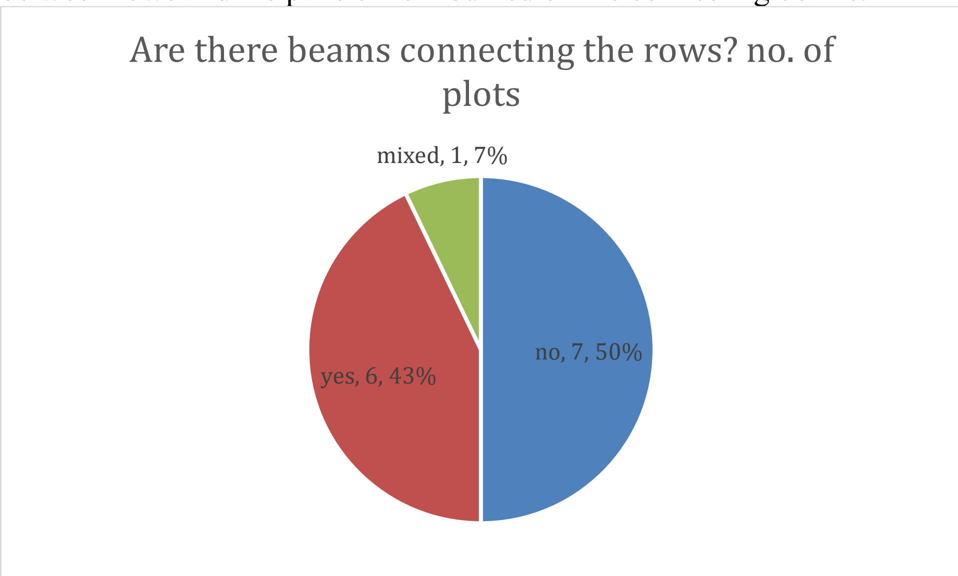

Figure 48: Existance of beams connectingt the rows,agri-PV projects in the survey (14 plots in 6 projects)

<u>The total amount of iron in the mounting structure</u>: the weight of the components of the mounting structure (ground screws, pillars and beams) was calculated according to standard iron profiles, that are commonly used in the agro-voltaic industry. Each agro-voltaic site uses different iron profiles, and the weight of the profiles (kg/ m length) was calculated specifically for each site according to the specific profiles used and its specific array of pillars and beams.

The parameter was calculated for the 6 sites in the survey, but as one site had extremely high results it was excluded from the data set. One site had 4 plots, each

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with different structures' array, so each plot was included as a separate data point in the database.

The following chart presents the weight of iron components of the mounting structure per land size of open fields agri-PV projects (kg of iron / 1,000 m2).

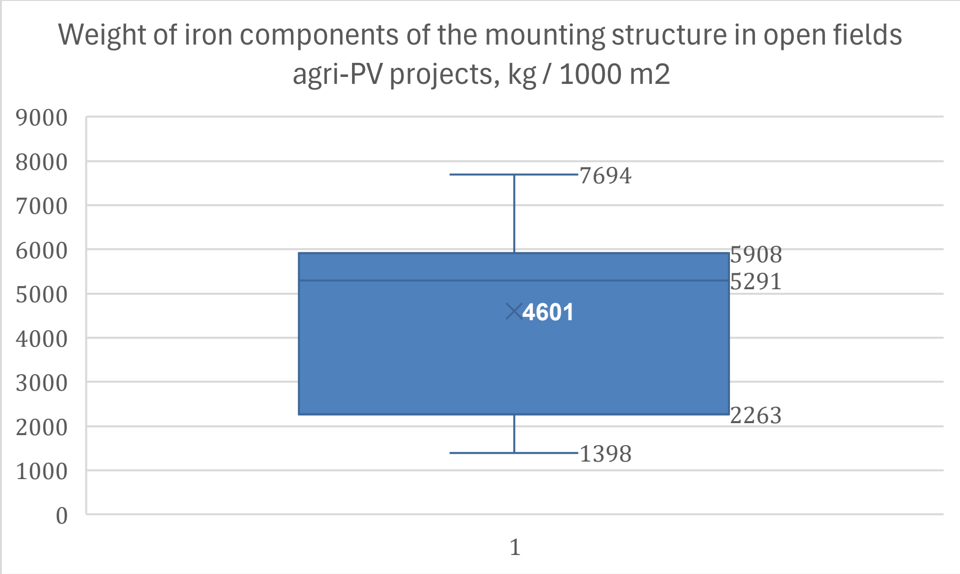

Figure 49: Weight of iron components of the mounting structure in open fields agri-PV projects, kg / 1000 m2

The weight of iron profiles in open fields agri-voltaic projects is about 4,600 kg / 1,000 m2, the median value is about 5,300 kg / 1,000 m2.

The following chart presents the weight of iron components of the mounting structure per electrical power in open fields agri-PV projects (kg of iron / kW installed).

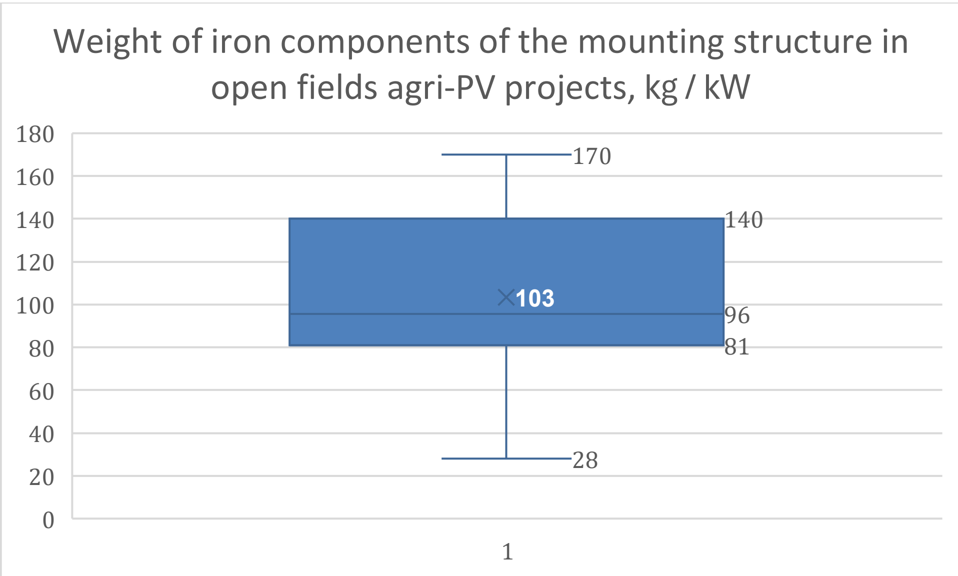

Figure 50: Weight of iron components of the mounting structure in open fields agri-PV projects, kg / kW

The weight of iron profiles in open fields agri-voltaic projects is 103 kg / kW installed power, the median value is 96 kg / kW installed power.

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Capital costs and labor in installation

The average investment cost in the agri-PV projects is 1,356 Euro / kW, which is in line with the findings of the literature review (1,200 Euro / kW, see previous chapter). The range is between 913 Euro / kW in an experimental project in vineyard, and 1,923 Euro / kW at a large commercial project that includes energy storage (all other projects don't include storage). One outlier project with exceptionally high investment cost (4,930 Euro / kW, at a small experimental site) was excluded from the data shown.

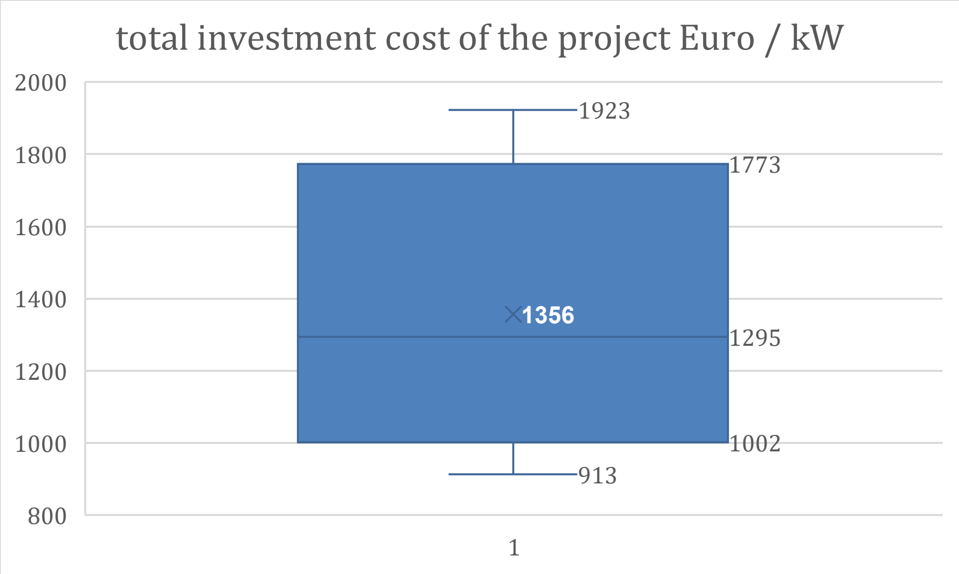

Figure 51: Total investment cost of the project Euro / kW, in the agri-PV projects in the survey (6 projects)

<u>Labor in installation</u>

Detailed information on the labor in installing the mounting structure was provided by one project only (in other sites – the projects' managers had no data regarding the labor in installation). It was estimated to be about 3 week of work * 2 people = 30 days of labor / 100 kW installed.

Farmland occupation by the structure of the agri-PV system

When integrated with plantation, the mounting structure does not occupy any farmland, as the poles are integrated in the trees' rows, between the trees. When the foundations are based on iron screws inserted in the soil – they hardly occupy any farmland.

In only 2 projects the mounting structure occupies a substantial share of the farmland. Both projects are integrated with field crops:

- A project in which concrete foundations are used, in which the foundations occupy about 3.5% of the farmland.
- A project in which the farmland under the panels is not farmed. In this case the mounting structure occupies 11% of the farmland.

Only the last result, which is an outlier in this survey, is in line with the findings of the literature review, which showed that about 8-10% of farmland is occupied by the agri-PV mounting structure.

Maintenance of the solar system: water, chemicals and system's monitoring

3 systems are washed by water, either using manual work (2 sites) or an automatic sprinklers system, installed on the panels.

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The range of frequency of washing is extensive: from 2-3 times per week with the automatic system; to 2-4 times / month and 2 times a year when the washing is done manually.
In 3 projects, washing was not yet performed, and their managers are contemplating how to do it (manually / automatically), how often, or whether at all it is worth doing, in a cost-benefit analysis.

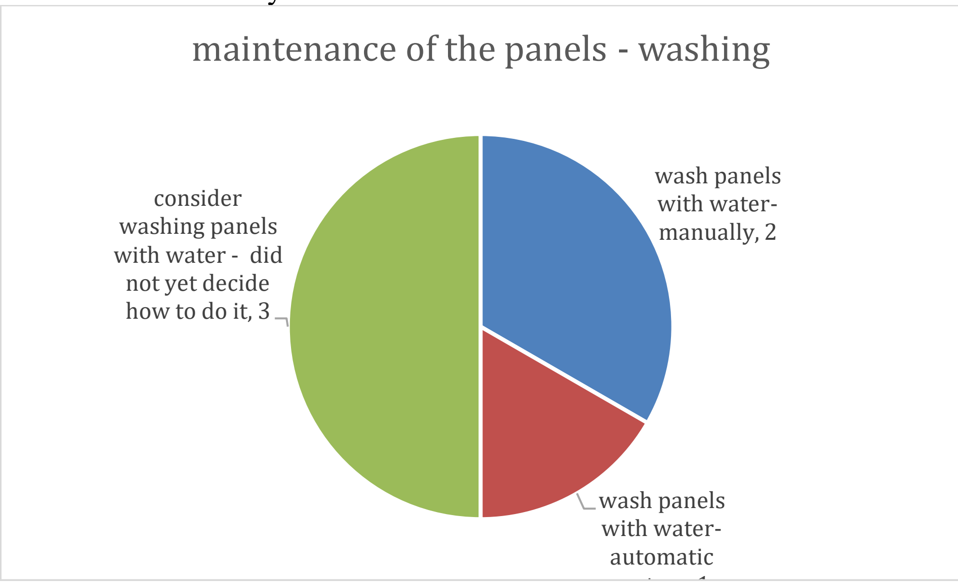

Figure 52: Maintenance of the panels – washing, agri-PV projects in the survey (6 projects)

Additional labor in farm operation

In 3 projects – no additional farm labor is necessary due to the solar system. In 3 projects the following additional farm labor is necessary due to the PV installation:

- Additional work during the harvest: the difference in shade and light in the field, due to the panels, lead to different time of flowering and fruit ripening in different areas of the field. This creates additional labor in harvest, as different areas need to be harvested at different time.
- In vineyards: the mounting structure of the agri-PV does not allow the use of mechanized harvesters. Hand-picking the grapes is time consuming[19].
- In the first years of the project, more manual work is required in pruning and use of pesticides, until all the farming protocols are studied and adjusted to the presence of the PV system.

Additional differences between open-fields agri-PV and greenhouses agri-PV

The agri-PV projects' managers were asked to point out additional differences between open-fields agri-PV and greenhouses agri-PV, to the best of their knowledge.
The additional differences that were mentioned are:
a. Advantages of greenhouses agri-PV over open-fields agri-PV:

- Many greenhouse crops need shade for better agricultural output. Farmers use shading nets in greenhouses, repalcing them with panels create synergies, that do not exist for open-field crops.
- Plants under the panels flower and produce fruit later than those in the sun. In greenhouses the harvest is mostly done manually, which allows to better adapt

[19] This challenge is less relevant for table-grapes vineyards or high-quality wine vineyards, that are harvested manually.

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to different times of flowering and fruit ripening. In open fields harvest is done with machines, and harvesting different rows in different times is complex and expensive.
- Greenhouses protect the energy systems; one can lock up expensive euipment inside the greenhouse, whereas in open fields the equipment is exposed to theft. In open-fields agri-PV projects need to be surrounded by a fence, that addes to the cost of investment.
- Fencing open-fileds agri-PV has ecological impacts – seperating the field from its surrounding landscape.
- In greenhouses there is usually one crop, season after season (mono-culture), whereas in open fields the common practice is of crop rotation, which means that the farmer has to identify 3-4 crops that are adaptable to the energy system and can be practiced together in crop rotation. In greenhouses - only one crop needs to adapt to the solar system.
- In greenhouses, the agricultural work is mostly manual or uses small tools. The mounting structure of the panels does not need to accomodate large agricultural machinery, which impacts the necessary height and span of the structure, and its cost. Some open-fields machinery, for example vineyard harvesters, is non-compatible with PV mounting structures.
- Dust - agri-PV in open fields in some areas may be less efficient due to dust. In greenhouses the panels are protected from dust.
- It is possible to diversify the crops within the greenhouse, adapting different crops according to their location in relation to the panels: shade-loving crops under the panels and sun-loving crops between the rows of panels. In open-fields it is unusual to combine together different crops in one field.

b. Advantages of open-fields agri-PV over greenhouses agri-PV:

- The radiation inside greenhouses is lower in comparison to open-fields, due to the plastic cover.
- The pillars of the mounting structure can support agricultural systems, for example frost prevention systems in avocado plantations or trellising of vineyards. The cost of trellising of vines of table grapes is about NIS 7,000 per 1,000 m2, synergy and cost savings can be achieved if some of the vines are trellised on the poles of the agro-solar system.
- It is difficult to fit an agro-PV system into existing plantation or greenhouses. The preferred way to construct an agro-PV system is to build it together with the greenhouse or with planting the plantation. Plantations are usually a sector with higher growth rate than greenhouses due to the lower cost of investment, which means that it is easier to find farmers that wants to start a new plantation than a farmer that wants to start a new greenhouse.
- The total area of greenhouses is too small to meet all renewable energy needs.
- In open fields, off-the-shelf products are used, in greenhouses the mounting structure is costume-made. Commercial companies prefer off-the-shelf products, to costume made systems.
- Agro-PV projects have economies of scale, as there is a large fixed cost: planning, measuring, maintenance etc. When the project is large, fixed costs are distributed over more land or electricity output, hence economies of scale. In greenhouses, projects are small and do not realize economies of scale.
- PV underperform in heat conditions. Agri-PV in greenhouse may be less efficient due to the heat.

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- The radiation from the panels might impact pollinators inside the greenhouse.
- The fence that is built around an agri-PV project can be used for mounting additional panels. In greenhouses projects there in no fence, no opportunity for additional energy production.

Greenhouses Agri-PV – panels on top of greenhouses' roofs

An established technology of greenhouses' agri-PV is placing the panels outside the greenhouse, either on top of the greenhouses' roof; integrating the panels directly into the roof of the greenhouse; or on the side walls of the greenhouse.
In order to understand the advantages of the technology tested in REGACE, a survey of farmers that built PV systems on their greenhouses was conducted.

Methodology

A survey was conducted among Israeli farmers who constructed agri-PV systems on top of their greenhouses. The Israeli regulations for permitting the integration of agri-PV systems on greenhouses were approved in 2021 and updated in 2023 (National Master Plan No 1/ 10, and The Ministry of Agriculture and Food Security, 2021; 2023). Since than a few dozen farmers constructed PV systems on the roofs of their greenhouses. Placing the panels on top of the greenhouse roof and on their sidewalls are the only settings that are allowed by the current Israeli regulations; placing them inside the greenhouse, as with the technology used in REGACE, is currently not allowed (although a change in this regulation is currently in the process of being approved).
To get a permit to build PV systems on greenhouses, Israeli farmers must apply to the Ministry of Agriculture and Food Security. In April 2023 a list of farmers who applied for permits was gathered from the Ministry of Agriculture and Food Security. The list contained 60 entries. The list was later enlarged based on talks with farmers' representatives, and names of farmers that were given by other farmers that were interviewed.
Some of the farmers in the database did not actually construct PV systems, and some could not be reached as the contact details were incorrect. Altogether 24 farmers that have PV systems in their greenhouses were interviewed. All interviews were conducted by phone calls, during December 2024 and July 2025.
The interviews were based on a structured questionnaire, with multiple-choice questions and open questions. The questions related to the following: background information on the site (size, year of establishment of the PV system and the greenhouse, crops, PV technology); construction materials (ground foundations, above-ground supporting structure); investment cost in constructing the system; work hours in constructing the system; system's maintenance. The impact of the PV system on yields, water use, agricultural labor, pests and other agricultural parameters. The interviewees were also asked to specify, in their opinion, what are the factors that distinguish between PV systems that are placed above the roof of the greenhouses and inside the greenhouse.

Results

General characteristics

<u>Year of establishment</u>

The largest number of PV systems in greenhouses were established in 2022, shortly after the regulation permitting them were approved. One system was established in 2019, but started producing electricity in 2022.

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This means that the farmers' experience in integrating a solar system in the greenhouse is short, up to three years of growth, and this should be taken into account in relation to their statements regarding the impact of the system on yields and other agricultural parameters. It is possible that the effects will become apparent only over a longer period.

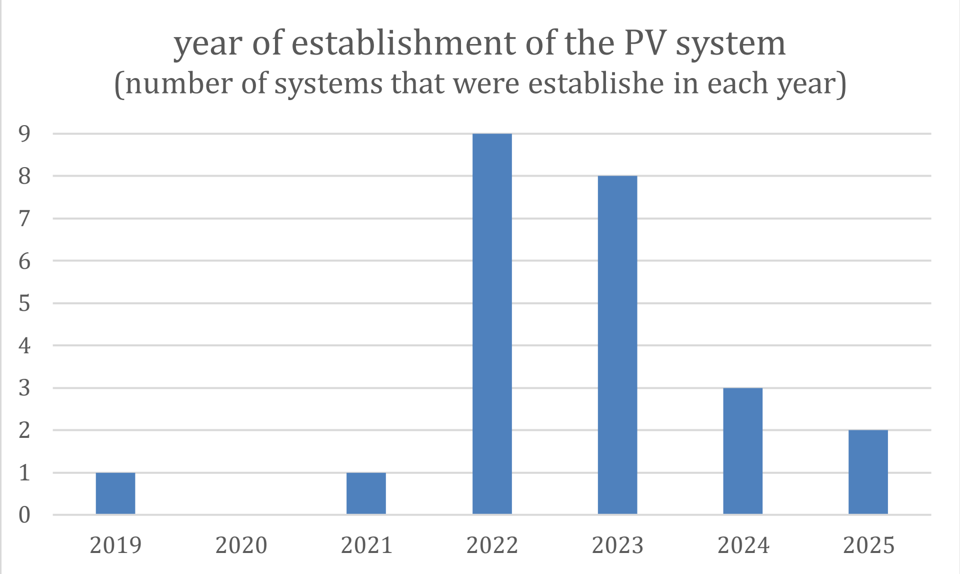

Figure 53: year of establishment of the PV system

83% of the greenhouses over which the PV systems were installed were existing greenhouses, whereas in 17% of the projects (4 projects) – the greenhouse was built together with the PV system. 42% of the greenhouses are old and were built before the year 2000. 21% of the greenhouses were established in the last 5 years (from 2021).

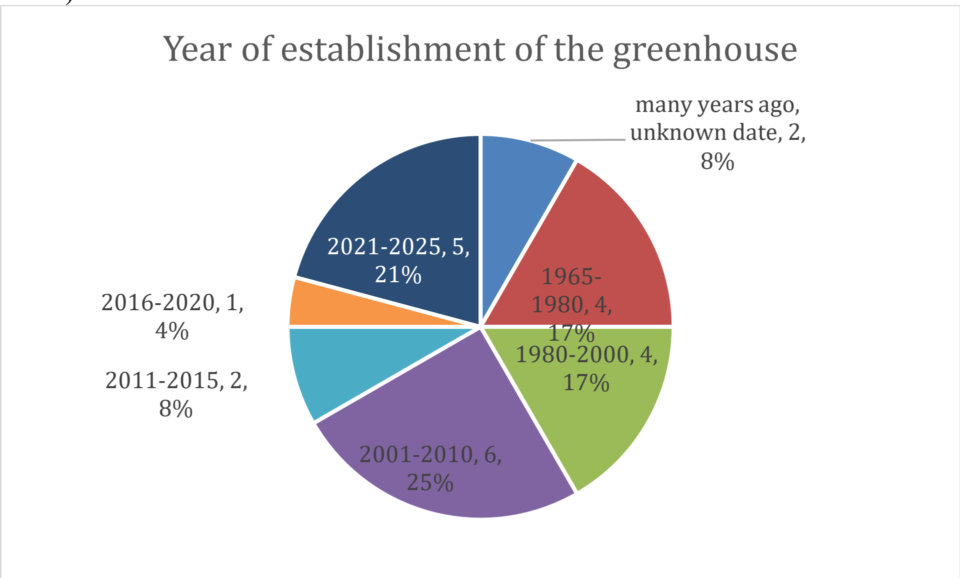

Figure 54: Year of establishment of the greenhouse

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Location of the farms

50% of the farms in the survey are in the temperate- Mediterranean climatic zone, in the center of Israel. The other 50% are located in the south of Israel, in either a desert (10 farms) or a steppe (2 farms) climatic zone.

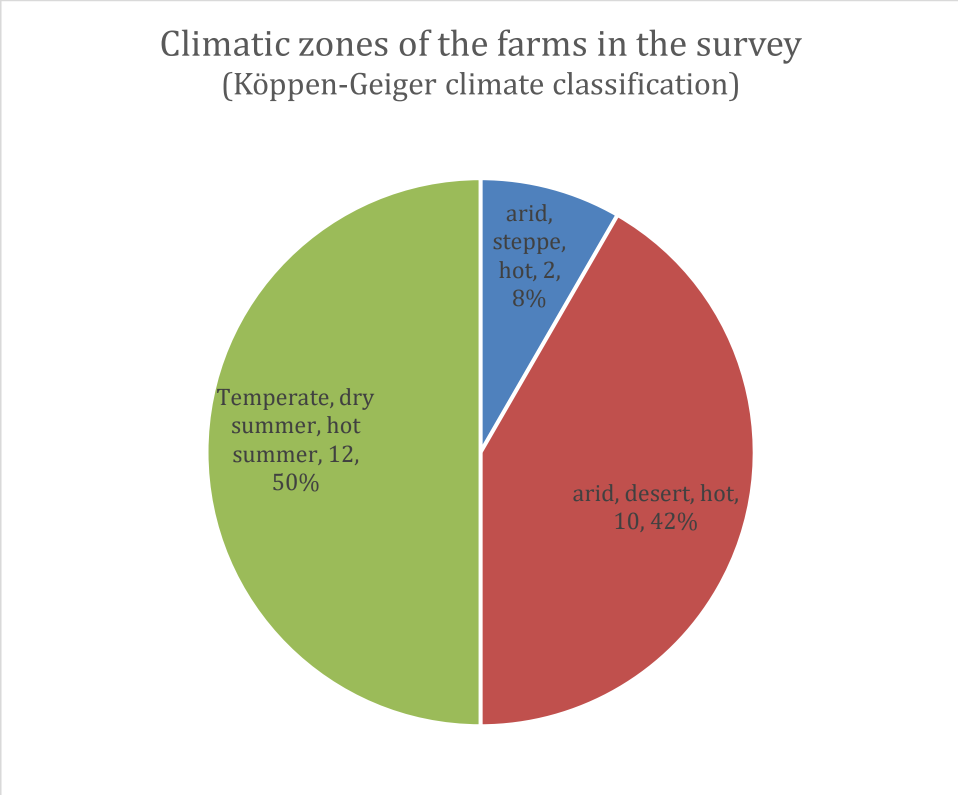

Figure 55: Climatic zones of the farms in the survey

Size of agri-PV installation

The average size of a greenhouse PV project is 8,152 m2. This is the total size of the greenhouse (or greenhouses) in the project; the PV panels are located on part of the greenhouse' roof . In some of the projects – there are more than one greenhouse.

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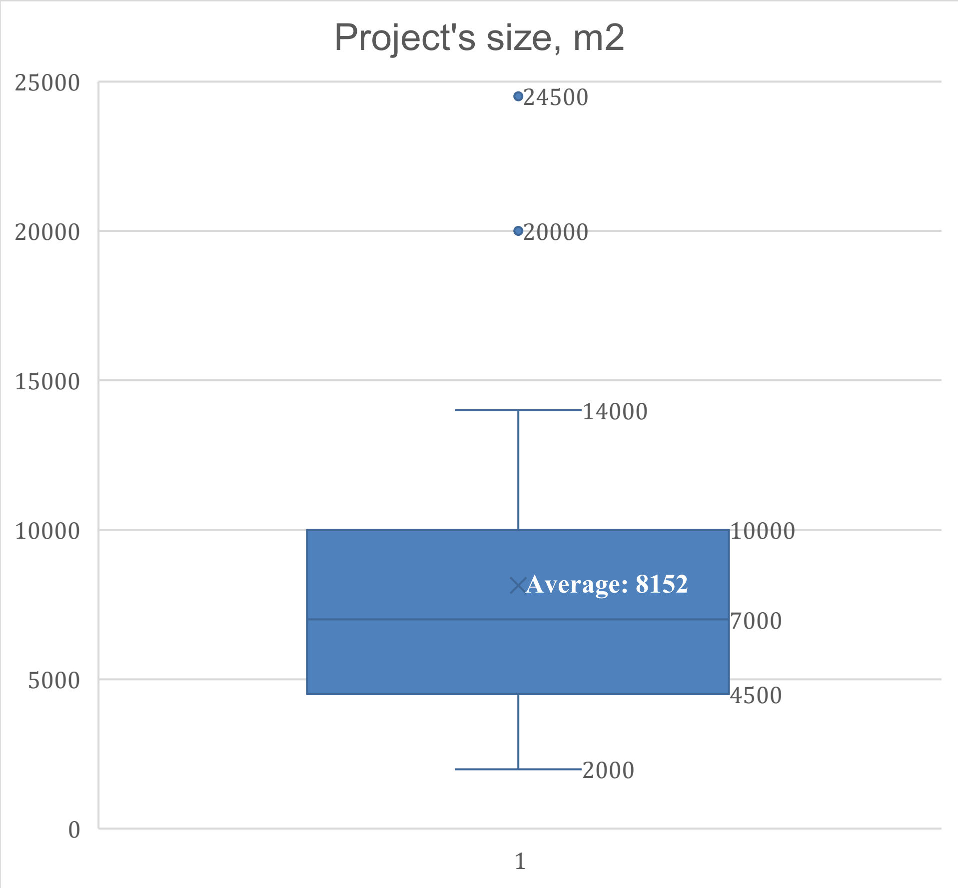

Figure 56: greenhouse solar project size

Coverage rate of the panels

The regulations in Israel allow for coverage rate of 15% in greenhouses. However, only 54% of the installations have a coverage rate of 15%. 16% have lower coverage rate, and 13% have higher coverage rate.

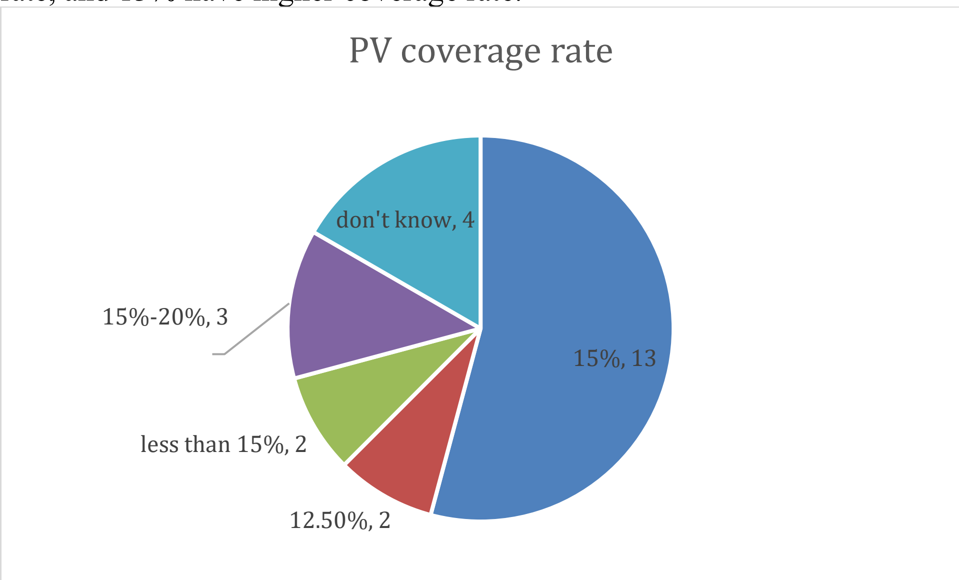

Figure 57: PV coverage rate

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Installed power and power density

The average installed power density in the survey is 30.4 kW / 1,000 m2 (compared with 39.6 kW / 1,000 m2 in REGACE installations). 3 installations had the maximum power density of 50 kW / 1,000 m2.

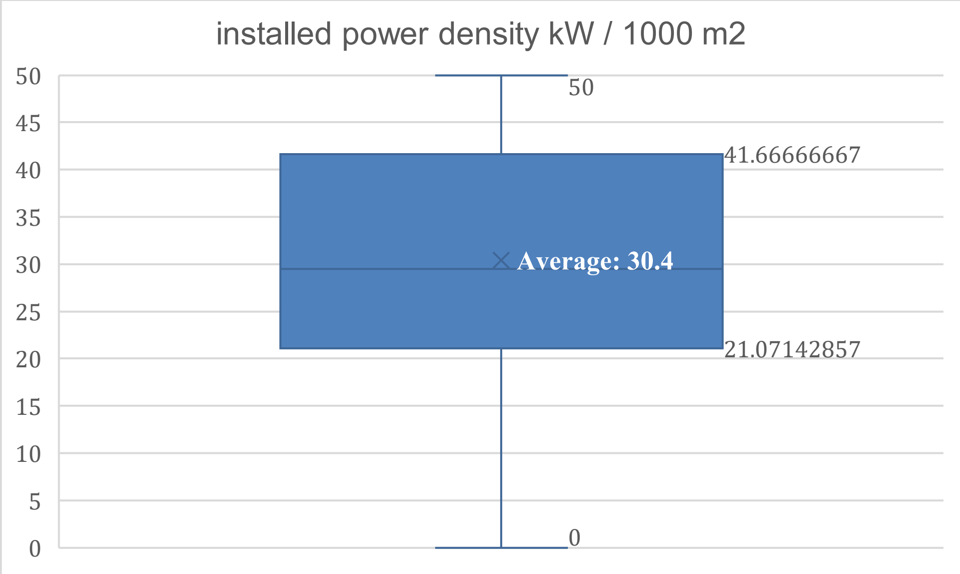

Figure 58: Installed power density kW / 1000 m2

Crops

The largest number of systems were installed in greenhouses for flowers and ornamental plants, or for cherry tomatoes. This does not reflect the distribution of greenhouse' crops in Israel, where flowers and cherry tomatoes take 3rd and 4th place (tomatoes and bell peppers are the leading greenhouse crops).

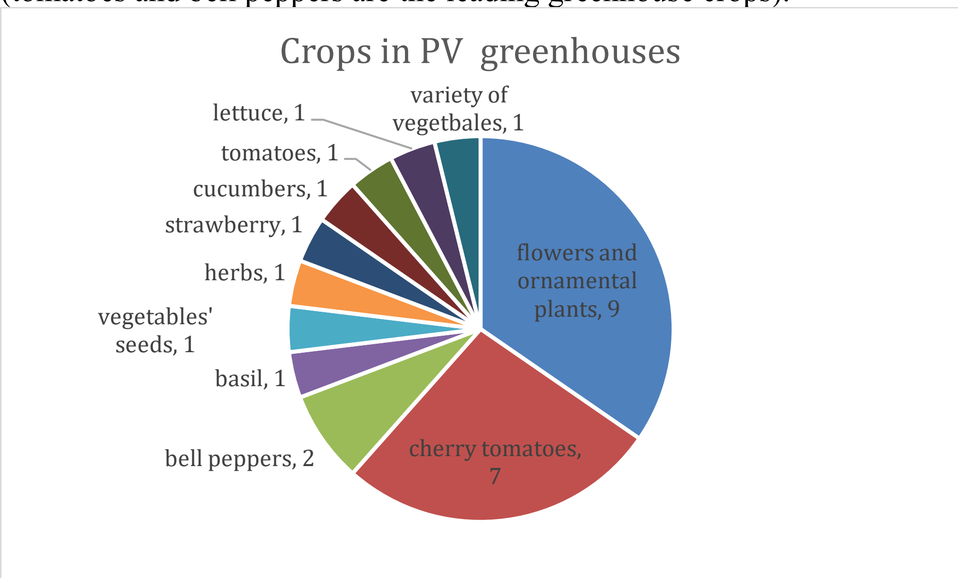

Figure 59: Crops in PV greenhouses

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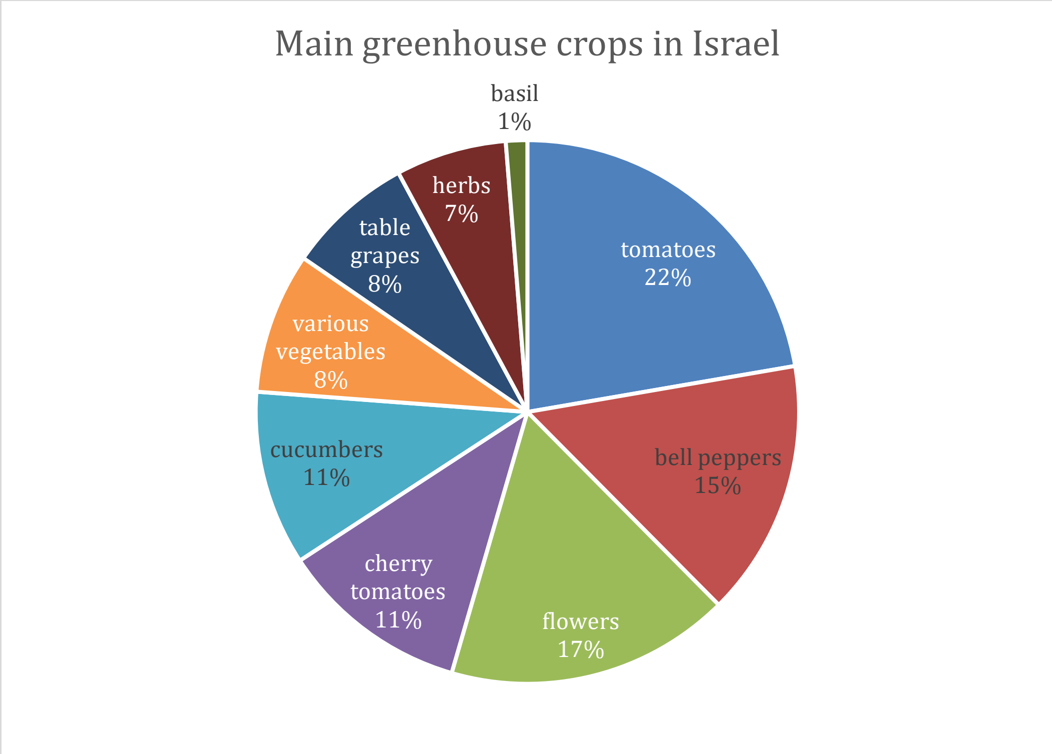

Figure 60: Main greenhouse crops in Israel

Panel technology

All the sites, but 2, use tracker panels. 2 sites use fixed panels.

Mounting structure

Foundations technology and materials

In 75% of the cases in our survey, the panels' mounting system required building separate foundations. Only in 25% of the cases the panels mounting system could be based on the foundations of the greenhouse.

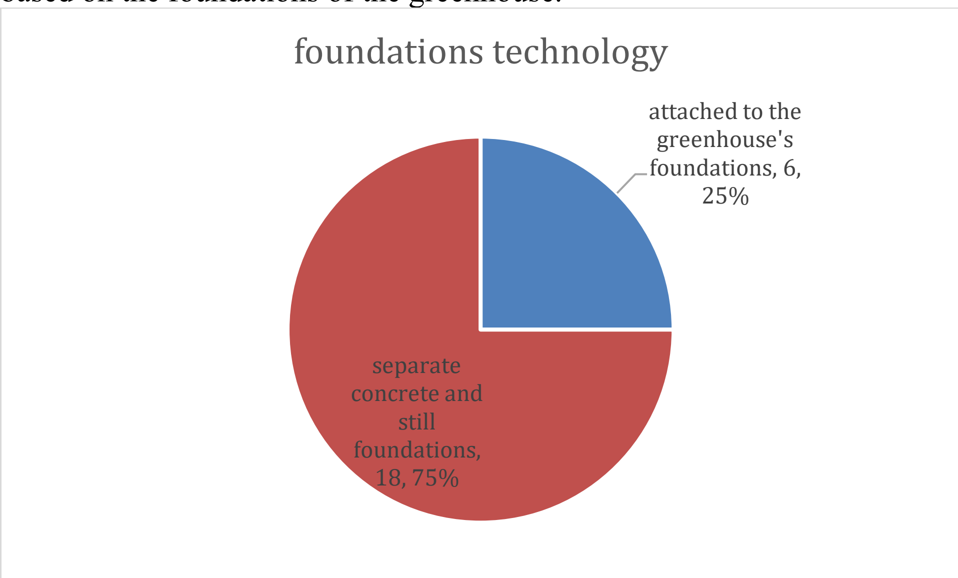

Figure 61: foundations technology

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All but one installation use concrete foundations. One installation uses a metal ground-screw (which is the dominant foundation technology in the survey of open-fields PV).
The foundation of each pillar contains, on average, about 0.75 cubic meters of concrete.

Above-ground structure

In 54% of the cases the mounting system of the PV does not rely on the structure of the greenhouse. A separate structure was built to carry PV panels, similar to PV in open fields.

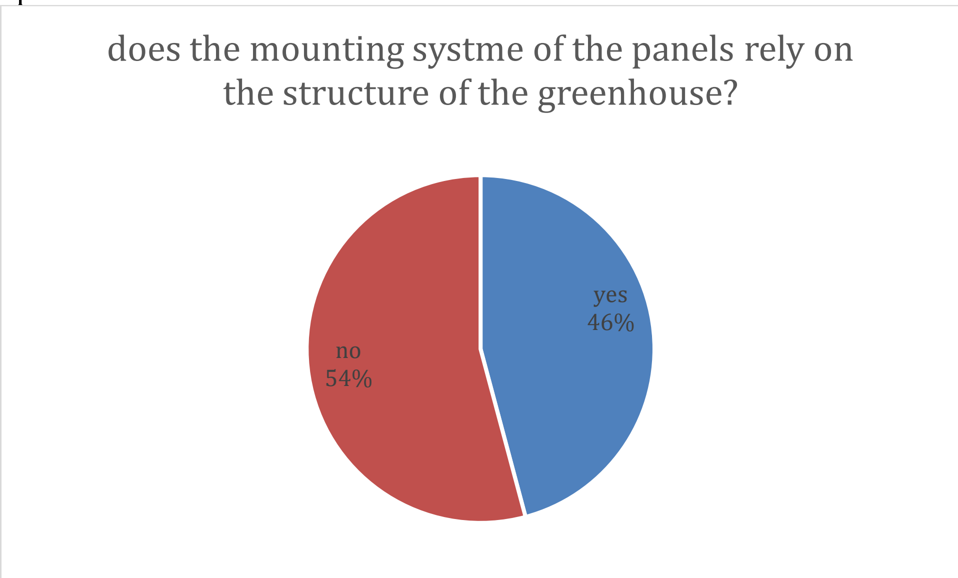

Figure 62: Does the mounting system of the panels rely on the structure of the greenhouse?

The most common technology of placing the PV panels on greenhouses is constructing pillars that lift the panels over the greenhouse roof. Old greenhouses are usually too weak to carry the load of PV panels, and therefore a mounting structure needs to be built to carry them. The pillars are attached to the existing structure of the greenhouse.

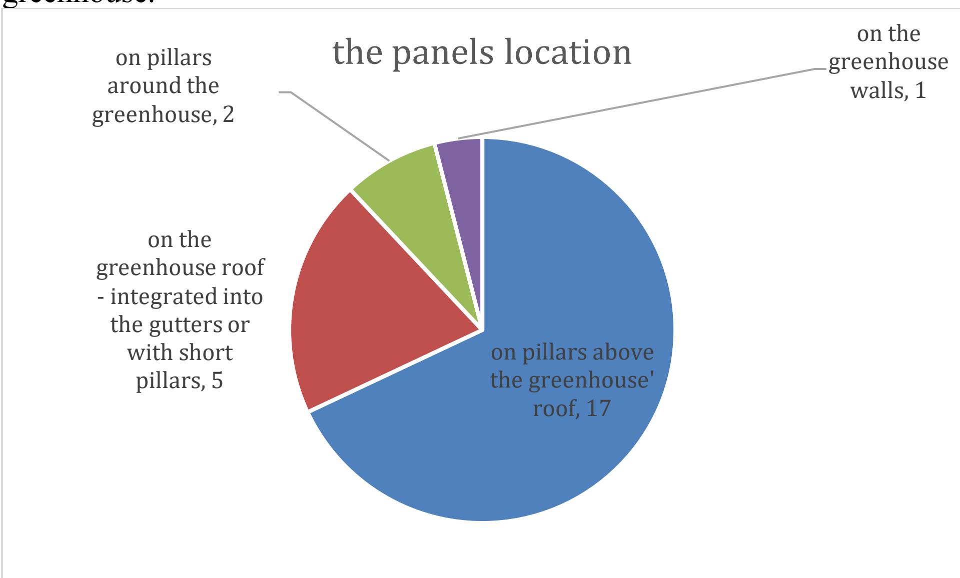

Figure 63: The panels' location

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All the pillars are built of galvanized iron.
The height of the pillars depends on the height of the greenhouse. The pillars must be 1.5-1.8 m higher than the pick of the greenhouse's roof, so that the tracker does not touch the roof while moving. Some greenhouses are 3 m high, and some are 4.5 m high. On average, the pillars are 5.3 m high (compared to average of 3 m in open fields).

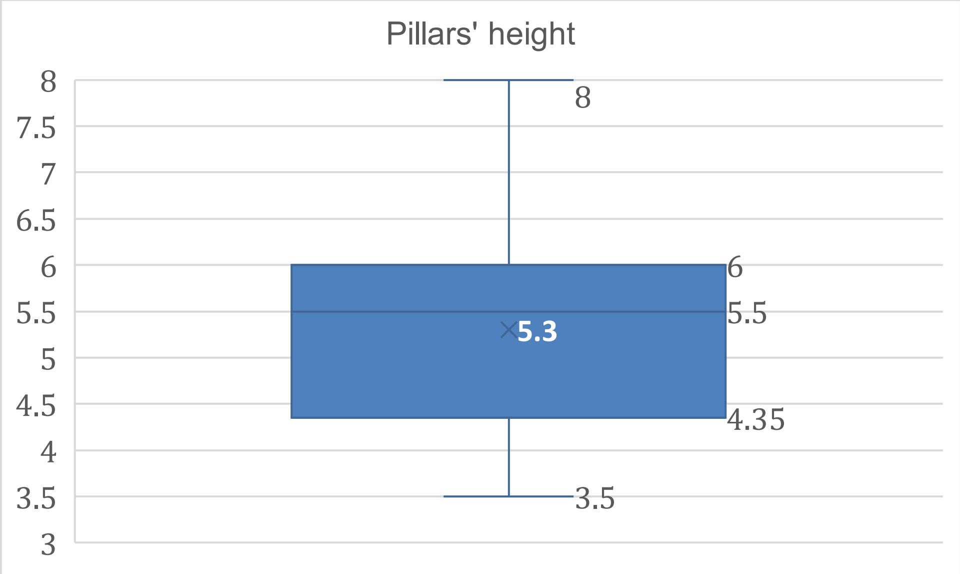

Figure 64: The pillars height

<u>The total amount of iron in the mounting structure</u>
The farmers in the survey could not specify the amount of iron in the mounting structure.

Capital costs and labor in installations

A study from Spain (Carreño-Ortega et al. 2017) found that agri-PV on greenhouses requires investment of approximately Euro 1725.70 / kWp, which is compatible with the investment requirements of a ground-mounted photovoltaic system (Euro 1700/ kWp).
Many of the greenhouses in the survey were built by an energy company so the farmers that were interviewed had no data regarding the costs of the installation.
Two farmers gave data regarding the cost of the mounting structure: one said it was about 423 Euro / kW (which is higher than the cost of the mounting structure in open fields agrivoltaics – 339 Euro / kW). The other said it was about 177 Euro / kW (which is lower than the cost of the mounting structure in REGACE greenhouses – 193 Euro / kW).
The total investment cost in PV system over greenhouses roofs is, on average, 1261 Euro / kW, which is slightly higher than the average cost of agri-voltaics in open fields (1,200 Euro / kW), and about 38% higher than in REGACE (see the following chapter).

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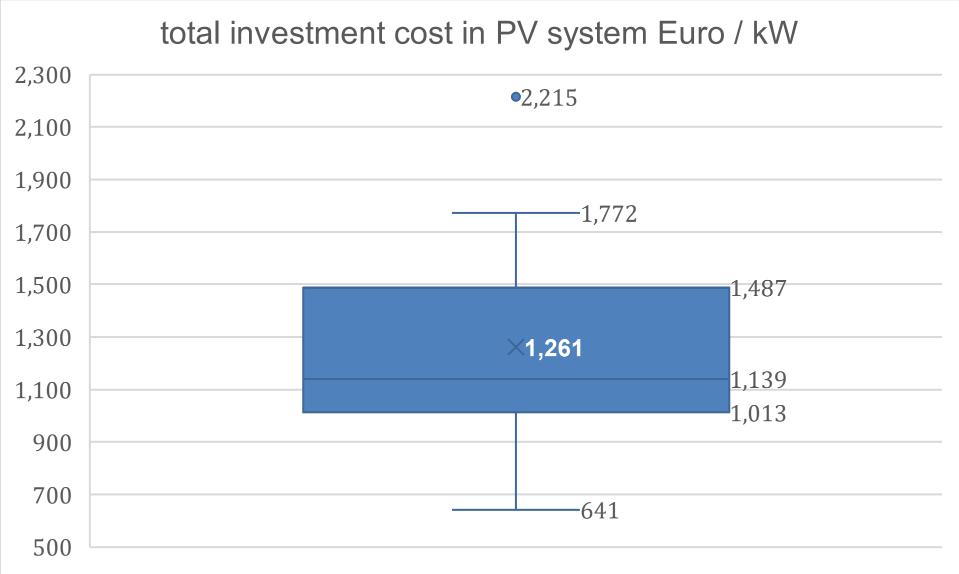

Figure 65: Total investment cost in PV systems on greenhouses, Euro / kW

Labor in installation

Almost half of the interviewees could not specify the number of working days in installing the system. 30% said that it took more than a month. One should consider that the projects have different sizes (from 2,000 to almost 25,000 m2).

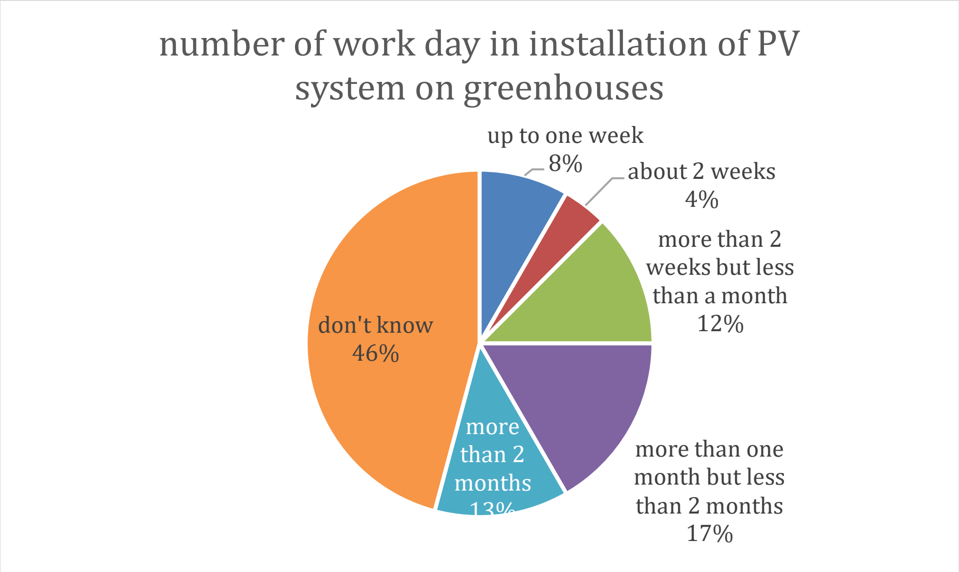

Figure 66: Number of work day in installation of PV systems on greenhouses

The number of workers needed to build the system is 4-10 workers. In 63% of the systems professional workers were required (usually electricians).

Maintenance of the solar system: cleaning and labor

The main maintenance activity in agrivolatics over greenhouses is washing the panels. It is conducted by 17 farmers (71%) in the survey. 11 farmers perform ongoing system testing (using a smart phone application).

The cleaning of panels is done using water only, none of the farmers reported using chemicals to clean the panels.

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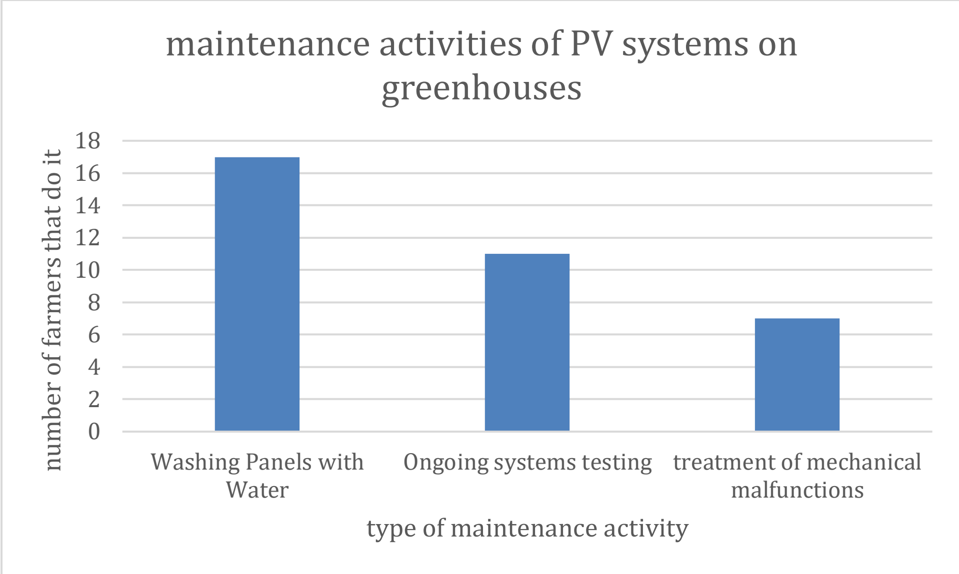

Figure 67: Maintenance activities of PV systems on greenhouses

Half of the farmers in the survey use an automatic sprinklers system to clean the panels. About 20% clean them manually, and the rest don't clean the panels.

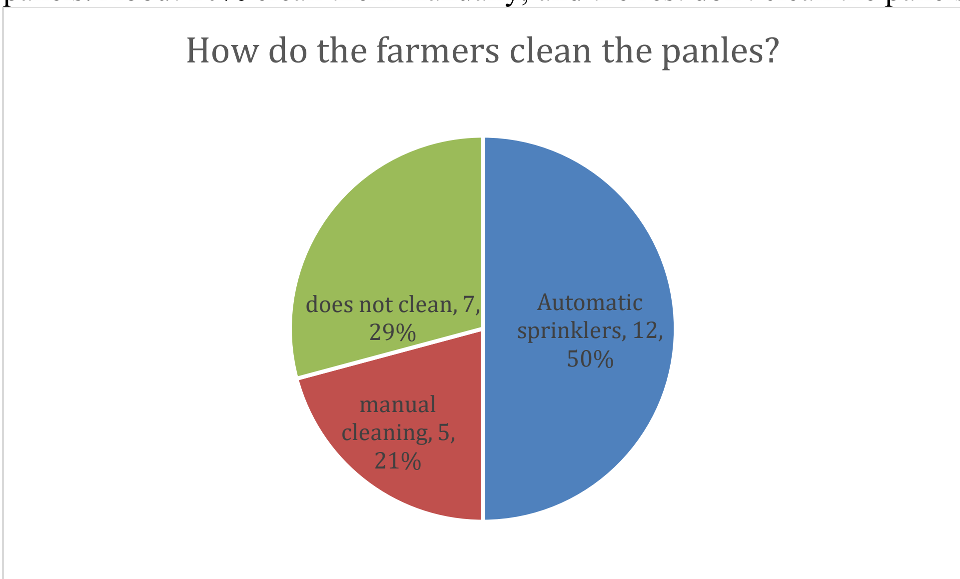

Figure 68: How do the farmers clean the PV systems on greenhouses

Half of the farmers clean the panels 2-3 times a week, or every day. The farmers that use automatic sprinklers do not invest labor in cleaning, however for those who clean manually – the cleaning takes 2-15 hours per cleaning session. Farmers report that cleaning is a challenge as the panels are high (5-6 m above the ground), are not easily accessible because they are placed over the gutters of the greenhouse, the use of a crane is sometimes necessary to reach the panels. An automatic sprinkler system is expensive.

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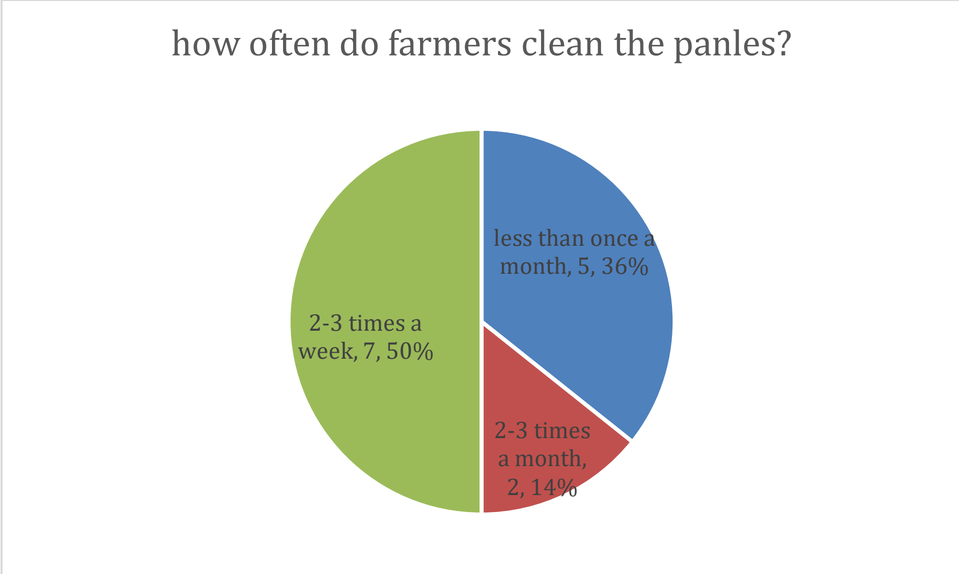

Figure 69: How often do farmers clean the PV systems on the greenhouses

40% of the farmers conduct system testing or fixing 2-3 times a month. Some of them reported that the energy company does the follow up on the system, some of them experienced problems with the trackers.

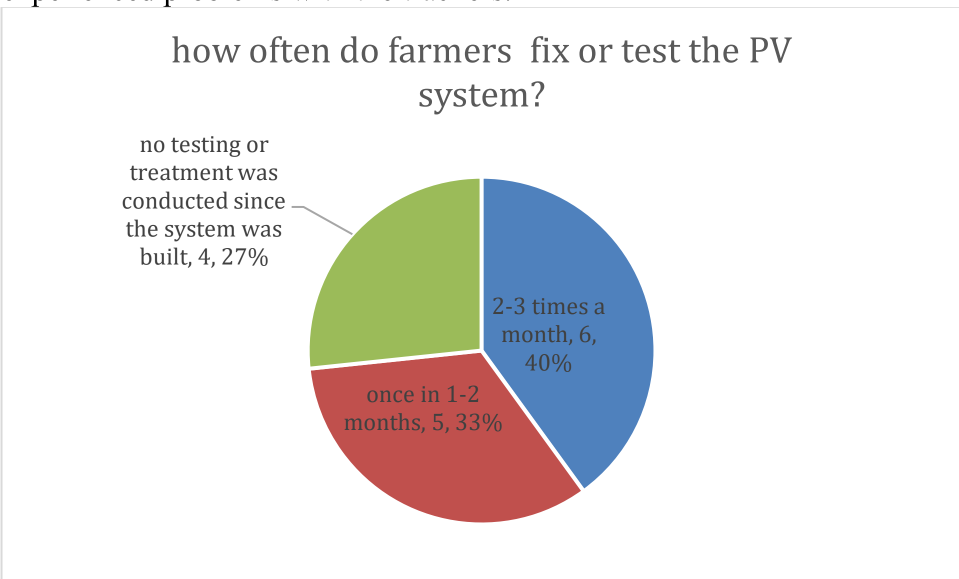

Figure 70: How often do farmers fix or test the PV systems on greenhouses

Additional labor in farm operation

71% of the farmers interviewed said that the installation of the PV system did not add agricultural work in the greenhouse.

3 farmers said that the PV system makes it more difficult to change the greenhouse cover sheets, a work that takes place once a year. One of them said that due to the PV system he changed the type of sheets to thicker sheets that need to be changed only once in 3 years.

4 farmers said that they needed to change the location of some of the growing beds to adjust them to the PV system.

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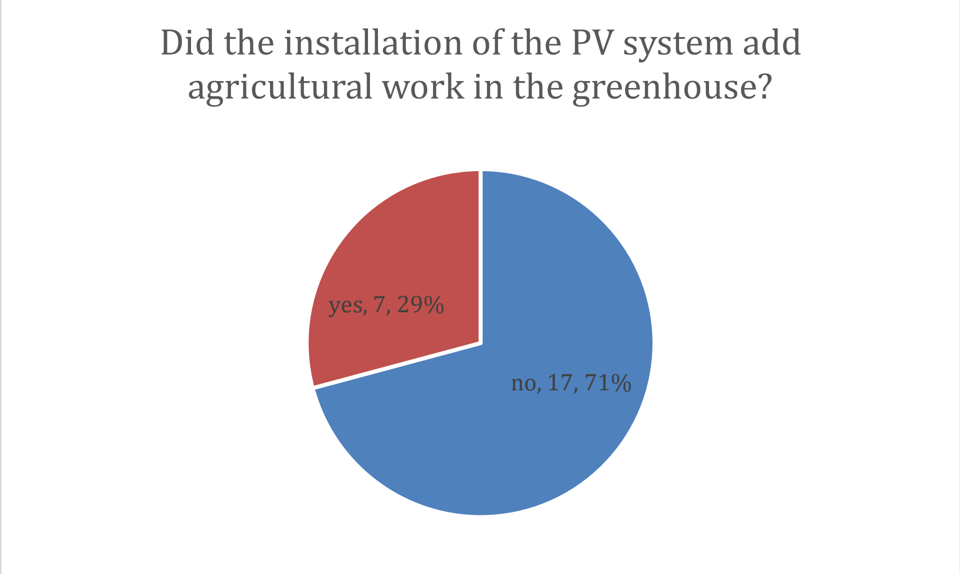

Figure 71: Did the installation of the PV system add agricultural work in the greenhouse?

Impact of the PV system on agricultural parameters

In addition to labor in farming, the interviewees identified the following agricultural impacts, due to the installation of the PV system:

67% of the farmers interviewed said that the PV system does not impact the yields of the greenhouse.

Four farmers said that there is no effect on the yield because during summer there is too much radiation, and farmers use shade nets or paint the greenhouse sheets to lower the radiation over the crops. The PV panels do not create more shade than what the farmers aim to achieve anyway.

Two farmers stated that although the shade in summer does good to the crops, during winter – the shade hurts the yields.

One farmer said that during winter the plants under the PV are better protected from the cold, so the panels have negative impacts only during spring and autumn.

One farmer said that the impact depends on the crop: there is significant impact to lettuce but not so much to celery.

One farmer stated that there is no effect on the yield because the panels are located above the paths between the growing rows.

One farmer said that the impact of the panels depends on the placement of the greenhouse. When it is built on a north-south axis – there is no shade and no impact. When it is built on a east-west axis – there is shade and impact on the crops.

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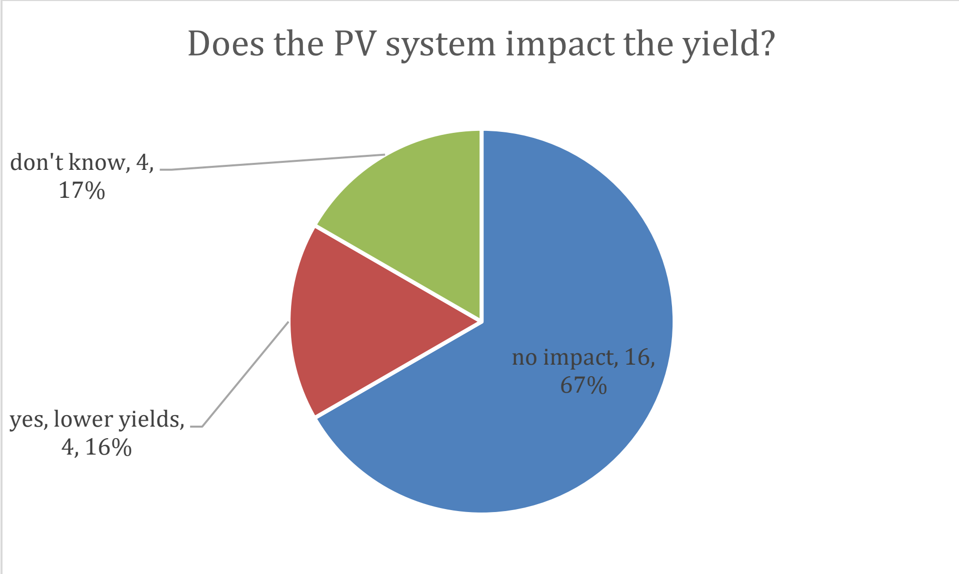

Figure 72: Does the PV system impact the yield – farmers' answers

75% of the farmers interviewed said that the PV system does not impact the quality of the produce of the greenhouses.

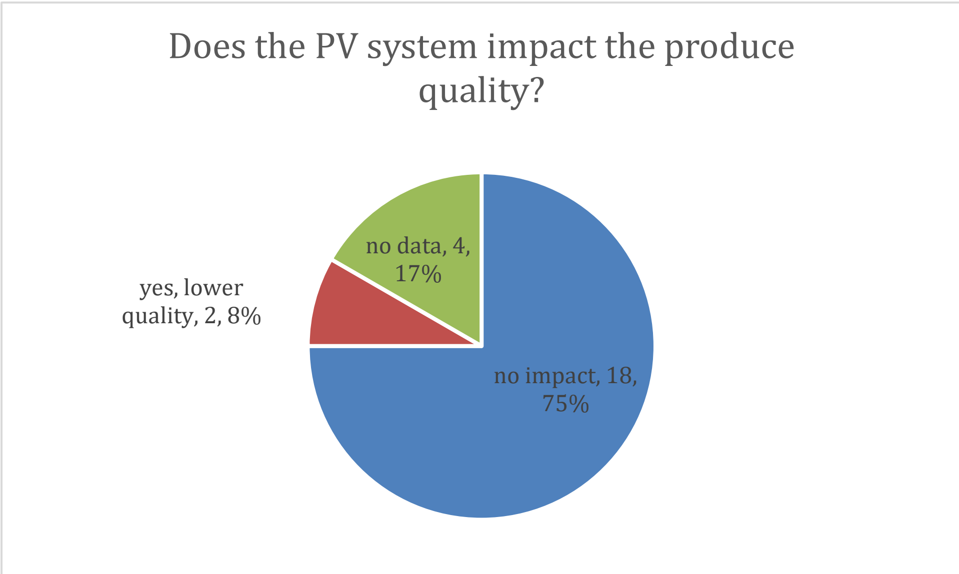

Figure 73: Does the PV system impact the produce's quality – farmers' answer

79% of the farmers interviewed said that the PV system has no effect on the presence of pests and diseases in the greenhouse.

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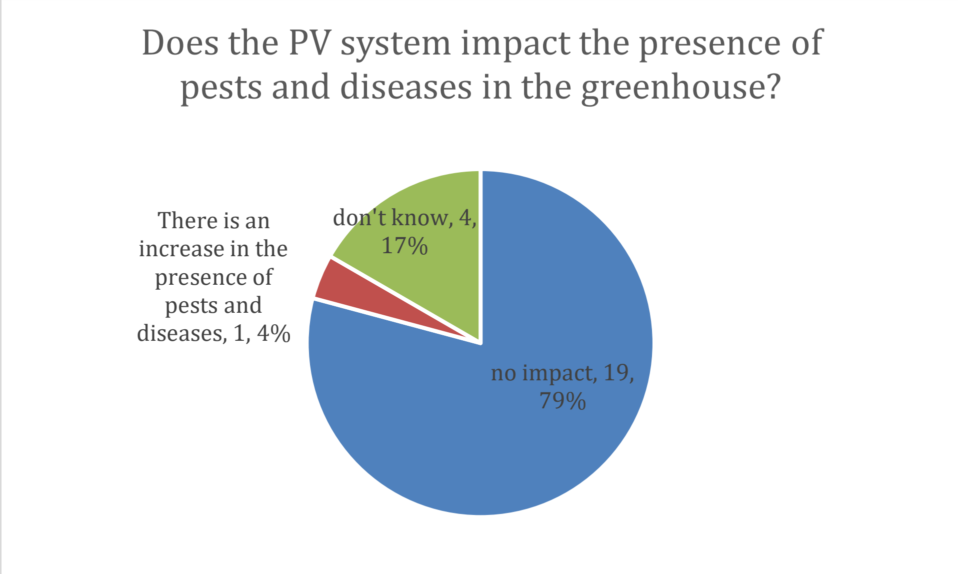

Figure 74: Does the PV system impact the presence of pests and diseases in the greenhouse? Farmers' answers

83% of the farmers interviewed said that the PV system has no effect on the amount of water used for irrigation in the greenhouse. Only 17% (4 farmers) said that the PV system lowers the amount of water used for irrigation in the greenhouse.

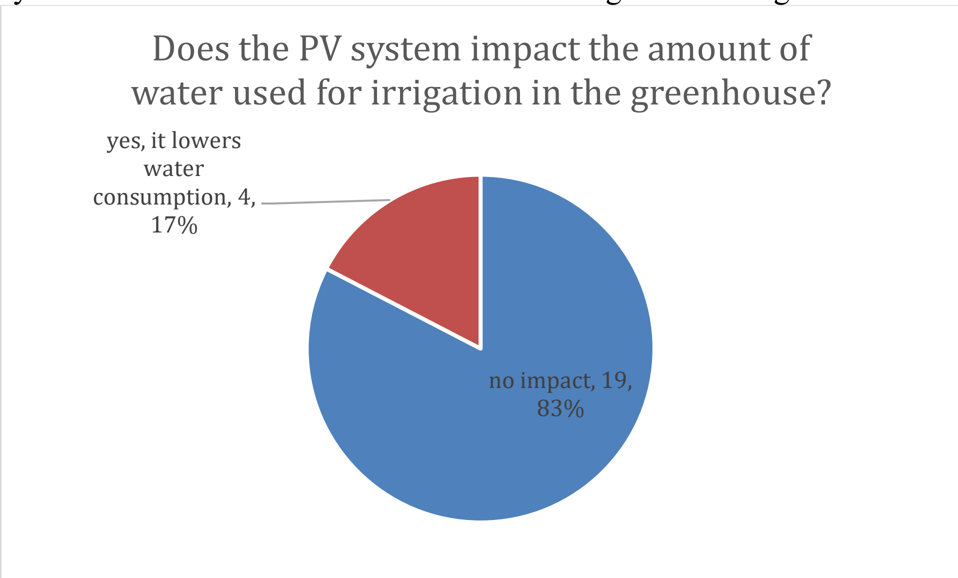

Figure 75: Does the PV system impact the amount of water used for irrigation in the greenhouse? Farmers' answers

54% of the farmers interviewed said that the PV system impacted the structure of the greenhouse: 3 farmers built a new greenhouse with a PV system. One farmer had to tear down an old greenhouse and build a new one, as the old greenhouse could not carry the PV system. 4 farmers said that the mounting structure that was built to carry the PV system made the structure of the greenhouse stronger. 2 farmers said that they are worried that changing the greenhouse's cover sheets will be harder once the PV system is installed. One farmer said that he had to add pillars inside the greenhouse, but it does not influence the agricultural activity.

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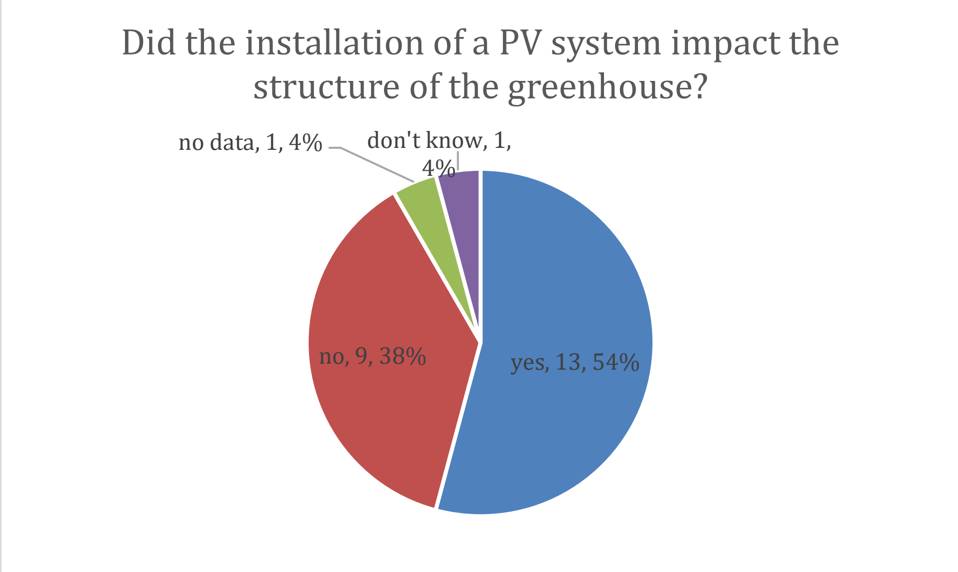

Figure 76: Did the installation of a PV system impact the structure of the greenhouse? Farmers' answers

All the farmers, but two, said that the PV system did not have an impact on the facilities inside the greenhouse. One farmer said that he had to change the type of net they use over the greenhouse in summer (from black net to white net) and the type of nylon they use in winter, in order to disseminate the light more equally over the greenhouse.

Attitudes Regarding the Integration of a Solar System in Greenhouses

<u>Advantages and disadvantages of placing agri-PV on roofs of greenhouses versus under the canopy of the greenhouse</u>

The farmers in the survey were asked about the differences between agri-PV on roof of greenhouses and under their canopy.

Here are the disadvantages that farmers have identified in placing panels inside greenhouses:

1. Some of the radiation is lost inside the greenhouse, especially once the plastic gets dirty.
2. In some places and time farmers change the nylon sheets to nets. Can the panels produce energy under nets? For example, in the summer, when the radiation is too harsh, farmers cover the greenhouse with black nets or paint the cover sheets to lower the radiation. In this case, panels inside the greenhouse will not produce any energy.
3. Placing the panels inside the greenhouse might lead to too much shade over the crops.
4. Installing panels on top of the greenhouse might be more efficient for reducing radiation over crops, when and where it is needed.
5. Many existing greenhouses have low ceiling, whereas the crop grows high. For example, tomatoes may grow to 2.5 m, and some greenhouses are 3-3.5 m high. There is not enough room to place panels between the crop and the greenhouse ceiling, especially if trackers are used.
6. The installation inside an existing greenhouse could be much more complex than over the roof of a greenhouse. The construction of the panels on top of a greenhouse is by assembling a whole beam on the ground and then lifting it up. Inside a greenhouse the assembling of the panels must be done piece by piece.

7. Cleaning the panels is more difficult inside the greenhouse; the cleaning water falls on the crops and might contaminate it; it is also more difficult to reach the panels for cleaning when they are placed directly over the crop.
8. Pesticides that are used in the greenhouse may damage the PV panels, for example, sulphur.
9. An external PV system does not interfere with farming. Farmers don't like it when people (e.g. employees of the energy company) enter the greenhouses during the high season.
10. Fixing malfunctions in a PV system that is inside a greenhouse is difficult – there is no room to place a ladder or crane between the rows of crops, some crops (e.g. tomatoes) are very densely grown.
11. The temperature inside the greenhouse, close to the canopy, can reach 60^0 in the summer, can the equipment survive this temperature, and can it produce adequate amount of energy?
12. Bi-facial panels on top of greenhouses absorb the radiation coming from the sun as well as from the roof of the greenhouse, especially when in it painted white during summer (to reduce the radiation inside the greenhouse).
13. The technology of placing the panels inside the greenhouse is unfamiliar.

Here are the advantages that farmers have identified in placing panels inside greenhouses:
1. Placing the panels inside the greenhouse would make it easier to change the cover sheets of the greenhouse, an action that takes place 1-2 times a year. It is a challage to change the cover sheets when PV panels are placed on the roof of the greenhouse.
2. Placing the panels inside the greenhouse lowers the investment cost as there are no foundations in the ground.

Challenges of integrating a PV system in a greenhouse farm
1. Challenges in the physical installation of the system (8 farmers):
    a. Some greenhouses are not easily accessible.
    b. Lifting the panels over the greenhouse is a challenge. It requires a large crane, which is not easy to find.
    c. The road next to the greenhouse was not stable enough to secure the crane. The road leading to the greenhouse had to be improved to allow the crane to reach the greenhouse.
    d. There was not enough space near the greenhouse to assemble the system before lifting it over the greenhouse.
    e. During the time of the installation the crops had to be taken away to make room for digging the foundations of the mounting structure.
2. The regulatory system (3 farmers).
3. Safety of working at height, on the greenhouse gutters.
4. Design of the system, which is still experimental.

38% of the interviewees said that, in retrospect, they would have placed the solar system in the greenhouse in a different way. Here is what they would change:
1. Use fixed panels instead of trackers that have too many malfunctions (2 farmers).
2. Build a new greenhouse with PV system, instead of installing on an existing greenhouse (2 farmers).

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3. Cover the whole greenhouse with panels.
4. Employ a different installation company.
5. Lowers the pillars of the mounting system.
6. Change the placement of the panels so it would be easier to clean them.
7. Strengthen the structure of the greenhouse and lean the panels over it, should lower the investment costs.

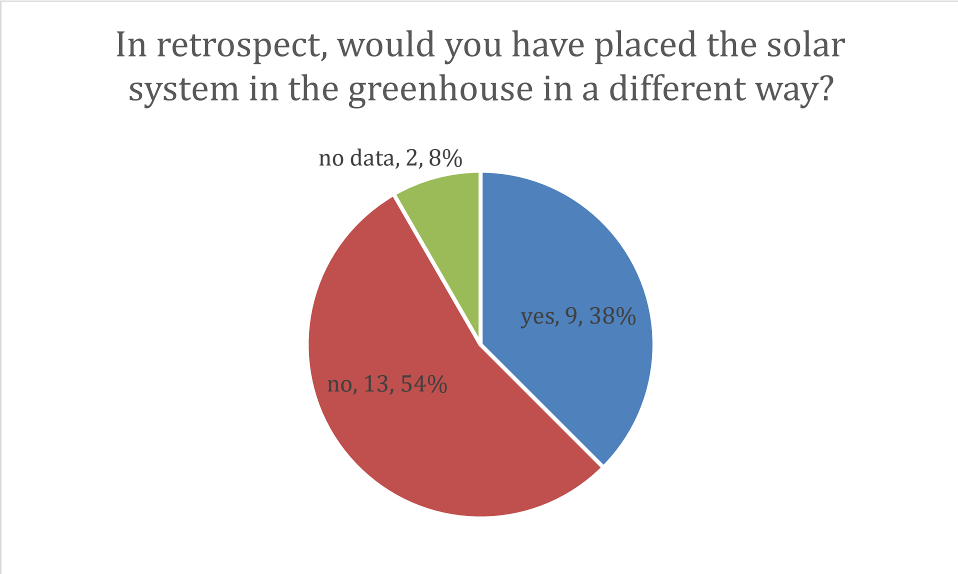

Figure 77: In retrospect, would you have placed the solar system in the greenhouse in a different way? Farmers' answers

All the interviewees, but 3, said that the current regulation for permitting PV panels over greenhouses needs to be changed. Here is what the interviewees think needs to be changed:

1. To permit a higher cover rate (14 farmers)
2. The government should not interfere, let the farmers decide for themselves (3 farmers).
3. To allow the concentration of the panels in one area of the greenhouse instead of spreading them all over the greenhouse. It would lower the costs of the mounting structure.
4. To permit solar systems over net-houses, and not only over greenhouses (2 farmers)
5. Not to oblige farmers to grow agricultural crops in a greenhouse, agriculture is not economical.
6. The national electricity company should enlarge the grid and allow more solar energy production.
7. To make the approval process less complicated, for example – to cancel the need for approval of the fire department.

All interviewees, but one, said that there is a win-win between agriculture and energy production. The following describe where they see the win-win:

1. The income from energy production is stable, and farmers can grow their farming business based on this stable income (7 farmers).
2. The farmer's income is improved (4 farmers).
3. Placing solar panels on the ground – is a waste of natural resources. Placing PVs over existing structures is a better utilization of the area (2 farmers).

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4. There are agricultural crops that benefit from the shade provided by the PV system (2 farmers).
5. Producing electricity can provide older farmers with stable income for retirement. This could bring about a younger generation of farmers – the model should be that the younger generation does the farming while the older generation gets income form the electricity production (2 farmers).
6. The PV system brings about an upgrade of old greenhouses.
7. The energy produced by the PV system can be used for farm operation, for example for electrical cars.
8. The PV system provides energy security in times of crisis.

Only one farmer said that electricity production does not pay off, and does not compensate for the loss of agricultural produce caused by the PV system.

REGACE - Agri-PV in greenhouses – panels inside the greenhouses

Methodology

The data was collected from the installations of solar panels for the REGACE project, in 6 sites, as follows (the table is organized chronologically):

Table 23: Locations and dates of REGACE installations

Location	Date of installation	Comments
Italy, Fattoria Solidale del Circeo farm	October and November 2023	A farm
Austria, University of Natural Resources and Life Sciences, Vienna	February 2024	A university
Germany, Bio-Gärtnerei Watzkendorf GmbH	March – April 2024	A farm
Israel, Triangle Research and Development Center	April 2024	A research institute
Germany, Humboldt University of Berlin	May 2024	A university
Greece, University of Thessaly	August 2024	A university

Source: data on REGACE installations

The system size and power density for each site are detailed in the table below.

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Table 24: system size and power density of REGACE installations

Site	System size m2	System size kW	System power density kw / 1,000 m2
Italy, Fattoria Solidale del Circeo farm	100	4.8	53
Germany, Bio-Gärtnerei Watzkendorf GmbH	384	16	32
Israel, Triangle Research and Development Center	280	12.4	44.3
Austria, University of Natural Resources and Life Sciences, Vienna	42	1.32	43.2
Germany, Humboldt University	151.2	3.78	25.3
Greece, University of Thessaly	400	16	40
Average			**39.63**

Source: data on REGACE installations

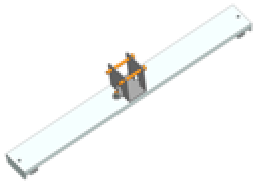
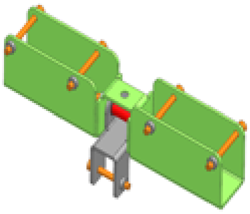
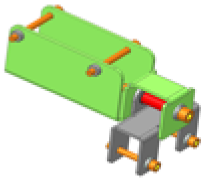
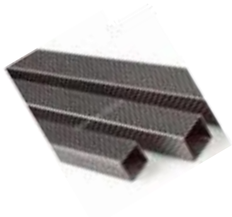
Detailed information for each installation and site is presented in Annex 3.
The hours of labor at each installation were monitored and registered, as detailed in Annex 3.
A list of the physical components at the installations was compiled, including their end-user price (as of April 2024, in US $). The list of components is detailed in REGACE deliverable of September 2023.

Results

Mounting structure

The technology of REGACE does not require building a separate mounting structure for the PV panels, as they are hung on the structure of the greenhouse. Since the panels are hung inside the greenhouse, they don't have to stand the stress of wind and other environmental elements, and the structure needed for their support is minimal. There is no need for supporting pillars or ground foundations, only rails as supporting beams.
The following table details the components of the mounting system used in the REGACE installations.

Table 25: The components of the mounting system, REGACE installations

Item Name	Picture	item weight, kg	Description	Quantity/1,000 m2, cover rate 30%	Total weight KG/ 1,000 m2
Solar panel holder		0.5	Aluminum Metal panel holder	560	280
Middle connector		0.8	Middle Iron rail holder	240	192
Side connector		0.45	Side Iron rail holder	80	36
Panel Rail 350 cm		1.8	Iron rail to hold panels	665	1197
Actuator iron rail 2.5*2.5 cm2		13.7	Iron rail to connect panel rows with actuator	4	54.8
Total weight kg /1000 m2					1759.8
Iron weight kg / kW scenario 1: 39.63 kW / 1,000 m2, the average in REGACE installations					44.4
Iron weight kg / kW scenario 2: 50 kW / 1,000 m2, attainable for shade tolerate crops					35.2

As can be seen, the total wight of the mounting system per 1,000 m2 is about 1,760 kg.
As for the weight per kW electricity, this depends on the power density installed. Two scenarios are considered:

1. The average installed power density in the REGACE installation: 39.63 kW / 1,000 m2. The weight of iron in the mounting system is 44.4 kg / kW.

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2. 50 kW / 1,000 m2, which is attainable for greenhouses with shade tolerate crops (for example lettuce). The weight of iron in the mounting system is 35.2 kg / kW.

Capital costs and labor in installation

The following table presents the work hours for each installation.

Table 26: Work hours in REGACE installations

Site	total number of hours for installation	system size m2	hours of work / m2	system size kW	hours of work in installation / kW
Italy, Fattoria Solidale del Circeo farm	38	90	0.42	4.8	7.92
Germany, Bio-Gärtnerei Watzkendorf GmbH	186	384	0.48	16	11.63
Israel, Triangle Research and Development Center	192	280	0.69	12.4	15.48
Austria, University of Natural Resources and Life Sciences, Vienna	74	42	1.76	1.32	56.06
Germany, Humboldt University	274	151.2	1.81	3.78	72.49
Greece, University of Thessaly	546.5	400	1.37	16	34.16
Average			1.09		33.04

Source: data of REGACE installations

As can be seen, on average, about 1.1 work hours were spent on the installation of 1 m^2 of greenhouse, and about 34 work hours per kW installed.

The following table presents the cost of labor in installation. Data exists only for 3 installations. In 2 sites the installations were carried out by Trisolar personnel, with or without the help of students. In one site (Greece) the installation was carried out by a local contractor, and the data is partial.

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Table 27: Cost of labor in REGACE installations

site	cost per workday average Euro	cost per day unskilled worker, Euro	cost per day skilled worker, Euro	total cost of installation, Euro	cost of labor in installation per kW, Euro
Italy, Fattoria Solidale del Circeo farm	150			712.5	148.4
Germany, Bio-Gärtnerei Watzkendorf GmbH	90	75	150	2092.5	130.8
Israel, Triangle Research and Development Center	110	100	150	3300.0	266.1
Austria, University of Natural Resources and Life Sciences, Vienna	n.d. installation done by Trisolar personnel only				
Germany, Humboldt University	n.d. installation done by Trisolar personnel and students				
Greece, University of Thessaly		130	n.d.	n.d.	n.d.
Average					181.8

Source: data of REGACE installations

As can be seen, the cost of labor in the REGACE installations is on average 181.8 Euro / kW.

The REGACE installations were done in existing greenhouses, of which 2 are commercial-farming greenhouses and 4 are research greenhouses located in universities or research institutions. These greenhouses, and especially research greenhouses, contain many systems under their roofs, occupying the same space where the solar systems needed to be installed. This made the installations difficult, time-consuming and expensive. An option that may lower the cost of installation would be to integrate the panels into new greenhouses, that will be built with solar systems from the start.

The following Figure details the investment cost of REGACE installation, under two assumptions regarding power density:

1. 39.63 kW / 1000 m2 – the average power density for REGACE installations.
2. 30 kW / 1000 m2 –power density that corresponds with shade-intolerant crops.

In the more conservative scenario of power density of 30 kW / 1000 m2, the total investment cost is about 911.8 Euro per kW.

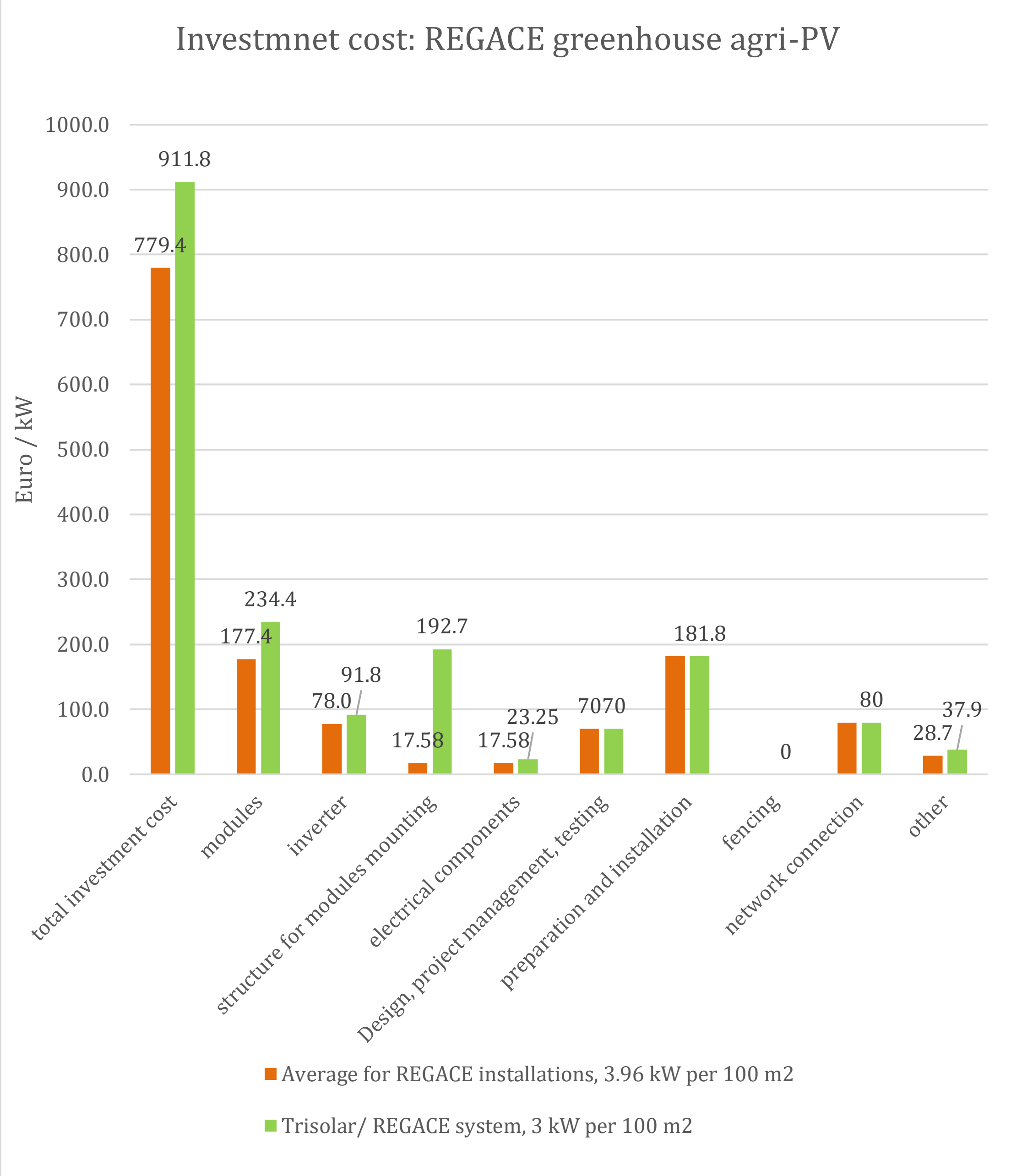

Figure 78: Investment costs of REGACE installations

Source: data of REGACE installations

The following Figure details the share of the different components of the total investment cost, at REGACE installations.

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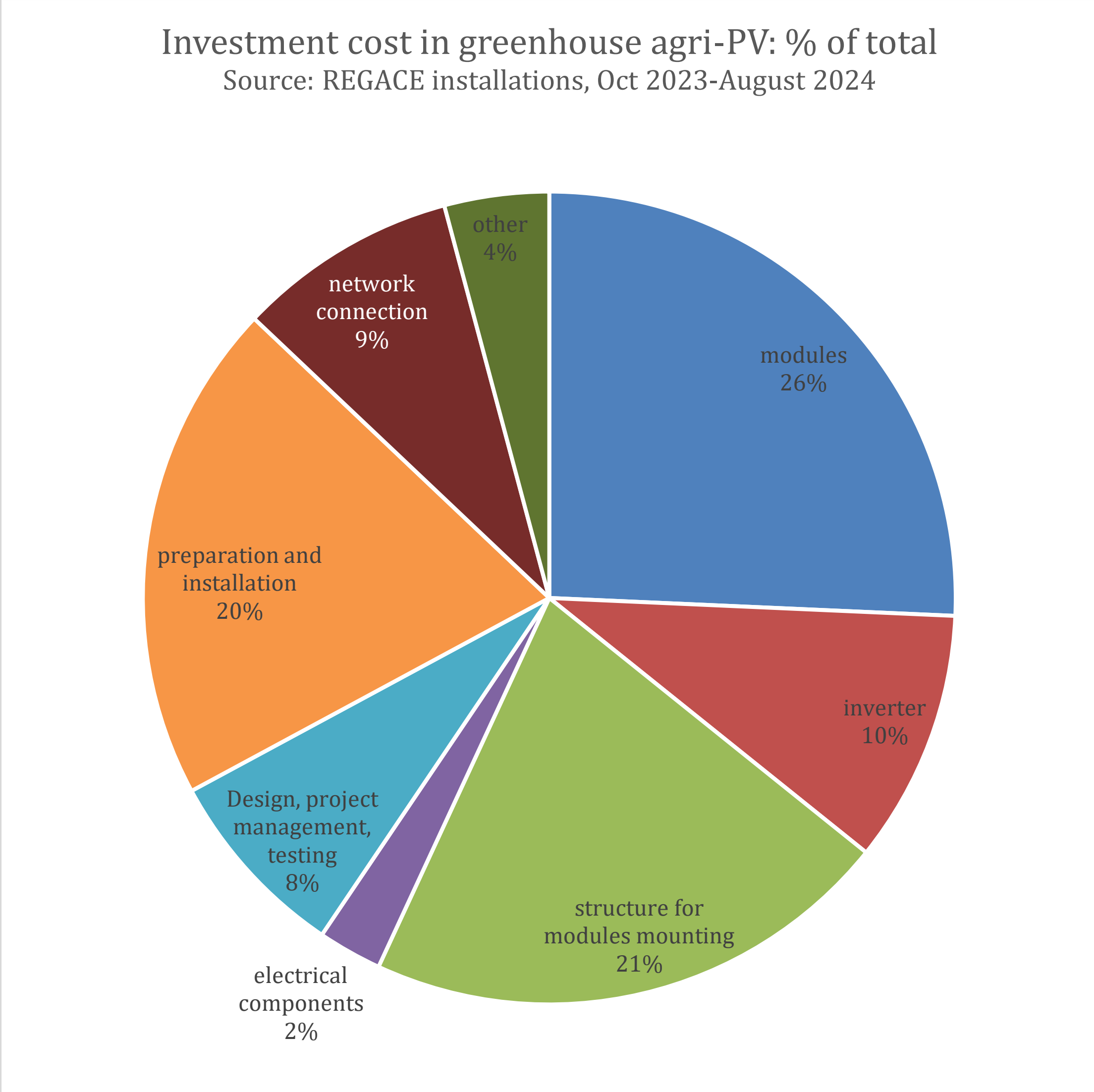

Figure 79: % of components of investment cost, REGACE installations, power density assumption 30 kW / 1,000 m2

Source: data of REGACE installations

Farmland occupation by the structure of the agri-PV system

REGACE technology doesn't occupy any farmland, as the panels are hung inside the greenhouse, using its structure as their frame.

Maintenance of the solar system: water, chemicals and labor

The REGACE technology does not require as much cleaning and maintenance of the panels, as they are placed inside the greenhouse, and therefore are less exposed to dust from the environment.

In small greenhouses, most of the farm work is done manually and no dust is created because of the use of agricultural machinery. In large greenhouses, part of the farm work is done using heavy agricultural machinery, thus creating dust on the surface of the panels that may require washing. However, washing does not need to be done often.

For example, in the greenhouses at TRDC, which are small greenhouses of about 180 square meters, all the farm work is done manually. In December 2024, 8 months after installation, the panels were tested for dirt and were found to be clean. The first

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cleaning of the panels took place on 16 January 2025. The second cleaning was done on 24 June 2025. Altogether 2 cleanings per year.
In Bio-Watzkendorf, where the greenhouses are large, the panels had to be cleaned 8 months after the installation that took place in April 2024, because of dust that was dispersed due to working with a tractor inside the greenhouse. The cleaning was carried out during December 2024 using pressure steam (water). This was the only cleaning conducted until September 2025. According to the farmer, there was need for another cleaning, but he didn't have time to do it before the growing season started.
In some greenhouses the ceiling is washed once per period (a year or so). The placement of panels inside the greenhouse, under the roof, might extend the time needed for washing the ceiling. Washing the panels could be combined into washing the ceiling.
No chemicals are used in cleaning the panels.
The risk of system damage and the need for repair is also lower, as the system is in a protected space inside the greenhouse.

Additional labor in farm operation

There is no additional agricultural work due to placing panels inside greenhouses.

Comparison between REGACE technology and other agri-PV technologies

General Characteristics

Coverage rate of the panels
In open fields PV projects, the coverage rate is on average 27%.
In greenhouses (on roof tops), most of the projects have coverage rate of 15% (this is the coverage rate permitted in Israel; if the farmers were allowed to choose the coverage rate freely, the results would probably be different).
In the REGACE site TRDC the coverage rate is 35%. At the site in Humboldt University, Berlin, the coverage rate is between 30% (in the most densely covered area) to 15%.
Installed power density
The following table presents a comparison of installed power density of REGACE technology, open-fields agri-PV and conventional greenhouse agri-PV (on roofs of greenhouses). As can be seen the power density of REGACE is lower than open-fields agri-PV, but higher than conventional greenhouse agri-PV.

Table 28: Installed power density - Comparison of open fields agri-PV and conventional greenhouse agri-PV to REGACE technology

Type of PV system	Average power density, kW / 1000 m2	Comparison to REGACE technology	Maximum power density, kW / 1000 m2	Comparison to REGACE technology
open fields agri-PV projects	60.6	53% higher than REGACE	90	69.8% higher than REGACE
Conventional greenhouse agri-PV (on roofs)	30.4	23% lower than REGACE	50	6% lower than REGACE
REGACE, agri-PV inside greenhouses	39.63		53	

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Panel technology

Solar trackers are the dominant technology in all types of agri-PV systems.
In the open fields agri-PV, 71% of the systems use trackers. In conventional greenhouse agri-PV, 92% of the systems use trackers.
REGACE uses a responsive tracking system, designed to optimize both energy and agricultural production.

Mounting structure

Foundation technology

The most common foundation technology (67% of the sites) in open-fields agri-PV is ground screw foundation. The most common foundation technology (96% of the sites) in conventional greenhouse agri-PV is concrete foundation. It isn't clear why ground screws are not used in greenhouse PV installations, as they are easier to use than to build concrete foundations. It could be that the pillars commonly used in greenhouses do not have suitable fasteners for ground screws.
REGACE technology does not require ground foundations, as the panels are hung on the structure of the greenhouse, without building additional pillars to support the system.

Above-ground structure

In open-fields agri-PV systems, the pillars are, on average, 3.28 m high.
In conventional greenhouse agri-PV systems the pillars are, on average, 5.3 m high, about 2 m higher than in open-fields system. This is because the panels have to be higher than the pick of the greenhouse's roof and allow for the movement of the tracker.
The panels used in REGACE are not supported by separate pillars but on the structure of the greenhouse.

Iron in the mounting structure

The following Figure presents a comparison between the weight of iron in the mounting structure of open field agri-PV (average for the Israeli projects that were surveyed) and REGACE installations (average for all REGACE installations).

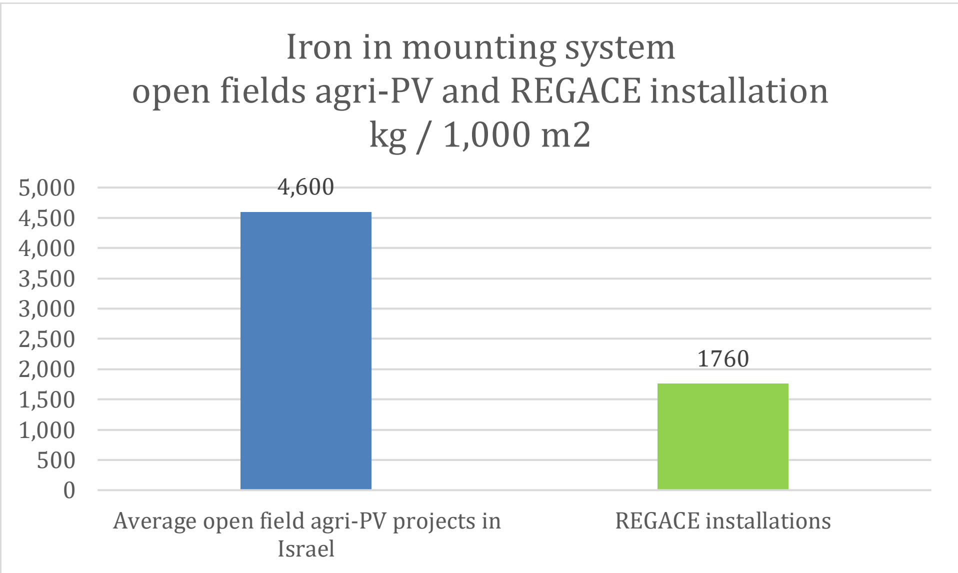

Figure 80: weight of iron in mounting system open fields agri-PV and REGACE installation kg / 1,000 m2

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As can be seen, the weight of iron in open-fields agri-PV is about 2.6 times higher per 1,000 m2 than in the greenhouses of REGACE installations.
The following Figure presents a comparison between the weight of iron per kW installed in the mounting structure of open field agri-PV (average for the Israeli projects that were surveyed) and REGACE installations according to 2 scenarios:

- Scenario 1: 39.63 kW / 1,000 m2, the average in REGACE installations
- Scenario 2: 50 kW / 1,000 m2, attainable for shade tolerate crops

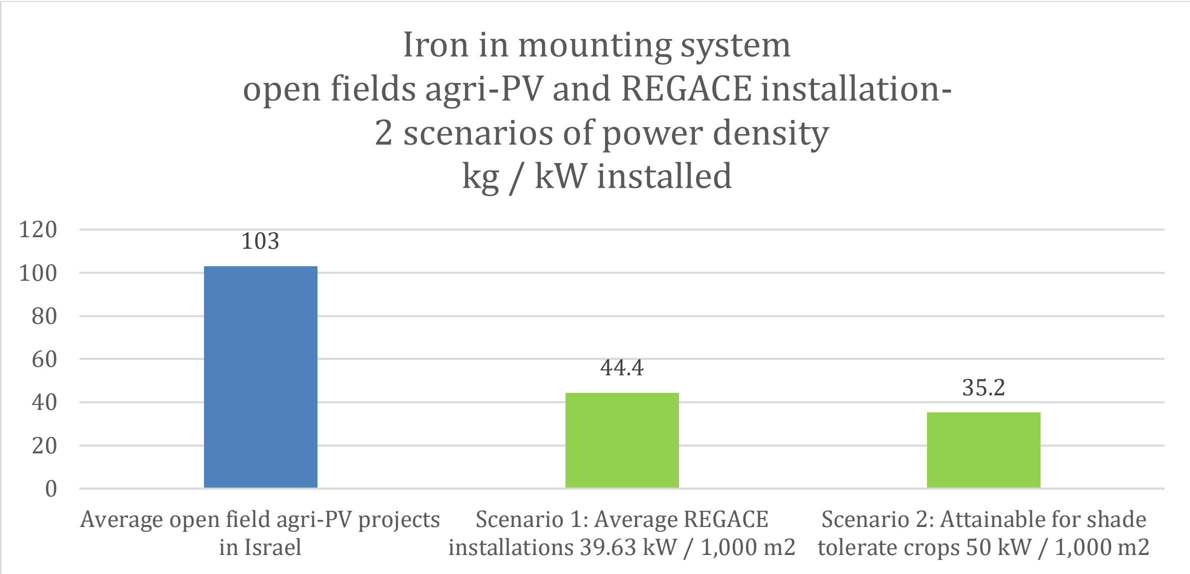

Figure 81: Iron in mounting system open fields agri-PV and REGACE installation- 2 scenarios of power density kg / kW installed

As can be seen, the weight of iron per kW installed in open field agri-PV is 2.32 to 2.93 times higher than that of REGACE installations, depending on the power density. As iron and other metals production is energy intensive, using large amounts of iron as part of an agri-PV project has an impact on CO2 emissions. The carbon footprint of various agri-PV technologies will be studied in the next chapter.

Capital Cost and labor in installation

Capital cost

The following chart compares the CAPEX- upfront cost of agri-PV systems in open fields (based on the literature survey), in conventional greenhouse agri-PV (based on the survey of farmers who installed PV systems on top of their greenhouses) and the investment cost of REGACE installations.

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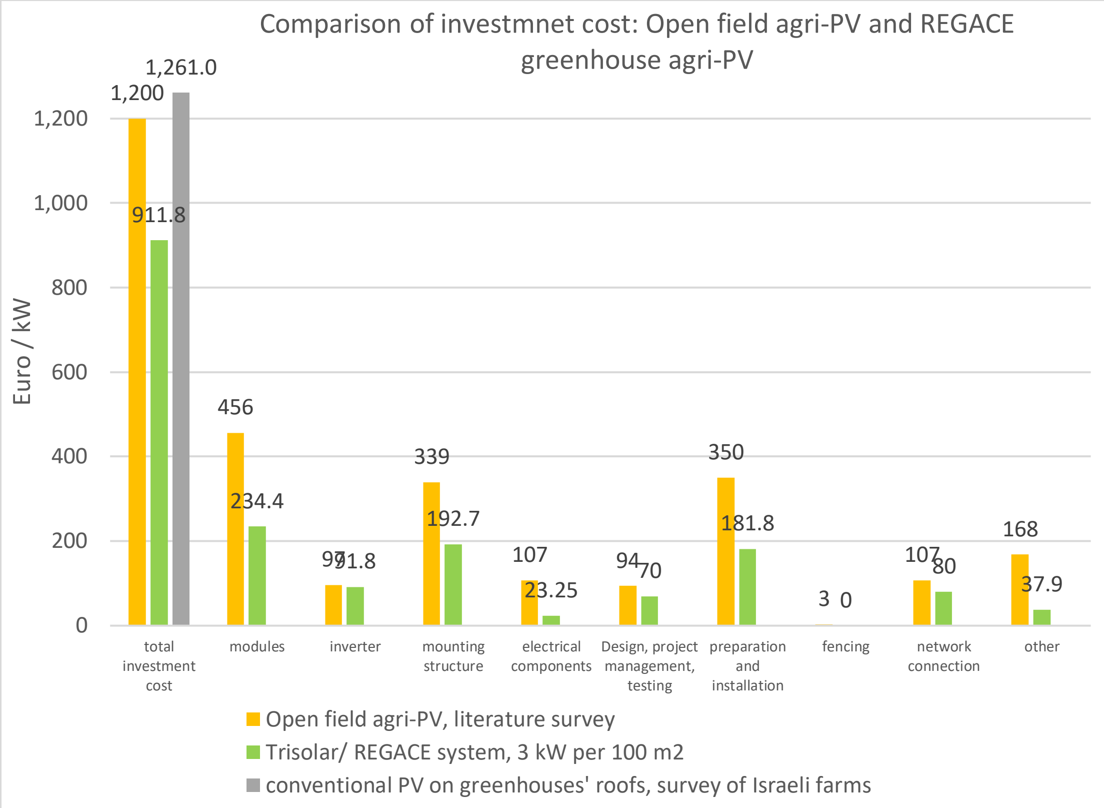

Figure 82: Comparison of investment cost: Open field agri-PV and REGACE greenhouse agri-PV.
Source: data of REGACE installations; literature survey; survey of Israeli farmers who have PV systems on top of their greenhouses (only the total investment cost could be retrieved from the farmers' survey)

As can be seen, REGACE technology is more efficient than open field agri-PV in all the components of the up-front investment. It is also more efficient than conventional PV on greenhouses' roofs. Altogether, the cost of investment in agrivoltaics in REGACE technology is **24% lower** than in open fields agrivoltaics, and **28% lower** than for conventional PV on greenhouses' roofs.
The following table details the difference between the cost of REGACE technology and the average cost in open-fields agri-PV of the various installation components. As can be seen, REGACE technology is more efficient than open-fields agri-PV, in all the components.

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Table 29: Comparison of investment cost: % difference REGACE technology to average open-field technologies

Euro / kW	capital cost	labor cost uskilled+ skilled	total investment cost	modules	inverter	mounting structure	electrical components	Design, project management, testing	preparation and installation	fencing	network connection	other
Open field agri-PV, literature survey	989	363	1,200	456	97	339	107	94	350	3	107	168
Trisolar/ REGACE system, PV in greenhouses, 3 kW per 100 m2	580.1	181.8	911.8	234.4	91.8	192.7	23.25	70	181.8	0	80	37.9
Average for REGACE installations, 3.96 kW per 100 m2	447.7	181.8	779.4	177.4	78.0	17.58	17.58	70	181.8	0	80	28.7
% difference Trisolar/ REGACE technology to average open-field technologies	41%	50%	24%	49%	5%	43%	78%	25%	48%	100%	25%	77%

Source: data of REGACE installations; literature survey

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The cost of the mounting structure within the REGACE project is 43% lower than the average for open fields agri-PV technology. This demonstrates the advantages of integrating PV panels into greenhouses, over placing them in open fields.
As for the share of different components in the up-front investment cost, there are no substantial differences between open-fields and greenhouses agri-PV systems, regarding the modules, mounting structure and costs of preparation and installation (see Figure below).

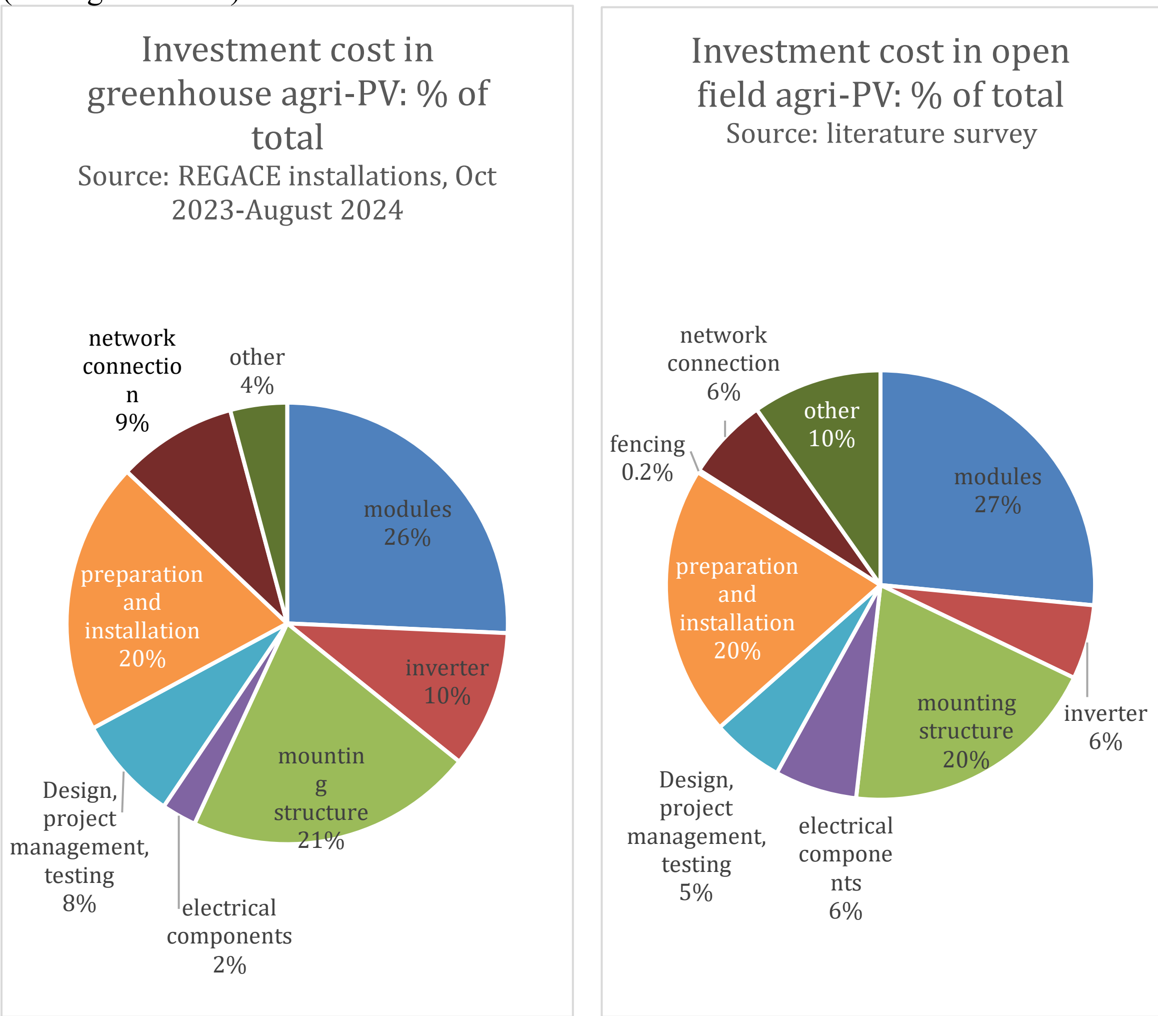

Figure 83: comparison of % of different componenet in the the investment costs, agri PV in greenhouses (REGACE technology) and in open fields

Labor in installations

The cost of preparation and installation within the REGACE project is **48% lower** than the average for open fields agri-PV technology (the cost of installation of conventional greenhouse agri-PV systems could not be retrieved from the survey).

Farmland occupation by the structure of the agri-PV system

Agri-PV in greenhouses don't occupy any farmland as the panels are installed on the structure of the greenhouse; whereas agri-PV in open fields occupy about 8.3-20% of the farmland where it is installed (Agostini et al., 2021, Feuerbacher et al. 2022, Trommsdorff et al. 2021).

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Maintenance of the solar system: water, chemicals and labor

In 50% of the open fields agri-PV systems the panels are washed. In other open fields agri-PV systems, no washing is carried out for the time being. Only one system is washed 2-3 times a week, and the other systems are washed less often than once a week.
In 71% of the conventional greenhouse agri-PV systems the panels are washed, half of them are washed 2-3 times a week.
Inside greenhouses, the panels are protected from dust and seldom washed. The panels of REGACE greenhouses were washed twice a year at the most.
This demonstrates the significant water savings in REGACE systems that do not need to be washed all that often.

Additional labor in farm operation

In open fields, agri-PV systems add about 5-10% to labor and machinery use (Feuerbacher et al 2022, 2021). Additional labor is necessary due to different times of flowering and fruit ripening in different proximity to the panels; or due to difficulty in using machinery in the plantation (such as grape-harvesters).
Conventional greenhouse agri-PV systems usually don't add farm labor. However in some cases they make it harder to change the cover sheets of the greenhouse, and activity that normally takes place 2 times a year.
Inside greenhouses, agri-PV systems don't add work to the operation of the farm.

Use of CO2 for compensation

The ability to use CO2 as compensation for the impact of the shade of PV panels on the crops, so that the agri-voltaic system does not impact the agricultural yield, is a unique feature of agri-voltaic in greenhouses. CO2 enrichment can be done only in enclosed spaces. Since CO2 enrichment is vital for minimizing, or even reversing, the impact of the PV panels on the yields, this is a major advantage of integrating the PV panels into greenhouses, over constructing them in open fields.

CO2 footprint and water footprint

A carbon footprint is a calculated value or index that makes it possible to compare the total amount of greenhouse gases that an activity or product adds to the atmosphere. The water footprint of an activity or product is defined as the total volume of water used to produce the activity or product.
Within a CO2 footprint analysis, the entire process of production and use of the product or system are considered, from the mining of raw materials to the manufacture of its components, shipping, maintenance and, finally, recycling (Carreño-Ortega et al. 2017). The same is true for water footprint.

CO2 footprint

There is very little evidence in the literature regarding the CO2 footprint of agri-PV. Agostini et al. (2021) found that for a standard open-field agri-PV system with concrete foundation and steel poles, the carbon footprint is 614.1 gCO_{2Eq} / MJ, which is about 2.2 $kgCO_{2Eq}$ / kWh. Carreño-Ortega et al. (2017) calculated the carbon footprint of a greenhouse agri-PV system at 0.4-0.6 $kgCO_{2Eq}$ / kWh (for a greenhouse of 18,000 m^2, with an installation of 260 kWp).
These estimations consider the entire agri-PV system, including solar panels, inverters and other electrical components. However, when it comes to comparing open-field agri-PV to greenhouses' PV, the main difference is the mounting system, which is

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substantial for open-fields agri-PV, moderate for roof-top greenhouses PV, and light for the REGACE technology that inserts the panels inside the greenhouse. The CO2 footprint, and water footprint analysis will therefore focus on the mounting system.
The production of iron and other metals used in the mounting system of agri-PV is energy intensive and significant amounts of CO2 are emitted during its production. World Steel Association reports that the steel industry world-wide is responsible for 6.7% of the total CO2 emissions (Sohn, 2019). The steel industry consumes the second largest amount of energy and emits the greatest volume of CO2 (30%) of any industry (Sohn, 2019). The most widely used technology for ironmaking is blast furnace, which currently produces more than 90% of the world production (Sohn, 2019). Although it is a highly efficient reactor in terms of energy and chemical reactions, the coke used in this process generates large CO2 emissions. The process emits 1.9 tons of CO2 for every ton of iron produced (Sohn, 2019).
These data enable the calculation of the carbon footprint of various agri-PV technologies, as follows from the amount of iron used in their mounting structures. The following Figure details the results.

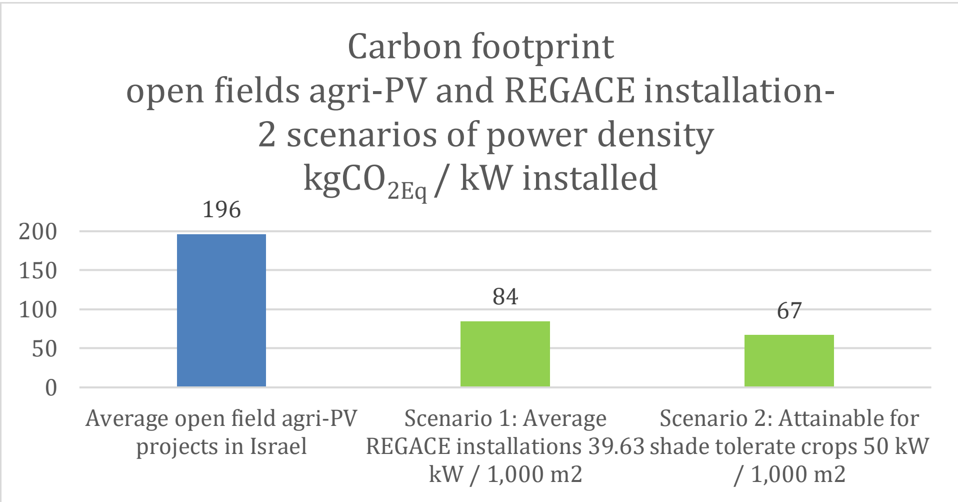

Figure 84: Carbon footprint of the mounting system of open fields agri-PV and REGACE installations (2 scenarios of power density) kg CO2 emission / kW installed

As can be seen, the carbon footprint of REGACE technology is 57% lower than that of open-fields agro-PV, when focusing on the amount of iron in the mounting system of the PV panels.

Water footprint

Water footprint is a comprehensive indicator for assessing water resource consumption and pollution caused by anthropogenic activities (Ma et al, 2018). This indicator considers direct and indirect processes.
The iron and steel industry is associated with significant water consumption and water-related hazards (Gu et. al, 2015). Water is used in mining, processing, and cooling during the smelting or refining stages of iron. Water is used directly in iron production plants, and in upstream processes (such as mining) and downstream processes (such as recycling of iron products). Water is also used for producing inputs and energy for iron production. Another aspect of water footprint is the wastewater produced in iron making.

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There are several indicators of water footprint in the iron industry, for example: water consumption (cubic meters) per 1 ton of iron produced. Other indicators consider also the "virtual water" (water used in the process of producing the inputs for iron production, including energy) and the wastewater produced in the process (Gu et al., 2015). The water footprint of iron includes "blue water" (surface or ground water that is used for the production process) and "grey water" (water that is needed to dilute pollutants produced during the iron production process). The iron industry can significantly affect water environments via wastewater discharge (Gu et. al, 2015). There are very few studies regarding the water footprint of iron and steel. Choudhury et al (2023) looked at consumption of water in steel factories in India and found that the water intake for 1 ton of steel manufactured is between 2 and 20 m3. They found that a significant proportion of this water is used for cooling, which does not contribute to wastewater generation. The estimated quantity of wastewater discharged is 25–26 m3/ ton of steel produced. Some unit operations in iron plants generate highly complex wastewater rich in polycyclic aromatic hydrocarbons (PAH), cyanide, ammonia, non-consumed acids, benzene, toluene, xylene, oil, grease, etc. These contaminants are generally treated and neutralized using physicochemical and membrane-based systems, recovering about 90% of the water. However, the treatment process yields hazardous sludge, which is landfilled. The abundance of leachable heavy metals makes recycling and reusing the sludge challenging.

Gu et al. (2015) studied the water footprint of a steel plant in China, and expended the view to consider, in addition to the direct consumption of water in steel production plants, also "virtual water", the water used in the process of producing the energy and inputs for iron production. They found that about 6 m3 of water is consumed in the production of 1 ton of steel, mostly in producing the energy needed for iron production. They also assessed that about 146 m3 of water is polluted in the process of producing 1 ton of steel ("grey water").

Ma et al. (2018) studied the iron industry in China and found that the water footprint of one ton of crude steel is 7.19 m3 "blue water" and 12.04 m3 of "grey water". They found that the grey water footprint of each iron-making workshop was mainly from upstream material production, whereas its own energy consumption and wastewater discharge accounted for a small proportion. They concluded that water pollution in the supply chain, rather than direct water consumption, was the main problem in the studied iron industry. They also found that the water depletion in the iron industry in China is lower than in Europe: whereas in China water depletion is about 12.3 m3 / 1 ton crude steel, in Europe it is 47.6 / 1 ton crude steel, and in Poland it is 87.4 / 1 ton crude steel.

Based on Ma et al. (2018) findings, the following Figure details the water footprint of open fields agri-PV in comparison to REGACE technology (3 power density scenarios).

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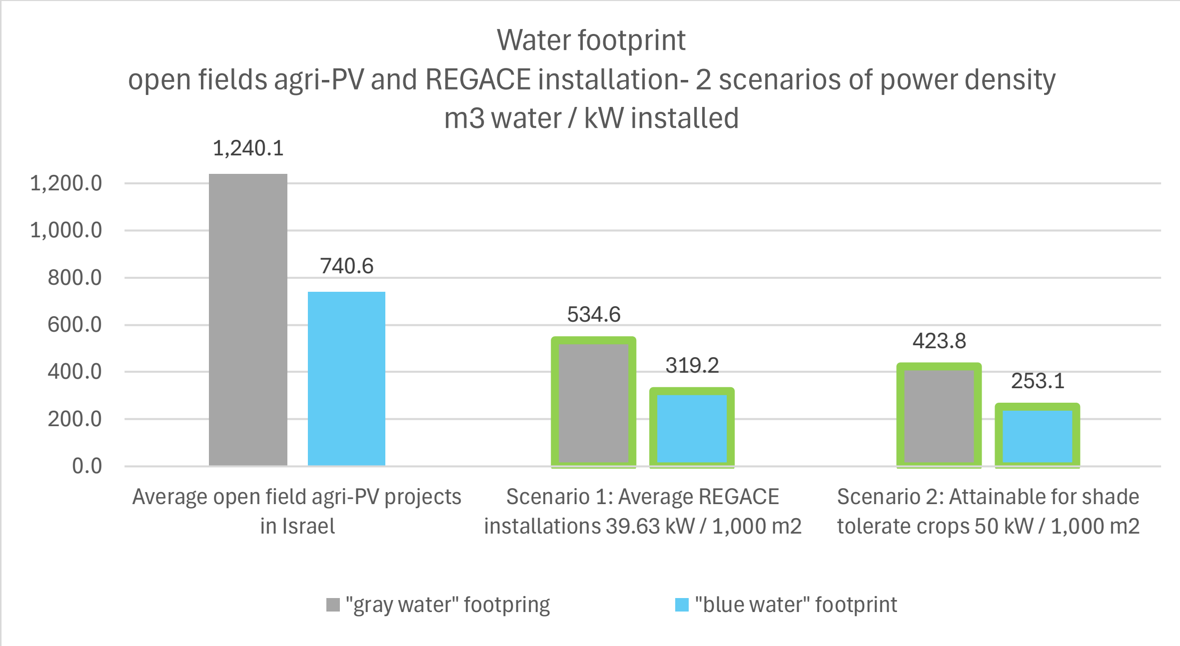

Figure 85: Water footprint of the mounting system of open fields agri-PV and REGACE installations (2 scenarios of power density) water m3 / kW installed

Chapter 4 - Circularity Potential

Circularity, or circular economy, refers to a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible.

The circularity potential analysis of REGACE will focus on the following:

3.1. Biowaste circularity. Examining whether the greenhouses' organic waste can be used for CO2 enrichment in the same greenhouse where it was produced.

3.2 Use of solar energy produced in the greenhouse for agricultural production, for example: heating or cooling the greenhouse, lighting at night, or other necessary agricultural activities.

3.3 Examining the overall energy efficiency in the food system, due to the ability to produce vegetables in greenhouses in cold climate countries, thereby reducing the need for food transportation, and importing from warmer countries.

Methodology

Biowaste circularity

Circularity is especially important when it comes to greenhouses, as this agricultural technique is highly intensive, and creates a lot of organic waste (stems, leaves and produce that is unfit for marketing) in 2-3 production cycles a year.

Circularity can be demonstrated by using the greenhouses' organic waste as part of the CO2 enrichment process, thereby putting the waste into productive use.

CO2 enrichment is one of the is one of the tools that make it possible to compensate the crops for the loss of light because of the integration of solar panels in agricultural areas and thus prevent or reverse the impact on yields. CO2 enrichment can be done using CO2 bags, mushrooms, or agricultural waste.

The goal is to see whether the organic waste of the greenhouse can be used for CO2 enrichment in the greenhouse, therefore tackling simultaneously the waste and the compensation for shade challenges.

In order to set the research, consultation with the following agricultural experts was conducted (all in March 2023):

- Dr. Zafrir Greenhut, head of the department for agri-ecology at the Israeli Ministry of Agriculture.
- Dr. Tali Ilani, researcher at Darom agricultural R&D center, Israel, who studies the use of biowaste in greenhouses.
- Sheli Ganz, chief agricultural instructor for tomatoes at the Israeli Ministry of Agriculture.

A 2nd consultation with Dr. Tali Ilani was conducted in April 2024, following by a study of her research results regarding the use of biowaste in greenhouses.

Use of solar energy for agricultural production

Energy is used in greenhouses for heating in cold seasons; for cooling in warm seasons; for lighting; for operating irrigation systems; etc. The energy needs of greenhouses depend on the location of the farm. For example, in Israel, greenhouses consume very little energy, so little that the item "energy" hardly appears in the standard economic farm calculations of the Israeli Ministry of Agriculture (Israel Ministry of Agriculture, 2024). On the contrary, in cooler climates, energy is a major agricultural input. For example, in Italy, the cost of energy procurement is estimated to account for more than 20% of farms' variable costs (Di Francia and Cupo, 2023).

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The goal is to see whether the energy produced with REGACE PV system can cover the needs of a standard greenhouse, therefore enabling the operation of greenhouses in cold climates without consuming energy from other sources.
The methodology used for tackling the goal is as follows:

1. Collecting data regarding the energy consumption of a standard greenhouse, in the partners' countries.
2. Calculating the amount of energy that can be produced using REGACE PV system.
3. Comparing the energy consumption of a standard greenhouse to the energy production of REGACE PV system, and concluding whether the system can cover the farm's energy needs.

Calculating the amount of energy that can be produced using REGACE PV system was based on the power density of the systems installed within the project doubled by the number of annual sun hours (source: Global Solar Atlas https://globalsolaratlas.info/map, the parameter: "specific photovoltaic power output").
The data on the energy consumption of a standard greenhouse was collected from the following sources:

1. Results of previous studies.
2. Energy Audit conducted within REGACE project (July 2023), based on data from farms in the partenrs' countries.
3. Energy Audit conducted in Bio-Watzkendorf farm, Germany, the most northern research site of REGACE (July 2023).
4. Monitoring of the energy consumption of the control greenhouse (without panels) in Bio-Watzkendorf farm, Germany, during 2024.
5. Monitoring of the energy consumption of the control greenhouse (without panels) in the experimental site at the University of Thessaly, Volos, Greece, during February – September 2025.

The monitoring of energy in the greenhouses was not conducted in Israel and Italy, as in these countries greenhouses hardly consume energy.
The monitoring of energy in the greenhouse was not conducted at the universities in Austria and Berlin, as their greenhouses include experimental equipment that consume electricity and is not present in a standard agricultural greenhouse. Such equipment exists also at the greenhouse of the University of Thessaly, and its impact should be considered.

The overall energy efficiency in the food system

Examination of the projected impact of the solar energy developed in REGACE on the overall energy efficiency in the food system. By leveraging solar energy within greenhouses, some of their energy needs can be met. As a result, greenhouse gas emissions from farming can be reduced, thereby lowering the impact of food systems on climate change.
A preliminary phase of the research included a literature review of aspects of sustainability in local and global food systems. The review concluded that the existing food system, based on import and export of food across the globe, is in fact more energy efficient and emits less GHG than attempting to locally grow crops in colder climates. However, there are other sustainability aspects (social, economic) for which local food systems are preferred. The conclusions of the literature review are presented in appendix 1.

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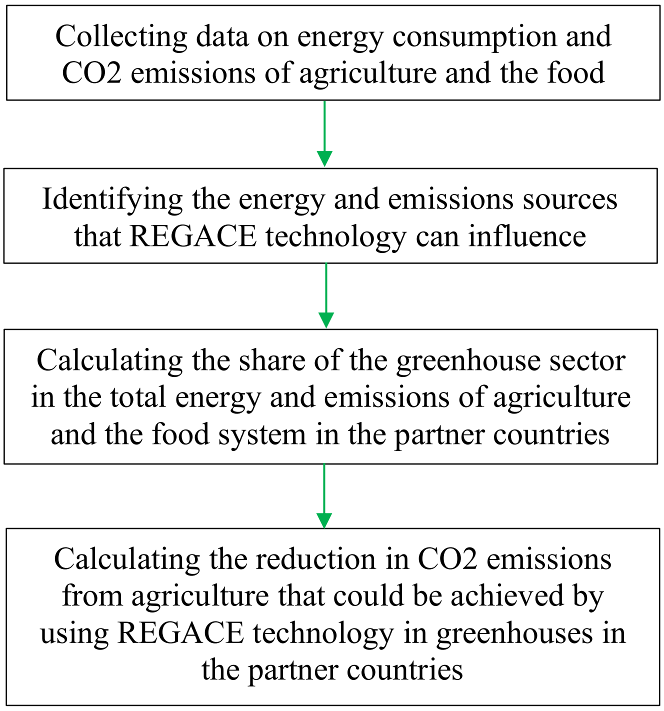
A second preliminary phase included the study of trends in the import and export of greenhouse vegetables in the partner countries, assuming (as presented in the project's proposal) that the existing food system is based on a one-way movement of vegetables grown in warmer countries into colder countries. However, the existing food system is characterized by a complex matrix of movement, as detailed in appendix 2.

Considering the results of these preliminary stages, the analysis turned to looking at the benefits of reducing emissions from greenhouse production, by covering (some of) their energy needs.

The research method will be in accordance with the following flow chart:



The data sources are: FAOSTAT regarding CO_2 emissions from agriculture and the food system; results of previous studies regarding energy consumption in open fields agriculture and greenhouses; and the results of REGACE.

Results

Biowaste circularity

Circular economy in the production sectors and in farming specifically is one of the main principals of the European Green Pact and the Farm to Table strategy of the EU (Castillo-Díaz et al., 2023). Using greenhouses' waste as an input in the same greenhouse manifests the principle of circularity as it turns waste into resource and reduces the need for central treatment facilities and transportation of waste outside the farm. It can have additional environmental benefits such as reducing the use of chemicals in farms (fertilizers and pesticides, that can be replaced by crop residues), the environmental damage that can be caused when agricultural waste is not properly treated, and CO_2 enrichment that can improve yields.

Self-management of agricultural biomass from the previous season can lower the production costs of greenhouse horticultural crops, as they replace purchased chemicals and minimize the costs of waste treatment. Castillo-Díaz et al. (2023) have estimated that it can save up to 6.1% of the farm's costs.

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Greenhouses produce a lot of organic waste, as this agricultural technique is highly intensive. There are 2-3 production cycles a year in which, in addition to the produce, a large amount of organic waste is created - stems, leaves and produce that is unfit for marketing.
For illustration, in Israel it is estimated that greenhouses produce about 25.5 tons of organic waste / ha / year[20]. The organic waste of plantations in Israel is estimated at about 4.8 tons / ha / year, about 19% of greenhouses' waste.
Organic waste creates environmental challenges in areas where greenhouses are abundant. Although treatment of organic waste is often easier than other types of waste, as it can be easily converted into compost and used for enrichment of farm soil, or used for energy production, there are still many challenges. In some areas, the farmland is not large enough to absorb the abundant organic waste of greenhouses. Compost production or energy production facilities are not always available. A specific obstacle to using organic waste from greenhouses is that it is often mixed with un-organic waste, such as the wires on which the plants are grown (bio-degradable wires are available but are more expensive). Separating the plant material from the wires takes substantial time, which translates to higher labor costs. The result is that few greenhouse farmers treat their organic waste sustainably. For example, in Almeria in Spain, one of the most important greenhouse areas in the EU, only about 15% of the farmers self-manage their crops residues on their farm (Castillo-Díaz et al., 2023).
As part of the study of circularity potential, REGACE project investigates whether it is possible to use the greenhouses' organic waste as part of the CO2 enrichment process, thereby putting the waste into productive use. Using organic waste in the CO2 enrichment process will turn it from waste into a useful by-product of the agricultural production, in line with circular economy principals.
CO2 enrichment is needed to increase crop production and compensate for lack of light due to the photovoltaic panels. The CO2 enrichment within REGACE is tested using different approaches: CO2-cylinders (HU), CO2-bags (CO2BAG®Finland CO2 Products Oy; BOKU), dry ice (BOKU), mushroom cultivation (BOKU) and compost (AZS). The Bio- Watzkendorf farm also uses compost for CO2 enrichment. However, the compost used for CO2 enrichment at AZS is from commercial production, and the compost used at Bio Watzkendorf farm is generated in a neighboring farm.
To reach circularity, the organic material used for CO2 enrichment (as raw material or after composting) should be the by-product of the greenhouse itself. Using the organic material generated by the greenhouse inside that very greenhouse will create a local solution, reducing the need for transportation of organic waste to treatment facilities, and eliminate the need for establishing regional treatment facilities. The simplest way to enrich the greenhouse with CO2 would be to integrate the organic by-product into the greenhouses' soil. A more complex approach would be to produce compost out of the organic by-product and use it for CO2 enrichment; this requires the establishment of a composting facility at the greenhouse and investing funds and labor into composting.
The simplest solution is to integrate the crop's debris into the soil. However, in this case, there is concern about soil contamination due to pests and diseases that affect

[20] The calculation is based on the following sources: The amount of organic waste from greenhouses and from plantations: Israel Ministry of Environmental Protection, 2019; The ha size of greenhouses: Israel Ministry of Agriculture, GIS data (see chapter regarding land use impact of PV systems); The ha size of plantations: Israel Ministry of Agriculture, 2023.

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the raw organic material and are carried from the previous growing season (Castillo-Díaz et al., 2023). It is necessary to develop a protocol that will prevent soil contamination and inactivate pests and diseases from the previous crop.
Different crops react differently to the treatment of integrating the previous crop residues in the soil. Ongoing research at the Darom agricultural R&D center in Israel, is conducted in tomatoes' shade-houses, where in some plots raw residues from the previous crop are integrated into the soil; in some plots compost based on residues from the previous crop is integrated into the soil; and in other plots no additives are used. In the first year of the experiment (two growth seasons, spring and autumn) no differences were observed between the treatment plots. Nevertheless, the researchers are reluctant to say that the treatment is safe to use for tomatoes, after only one year of experimentation; the cumulative effect might be manifested after implementing the treatment for several seasons (Illani et al, unpublished).
For bell peppers, the treatment was shown to have no negative impact: at a 6 years experiment at Central & Northern Arava R&D center in Israel, integrating the previous season's bell pepper residues into the soil did not harm the subsequent crop, conditioned on there being no significant presence of soil pests, such as nematodes (Pivonia et al., 2012).
To lower the risk of contamination with soil diseases, several options can be considered. They are presented here in order of feasibility for farmers:

1. Composting the organic material before using it at the greenhouse. Compostation should eliminate the risk of soil diseases. The compost pile on the farm should take up a few m^2 only. The quickest way to make compost would be to mix the plant material with livestock waste; however, compost can be produced also without livestock waste, although it takes longer time (about 6 months, in mediterranean climate conditions).
2. Biodisinfection – this is a technique that uses crops' debris for both fertilizing and disinfecting against soil pathogens. In biodisinfection, the crop's debris is integrated into the soil and then covered with plastic sheets. Hyperthermic fumigant action is obtained from the solar energy captured by the plastic film and from the energy released by the metabolism of the microorganisms that participate in the bio-decomposition process of the organic amendments, in combination with the disinfectant action harvested by the volatile substances generated during this bio-decomposition and retained by the plastic film. Biodisinfaction allows for the use of biomass in the same field or greenhouse where it grew, as the heat inactivates pests and diseases that might exist in the organic material (García-Raya et al. 2019). This technique, that was successfully used in the greenhouse of Almeria in Spain (Castillo-Díaz et al., 2023) achieves many circular economy goals, as it reduces agricultural waste and use it for fertilizing and disinfecting the soil, therefore also reducing the use of chemical fertilizers and pesticides. It can also save up to 6.1% of the farm's costs and does not reduce the density or the biodiversity of agricultural soils (Castillo-Díaz et al., 2023). A disadvantage of the technique is that it takes a few months to preform, and in intensive greenhouses crops – this time is not always available. It is also not clear if this technique can contribute to CO2 enrichment in the greenhouses, as CO2 from the residues is probably contained in the soil by the plastic sheets.
3. Change the type of crop from one season to the next; diseases of tomatoes will not affect cucumbers etc. This could be an easy solution, however - most of the farmers do not change the crops between seasons, but practice monoculture in

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which one crop is grown repeatedly. Therefore, this solution is probably not feasible at a commercial level.

4. Using the organic by-products to make pellets, for burning in stoves to produce energy for heating the greenhouses. This is another productive use of the organic by-products of greenhouses, in addition to CO2 enrichment. This solution is more relevant in cold climates and less so in Mediterranean climates.

After considering all the options within the REGACE team, it was decided that it is impossible to conduct field experiments of integrating crop residues into the soil of the greenhouses for CO2 enrichment, within REGACE project. The options detailed above could be useful for the consideration of farmers, when taking up the technologies developed within REGACE.

Use of solar energy for agricultural production

The following table presents the results of previous studies regarding the consumption of energy in greenhouses in 6 European countries, and comparison to the projected production of energy of REGACE technology. The projected energy production was calculated using the power density of REGACE installations for the partner countries (marked in green). For other countries the power density from the REGACE installations were used for calculations, according to the relevant geographical area. As can be seen, for the lowest energy systems the technology of the REGACE project can produce substantially more energy than is necessary for operating the greenhouses. The extra energy produced can be sold out to other electricity consumers.
On the other hand, for the high energy systems, the technology of the REGACE project can provide only a portion of the energy needed for operating the greenhouses, depending on the location of the greenhouse. In the Netherlands it can cover 66% of the greenhouses' needs, however in Germany it can provide as little as 10% of the greenhouses' energy needs.

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Table 30: Comparison of energy consumption in greenhouses to energy production potential of the technology of REGACE

country	high energy greenhouses				low energy greenhouses GJ/ hectare				% electricity	power density REGACE	number of annual sun hours[3]	projected energy production REGACE technology	% of energy consumption that can be produced by REGACE technology	
	GJ/ ha		kWh / ha		GJ/ ha		kWh / ha			kW / ha		kWh / hectare	% of min consumption in the lowest energy systems	% of min consumption in high energy systems
	min	max	min	max	min	max	min	max						
Spain[1]	11000	18000	3,058,000	5,004,000	150	220	41,700	61,160	n.d.	500	1630	815,000	1954%	27%
Spain-2[2]							13,986			500	1630	815,000	5827%	
Greece[1]	7000	11500	1,946,000	3,197,000	n.d.	250	n.d.	69,500	n.d.	400	1505	602,000	866%	31%
Italy[1]	n.d.	n.d.	n.d.	n.d.	60	140	16,680	38,920	50%	500	1370	685,000	4107%	n.d.
the Netherlands[1]	1800	15500	500,400	4,309,000	n.d.	n.d.	n.d.	n.d.	26%	320	1033	330,560	n.d.	66%
Germany[1]	12300	12500	3,419,400	3,475,000	n.d.	n.d.	n.d.	n.d.	0.50%	320	1075	344,000	n.d.	10%
Portugal[1]	n.d.	n.d.	n.d.	n.d.	n.d.	275	n.d.	76,450	n.d.	500	1556	778,000	1018%	n.d.

[1] Source for Spain-1, Greece, Italy, the Netherlands, Germany and Portugal: Paris et al. 2022
[2] Source for Spain-2: Carreño-Ortega et al, 2017
[3] Source: the parameter "specific photovoltaic power output" from Global Solar Atlas https://globalsolaratlas.info/map

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A detailed energy audit was carried out by the REGACE partners of the University of Thessaly, Greece in July 2023. The results are detailed in the following table. As can be seen, different crops consume different amounts of energy. The technology of the REGACE project can produce substantially more electricity than is necessary for operating the greenhouses. For some crops (tomato) it can even cover more than the total primary energy (electricity and heating) necessary for operating the greenhouses. It covers only a portion of the primary energy needed for growing cucumbers and potted flowers.

Table 31: Comparison of energy consumption in growing different crops in greenhouses in Greece to energy production potential of the technology of REGACE

crop	total primary energy kWh/ hectare	electrical energy kWh/ hectare	% electricity	projected energy production REGACE technology in Greece	% of energy consumption that can be produced by REGACE technology	% of energy consumption that can be produced by REGACE technology
				kWh / hectare	% of total primary energy	% of electrical energy
cucumber	5,277,100	133,800	3%	602,000	11%	450%
potted flowers	955,670	59,980	6%	602,000	63%	1,004%
tomato	115,040	9,350	8%	602,000	523%	6,439%

Source: Energy Audit REGACE, for Greece July 2023

The following table presents the electricity consumption in the Watzkendorf farm, the most northern partner of REGACE for the years 2018-2020. The data relates to electricity consumption only, data on the total energy consumption (including heating) was not monitored in these years. The data relates to the energy consumption of the whole farm, as there were no separate electricity meters for the greenhouses in these years.
As can be seen, the technology of the REGACE project can produce substantially more electricity than is necessary for operating the farm. However, for these years, it is not clear how much of the total energy needs (including heating) of the farm could be covered by the technology of the REGACE project.

Table 32: Comparison of electricity consumption in Watzkendorf farm to energy production potential of the technology of REGACE, 2018-2020

year	Electricity consumption kWh / hectare, for the whole farm, including greenhouses	projected energy production REGACE technology in Germany	% of energy consumption that can be produced by REGACE technology
		kWh / hectare	% of electrical energy
2018	158,142	344,000	218%
2019	124,586	344,000	276%
2020	118,452	344,000	290%

Source: Watzkendorf energy Audit, July 2023

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Separate electricity and energy meters for the greenhouses were installed in Watzkendorf farm in the beginning of 2024 thus enabling the monitoring of the electricity and heating consumption of the control greenhouse. The energy monitored did not include the electricity needed to operate the water pumps on the farm.
The following table presents the results. As can be seen, the technology of the REGACE project can produce substantially more electricity than is necessary for operating the greenhouse (without the electricity needed to operate the water pumps on the farm). However, it produces only 20% of the total energy necessary for operating the greenhouse (including the energy needed for heating during the winter).

Table 33: Comparison of electricity and total energy consumption in Watzkendorf greenhouse to energy production potential of the technology of REGACE, 2024

year	crop	Electrical energy consumption kWh / hectare	projected energy production REGACE technology in Germany	% of electrical energy consumption that can be produced by REGACE technology	Total energy consumption kWh / hectare	% of total energy consumption that can be produced by REGACE technology
			kWh / ha			
2024	tomato	133,726	344,000	257%	1,685,546	20%

Source: Watzkendorf energy monitoring for 2024, December 2024

Electricity and energy meters were installed in the greenhouses of Thessaly University in Volos in the beginning of 2025.
The following table presents the results of the energy monitoring, and comparison to the projected energy production of REGACE technology in Greece. As can be seen, the technology of the REGACE project can produce substantially more electricity than is necessary for operating the greenhouse. However, it produces only 33% of the total energy necessary for operating the greenhouse (including the energy needed for heating during the winter).

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Table 34: Comparison of electricity and total energy consumption in the greenhouse of the University of Thessaly in Volos, to energy production potential of the technology of REGACE, 2025

year	crop	Electrical energy consumption kWh 0.24 ha greenhouse	Electrical energy consumption kWh, 1 ha greenhouse	projected energy production REGACE technology in Greece	% of electrical energy consumption that can be produced by REGACE technology	Total energy consumption kWh, 0.24 ha greenhouse	Total energy consumption kWh, 1 ha greenhouse	% of total energy consumption that can be produced by REGACE technology
2025	cucumbers	3,427	142,791	602,000	422%	43,519	1,813,297	33%

Source: the University of Thessaly in Volos energy monitoring for 2025, September 2025

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In conclusion, REGACE's technology generates more electricity than is required to operate greenhouses even in the cold climates of northern Germany. However, the amount of energy produced is not sufficient to cover the full range of energy needs of the greenhouses, including heating, but only 20-33% of it (depending on the location of the greenhouse). The rest of the energy needs to be supplied from other sources (biowaste, fossil fuels, or other sources). REGACE's technology contributes a significant part of the energy needs for cultivating vegetables in colder climates, based on renewable and non-polluting energies, and lowering the carbon emissions from agriculture.

The overall energy efficiency in the food system

The FAO collects data on emissions from the food system, relating to various emission types (N_2O, CH_4 and CO_2) and various sources of emissions, as detailed in the following table. From the various emission types, REGACE technology can impact CO_2 emissions, as they mostly originate from energy use.
The following table details the emissions of CO_2 from various components of the food system in the partner countries: their emissions value (kt CO_2) and their share of the total emissions of the food system.

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Table**35** : CO2 emissions from various components of the food system in partenr countries, kt CO2, 2022

Item	Germany		Austria		Greece		Israel		Italy	
	kt CO2	% of total	kt CO2	% of total	kt CO2	% of total	kt CO2	% of total	kt CO2	% of total
Agrifood Systems Waste Disposal	1,828.5	1.6%	186.5	2.5%	174.3	1.9%	37.4	0.5%	626.8	0.8%
Drained organic soils (CO2)	27,487.8	24.4%	287.5	3.9%	1,262.7	14.1%	0.0	0.0%	693.2	0.9%
Fertilizers Manufacturing	1,463.6	1.3%		0.0%	345.0	3.9%	83.0	1.0%	1,530.4	2.0%
Fires in organic soils	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Food Household Consumption	27,134.9	24.1%	1,247.4	17.0%	1,037.3	11.6%	1,311.8	16.1%	9,245.2	12.0%
Food Packaging	5,425.7	4.8%	720.6	9.8%	611.6	6.8%	88.4	1.1%	3,419.1	4.4%
Food Processing	15,887.7	14.1%	1,187.3	16.1%	1,548.3	17.3%	797.4	9.8%	38,462.5	49.8%
Food Retail	9,924.0	8.8%	453.3	6.2%	1,001.3	11.2%	955.4	11.7%	5,065.1	6.6%
Food Transport	12,754.2	11.3%	1,901.6	25.8%	1,361.0	15.2%	1,893.8	23.2%	8,304.9	10.7%
Net Forest conversion	0.0	0.0%	225.9	3.1%	0.0	0.0%	81.8	1.0%	0.0	0.0%
On-farm energy use	9,753.3	8.6%	1,054.7	14.3%	1,489.5	16.6%	2,790.4	34.1%	9,141.5	11.8%
Pesticides Manufacturing	1,123.0	1.0%	93.1	1.3%	124.3	1.4%	132.6	1.6%	781.0	1.0%
total CO2 emissions from the food system	112,782.7	100.0%	7,358.0	100.0%	8,955.2	100.0%	8,171.9	100.0%	77,269.8	100.0%

Source: FAOSTAT: Climate Change: Agrifood systems emissions- Totals and indicators- Emissions totals

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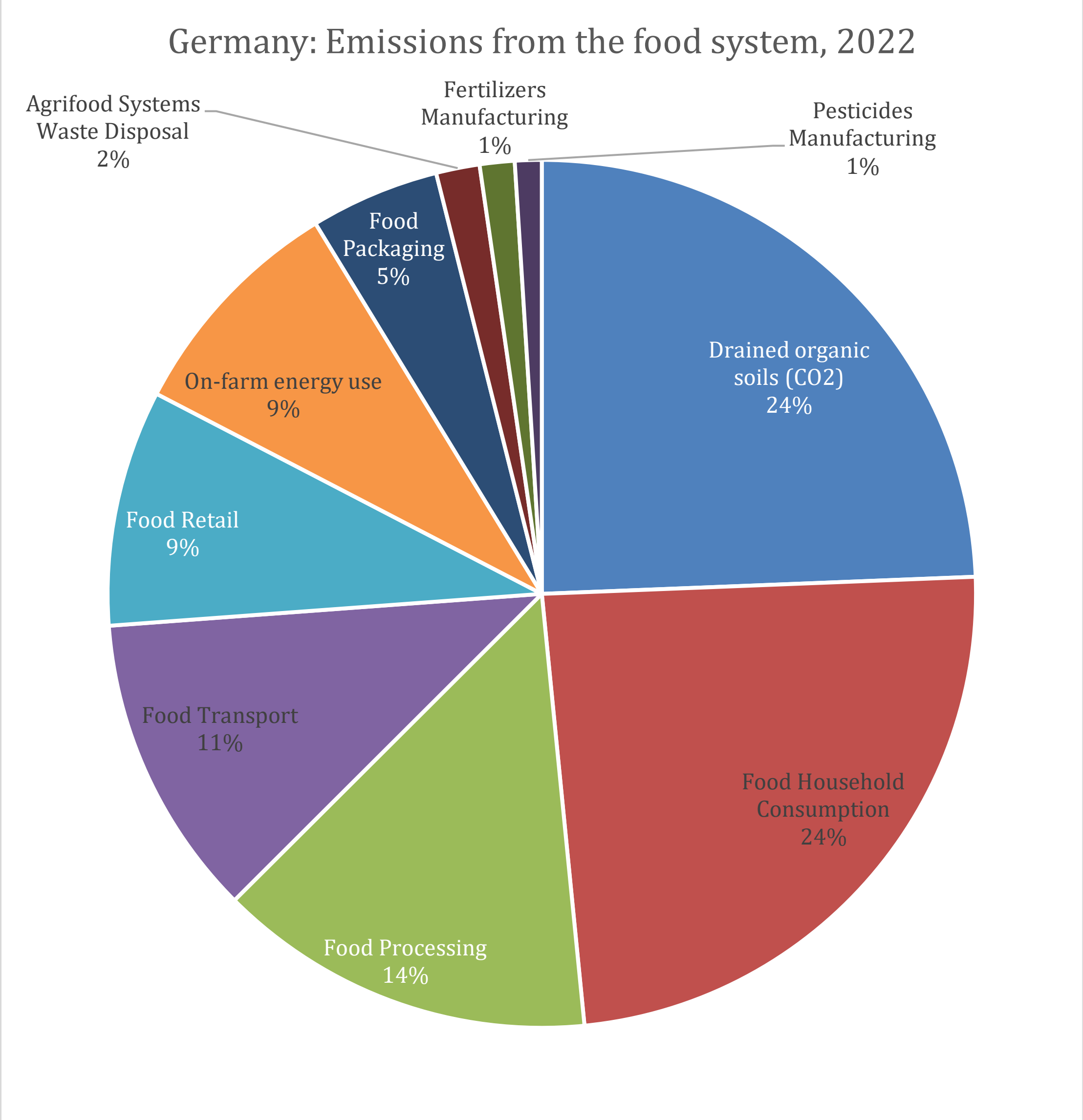
The main emissions source over which REGACE technology can influence is on-farm energy use. The PV panels in the greenhouses can generate energy for the operation of the farm.
It should be noted that the share of on-farm energy use of the total emissions in the food system varies between different countries: in Israel, 34% of the emissions of the food system originates in on-farm energy use, whereas in Germany – it is as little as 8.6%. The following Figures detail the share of various components of the food system emissions in these two countries.



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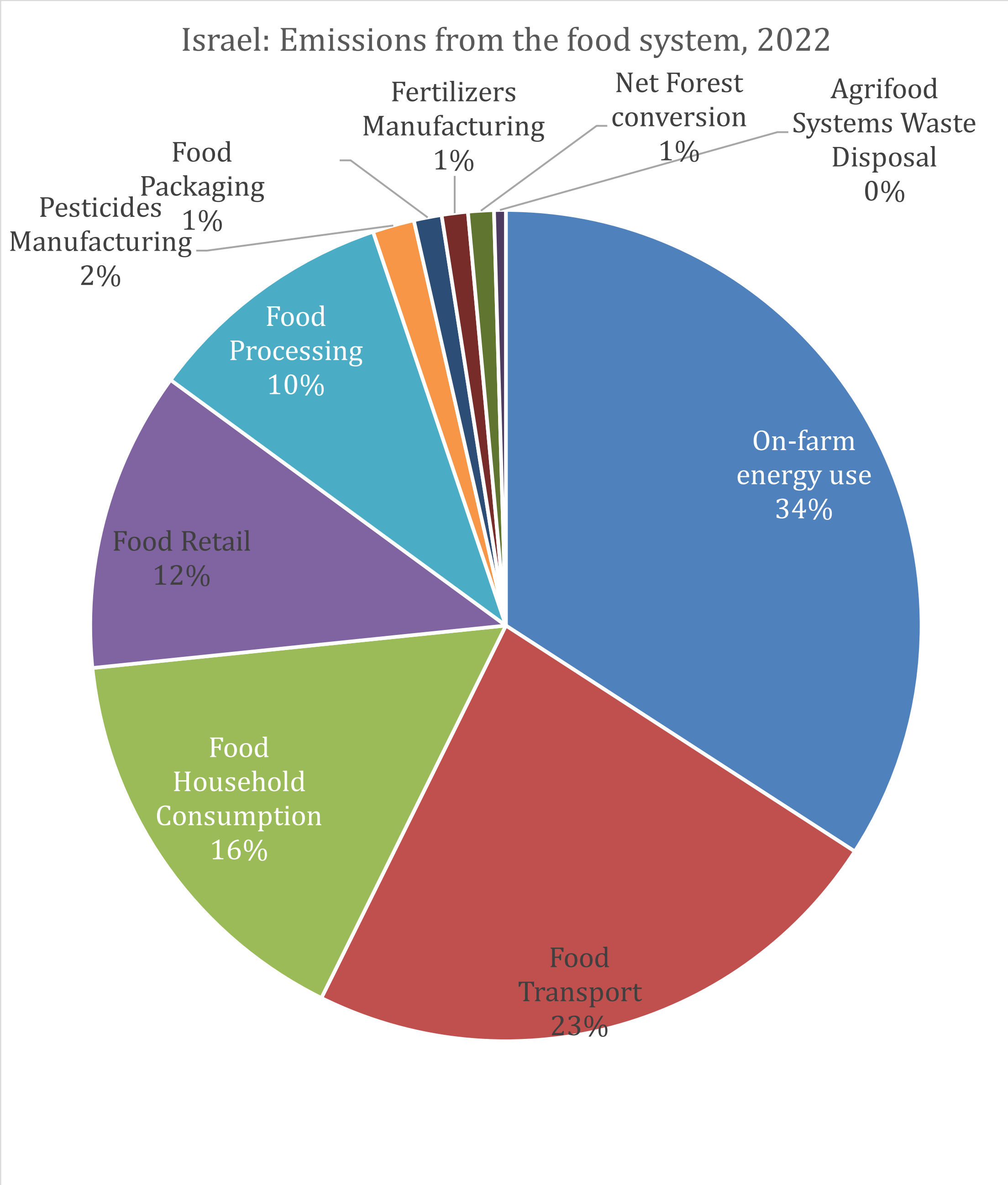

Figure 86: The share of various components of the food system emissions, Germany and Israel, 2022.
Source of data: FAOSTAT

When calculating the projected impact of replacing 20-33% of the energy in greenhouses with renewable solar energy, it should be considered that although greenhouses cover a small portion of the cropland in many countries, they are also very big consumers of energy, in some countries.
The share of greenhouses of the total cropland in the partner countries spans from 2.94% of the cropland in Israel to 0.04% only in Austria.
The energy consumed in greenhouses in different countries in Europe was studied by Paris et al. (2022 a), who divided greenhouses into two systems:

1. High energy systems, consuming around 12,500 GJ / ha in Germany and about 9,250 GJ / ha in Greece.
2. Low energy systems, consuming around 100 GJ / ha in Italy.

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Paris et al. (2022a) assert that in general energy use in greenhouses dependent on fossil sources; and that high energy greenhouse systems are dominant in northern Europe, and low energy systems are dominant in southern Europe; and that. It is therefore possible to say that the greenhouses in Austria are characterized as high energy systems, and in Israel – as low energy systems.
Paris et al. (2022b) studied also the energy consumption of open fields farming in Europe and found that it is about 20 GJ/ ha. Low energy greenhouses therefore consume 5 times as much energy per ha than open fields farming, and high energy systems consume up to 625 times as much energy per ha than open fields farming. Considering both the small share of greenhouses of the total cropland and their relative high energy consumption per ha, it is possible to calculate the share of greenhouses of the total on-farm energy use in each of the partner countries, as detailed in the following table.

Table 36: the share of energy in greenhouses of total on-farm energy use in the partner countries

Country	type of greenhouses	energy consumption GJ/ ha in greenhouses	The ratio of energy per unit area in a greenhouse to open field agriculture	% of greenhouses in total cropland	% energy in greenhouses of total on-farm energy use	comments
Germany	high energy	12500	625	0.05%	23.8%	
Austria	high energy	12500	625	0.04%	20.0%	assumption: energy consumption in greenhouses the same as in Germany
Greece	high energy	9250	463	0.16%	42.6%	assumption: all greenhouses are high energy
Italy	low energy	100	5	0.30%	1.5%	
Israel	low energy	100	5	2.94%	13.2%	assumption: energy consumption in greenhouses the same as in Italy

Source for energy consumption in greenhouses and open fields: Paris et. al 2022a, 2022b
Source for the share of greenhouses in total cropland: See previous chapter.

Based on the calculations of the previous table, the following table presents the share of greenhouses versus open fields agriculture in the emissions of on-farm energy use in the partners' countries.

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Table37 : Identifying the share of open-fields farming and greenhouses in the total emissions of on-farm energy use of the partners' countries.

Emission source	Germany		Austria		Greece		Israel		Italy	
	kt CO2	% of total	kt CO2	% of total	kt CO2	% of total	kt CO2	% of total	kt CO2	% of total
On-farm energy use	9,753.3	8.6%	1,054.7	14.3%	1,489.5	16.6%	2,790.4	34.1%	9,141.5	11.8%
of which:										
On-farm energy use in open fields agriculture	7,432.0	6.6%	843.8	11.5%	855.0	9.7%	2,748.5	33.7%	7,934.8	10.3%
On-farm energy use in greenhouses	2,321.3	2.1%	210.9	2.9%	634.5	7.2%	41.9	0.5%	1,206.7	1.6%

Source for total on-farm energy use: FAOSTAT.

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As shown in the previous chapter, REGACE technology can cover about 20-33% of the energy consumption of high-energy greenhouses, replacing it with energy from renewable solar sources, therefore reducing the emissions from on-farm energy use. The following table details the meaning of lowering about 20% of the emissions from on-farm energy use in greenhouses.
As can be seen, the emission from on-farm energy use can be reduced in up to 7% (in Greece) by using REGACE technology and replacing about 20% of the energy sources used in greenhouses with renewable solar sources. Also in Greece, about 1.2% of total the emissions of the food system can be reduced by using REGACE technology.

Table38 : The impact of lowering about 20% of the emissions from on-farm energy use in greenhouses on the total emissions from on-farm energy use and the total emissions from the food system

	Germany	Austria	Greece	Israel	Italy
	kt CO2	kt CO2	kt CO2	kt CO2	kt CO2
Total on-farm energy use, current situation, kt CO2	9,753.3	1,054.7	1,489.5	2,790.4	9,141.5
On-farm energy use in greenhouses when using REGACE technology, kt CO2	1,934.4	175.8	528.8	34.9	1,005.6
Total on-farm energy use when using REGACE technology, kt CO2	9,366.4	1,019.5	1,383.7	2,783.4	8,940.4
CO2 emissions from on-farm energy use saved by using REGACE technology, kt CO2	386.9	35.2	105.8	7.0	201.1
% of CO2 emissions from on-farm energy use that can be reduced by using REGACE technology	4.0%	3.3%	7.1%	0.3%	2.2%
Total CO2 emissions from the food system, when using REGACE technology, kt CO2	112,395.8	7,322.9	8,849.4	8,164.9	77,068.7
CO2 emissions from the food system saved by using REGACE technology, kt CO2	386.9	35.2	105.8	7.0	201.1
% of CO2 emissions from the food system that can be reduced by using REGACE technology	0.34%	0.48%	1.18%	0.09%	0.26%

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Conclusions

This deliverable has examined the environmental and economic implications of integrating PV systems into greenhouses. The findings demonstrate the opportunities and sustainability gains of deploying agri-voltaic solutions, as developed within the REGACE project.

The analysis of land use impacts shows that ground-mounted PV systems, while efficient in terms of energy density, pose significant risks to food security due to the direct occupation of productive farmland. In some partner countries, particularly Israel, the share of farmland required to achieve national renewable energy goals is already substantial and likely to increase, raising concerns over future food security. Conversely, agrivoltaics in greenhouses offer more sustainable pathways, mitigating land-use conflicts. Nonetheless, even in these systems, trade-offs remain, as partial shading can affect yields.

Greenhouse-integrated PV technology, as developed within REGACE, offers an innovative solution with distinctive advantages. The technology enables significant renewable energy generation, with the potential to cover a meaningful share of greenhouse electricity needs and contribute to national solar energy targets—especially in countries with high greenhouse density such as Israel, Spain, and Italy. Emission reduction analyses further demonstrate that PV-integrated greenhouses can support climate mitigation by lowering fossil fuel dependence and associated greenhouse gas emissions.

However, agronomic trials across multiple partner sites revealed yield reductions in most crops under PV conditions, averaging around 25%. Seasonal variations were observed, with yield penalties more pronounced in summer months. While CO_2 enrichment partially compensated for these reductions, it did not consistently restore yields to control levels. While water use efficiency improved in some cases, it deteriorated in others, particularly when yields were suppressed under shading. Pest and beneficial arthropod populations were also affected in complex and sometimes contradictory ways.

Farmers' perceptions corroborated these findings: while many reported little or no impact on yield, others identified specific challenges linked to crop variety, market requirements, or seasonal timing. These insights emphasize the need for crop-specific strategies and adaptive management to optimize outcomes.

Overall, the REGACE findings confirm that greenhouse-integrated PV represents a promising technology for advancing renewable energy goals. While ground-mounted PV will continue to play a role in national energy strategies, greenhouse-integrated PV can alleviate pressure on farmland.

In conclusion, the REGACE project demonstrates that integrating PV into greenhouses is both feasible and beneficial, but requires careful system design, crop selection, and supportive policies. By addressing these challenges, greenhouse-integrated PV can become a cornerstone of sustainable agriculture and renewable energy transitions in Europe and beyond.

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Annex 1: Questionnaire of survey of open fields agri-voltaic sites in Israel

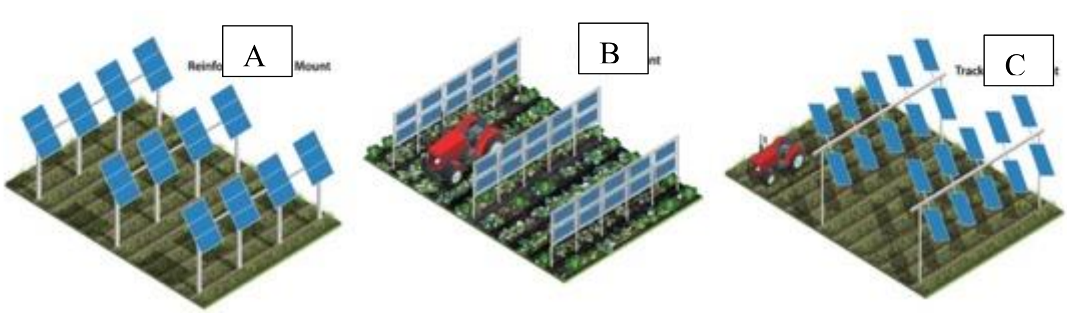
Questions for managers of agro-solar sites in open farmland (orchards and fields)

The interview is conducted as part of a study aimed at developing technology for integrating solar panels into greenhouses (under the covering sheets). The goal is to examine the "resource use efficiency" in comparison between agro-solar in greenhouses and agro-solar in open farmland. The study is funded by the European Union's Horizon Foundation and includes trial sites in four European countries and Israel. The study is coordinated by the Triangle R&D Center in Kfar Qara, and the interviews are conducted on behalf of Tel Aviv University, a research partner.

The two main factors that differ between a solar system in a greenhouse and a solar system in open farmland are the supporting structure for holding the panels, and the work involved in maintaining the system. Most questions will focus on these factors. The answers will be kept confidential and will be used for research purposes only.

<u>Background information</u>

1. How big is the site? _____ sqm
2. When was it established? Year_________
3. What is the agricultural crop in the area? _________
4. Status:
   A. Built and produces energy
   B. The supporting structure is built, the panels are placed but the system is not connected to the electricity grid
   C. The supporting structure is built, the solar panels have not yet been placed
   D. Other, Detail: _______________
5. What is the technology of the supporting structure that holds the panels?
   A. Conventional structure – concrete foundations and steel columns
   B. Vertical mounting ("fences")
   C. Lightweight stilt structure



6. Type of panel technology:
   A. Fixed panels
   B. Tracker Panels
7. What is the coverage rate of the panels? %____
8. What is the produced / planned power? ____kW

<u>Construction of the system</u>

9. Construction materials: How much construction material (tons/cubic meters) in the supporting structure:
   A. Ground foundations (data for the entire project / per 1000 sqm):

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i. Do they exist?
ii. What materials were built from? ____________
iii. How much concrete in them? _____ tons per ___ unit
iv. How much steel in them? _______tons per _______ unit

B. The above-ground supporting structure (data for the entire project / per 1000 sqm):
i. What material is built from? _____________
ii. How much material is required? Material type: _________ ________ tons per ______unit
iii. How much material is required? Material type: _________ ________ tons per ______unit
iv. How much material is required? Material type: _________ ________ tons per ______unit

10. What is the height of the pillars holding the panels? ____M
11. Number of pillars per 1,000 square meters? __________Pages
12. What is the span between the pillars? _______M
13. What is the total cost of building materials (data for the whole project / per 1000 square meters) (can be divided into costs of different materials)
    A. Total cost for concrete: ______ ₪
    B. Total cost per steel: _______ ₪
    C. Total cost of aluminium: ________ ₪
    D. Other material total cost: ________ ₪
14. Work in construction:
    A. How many working hours / working days / number of workers are required to build the mounting structure (data for the entire project / per 1000 square meters)?

    __________ working hours / _________ working days / ___________ number of workers
    B. Does the construction work require professional manpower? Yes / No. If so, which one? __________
    C. The total cost of manpower for the construction of the support structure (data for the entire project / per 1000 square meters)? _______ ₪
15. Are there additional costs for the construction of the supporting structure (unrelated to the cost of panels or the electrical system), beyond materials and labor? Yes/No. If so, for what? __________ what is the cost: _______ ₪

System maintenance

9. What types of maintenance work are required during system operation? (You can mark more than one section)
    A. Washing panels with water
    B. Cleaning panels with chemicals
    C. Cleaning the panels in a different way. Detail:____________
    D. Ongoing system testing
    E. Other, Detail: _______________
10. Does maintenance work require professional manpower? Yes / No. If so, which: ___________
11. How many hours of maintenance work is an average month, divided by types of work and types of manpower? Please fill in the following table:

Hours per month Unskilled manpower	Hours per month Skilled manpower	Type of work
		Panel washing
		System Control
		Other, specify:

12. In your opinion, are there other factors that distinguish between a solar system in a greenhouse and a solar system in an open farmland besides the support system and system maintenance? No / Yes. If so, please specify____

____

12. Can you connect us with other Agro Solar sites:
    A. In open fields
    B. In greenhouses

Thank you for your cooperation!

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Annex 2: Methodology for survey of agri-voltaic greenhouses in Israel

Sampling methodology

The initial sampling was based on a list of farmers that applied to the Israeli Ministry of Agriculture for permit to construct PV systems on their greenhouses. The list contained about 60 entries, however some of them did not include contact details. After contacting, it turned out that some of the farmers had not actually built a solar system, even though they had registered for a permit from the Ministry of Agriculture. All the farmers were asked at the end of the interview to give contact details of other farmers who have solar systems on their greenhouses. In addition, representatives of farmers' organizations were contacted. These actions resulted in the list of about 30 farmers that have solar systems on their greenhouses. All these farmers were interviewed.

Interviews

The interviews were conducted by phone, in December 2024 and May 2025. The interviews were based on a structured questionnaire that included 30 questions regarding:

i. The greenhouse and the PV system: size, time of establishment, crop, technology, PV's mounting structure, construction materials and amount of materials in the mounting system, labour in construction and maintenance, total investment cost for the PV system.
ii. Impact of the PV system on the yield, irrigation, pests, and other agricultural parameters (farmer's estimation).
iii. The farmer's attitude towards integration of PV systems in greenhouses, government policy, challenges.

The questionnaire was computerized using Google Forms software, and the answers were analysed as presented in the report.

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Annex 3: Detailed information about REGACE installations and sites

site	Installation date	System size m^2	System size kW	Type of greenhouse	Number of working days/ hours in the installation[21]	Cost per workday in installation	% skilled workers / unskilled workers	Who installed?
Italy, Fattoria Solidale del Circeo farm	October + November 2023	90 m^2	4.8 (5.3 kW/ 100 m2)	Polyethylene	38 hours, of which 32 for installation + 6 for connection and software	150 euros per working day*4.75 days = 712.5 euros per installation	50% skilled 50% unskilled	REGACE team
Austria, University of Natural Resources and Life Sciences, Vienna	13-18 March 2024 + 10- 12 June 2024	21 m2 * 2 greenhouses = 42 m2	55 W panels x24 panels =1.32 Kw	PC Polycarbonate	5 days of 10 hours a day for the mechanical part + 2 days of 12+ hours for 2 professional workers for the sensors and electronics enclosures	n.d.	100% REGACE engineer	REGACE team
Germany, Bio-Gärtnerei Watzkendorf GmbH	25 March – 2 April 2024 + 17 May 2024	384 m2	125 W panels x 128 panels = 16 kW	Glass. Producing seedlings and vegetables	186 hours, 19 workdays	75 Euro/ day unskilled worker, 150-250 Euro/ day skilled electrician	80% unskilled workers, 20% skilled	REGACE team + farm workers

[21] workers * number of days each worker * number of hours per day

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site	Installation date	System size m^2	System size kW	Type of greenhouse	Number of working days/ hours in the installation[21]	Cost per workday in installation	% skilled workers / unskilled workers	Who installed?
Israel, Triangle Research and Development Center	April 2024	280 m^2	12.4	Polyethylene	192 hours	n.d.	100% unskilled. Electricity work was done by the R&D staff	REGACE team + unskilled workers
Germany, Humboldt University of Berlin	8-19 May 2024	1 system with 3 openings each 4*3*12.6 = 151.2 m2, with different cover rates: 30% (16 panels) 15%, 7.5%.	36 panels * 105W per panel = 3.78 kW	Glass	8 workdays* 6 people* 8 hours per day = 384 hours	n.d., done by students and the REGACE team	n.d.	Students and the REGACE team
Greece, University of Thessaly	August 6-August 19 2024	200 m2 *2 = 400 m2 green houses = 400 m2	16 KW	Polyethylene hydroponics	546.5 hours, of which 265 hours professional work, 217.5 hours non-professional work, and 64 hours for scaffolding	n.d.	48% skilled work	A professional contractor

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Annex 4: The sustainability of local versus global food systems – A literature survey

Background and goals

This annex details a literature survey that was conducted to identify how the sustainable energy technology developed in REGACE can impact the overall sustainability of energy use in the food system, due to the ability to produce vegetables in greenhouses in cold climate countries. This will reduce the need for importing food from warmer countries, thereby saving on food transportation.

Previous studies concluded that the global food system, based on import and export, is in fact more energy efficient and emits less GHG than attempting to locally grow crops in colder climates. The energy that is used for transporting food is lower (or not higher) than the energy required for growing food locally in cold climates, where greenhouses need to be heated in winter (Cleveland et al., 2011; Cleveland et al., 2015; Majewski et al., 2020; Casey et al., 2022).

However, in addition to energy, there can be other aspects in which a local food system, where the consumers are geographically closer to the farmers growing their food, is more sustainable than a global system based on import and export of food. Sustainability includes environmental, economic, and social aspects that do not always align: the local may be more sustainable in one sustainability aspect, and the global – more sustainable in another aspect.

An in-depth literature review of sustainability aspects of local and global food systems was conducted to identify parameters by which sustainability of local and global food systems can be measured against each other.

Literature collection and selection

A systematic search of literature was carried out to produce a shortlist of studies. Strict exclusion criteria were applied to these studies to eliminate irrelevant material.

The following key words were used to retrieve relevant studies:

1. local food system
2. global versus local food systems
3. local production versus imported fresh products
4. domestic food system
5. sustainable food systems
6. food environmental impact
7. sustainable Food Supply Chain
8. food LCA
9. food miles
10. food footprint
11. food waste
12. agriculture multiplier effect

The search was conducted using DaTA search engine (Tel Aviv University libraries search system).

The papers were filtered according to the following criteria:

1. Peer reviewed papers, published since 2018 in English.

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2. As the initial search found millions of results, the search was narrowed down by choosing, for each search item, the 50 papers, that were defined by the search engine as the most relevant.
3. Duplicate papers were removed.
4. Papers that focus on vegetables and fruit only. As REGACE focuses on greenhouses, the reseach was narrowed to relate to produce of greenhouses, i.e fruit and vegetables. It was assumed that different crops may have different food system charachteristicrs. Papers that focus on other foodstuffs or agricultural products were filtered out: livestock and livestock' products, fisheries and marine agriculture, field crops, processed food, non-food agricultural crops (such as cotton, ornamental plants or energy crops), wild food (food that doesn't originate in farming). Papers that do not specify a food product – were included.
5. Papers that address Climate zones C (temperate) and D (continental)[22] only, as these are the the climatic zones of the countries participating in REGECE. It was assumed that different food systems of other climatic zones would have different charachteristicrs.
6. Papers that address the food system as an integrative system of supply and demand. Papers relating to either the agricultural production only, or the distribution system only were excluded, as the search is aimed to study the food system hollistically (both production and marketing of food). Papers that deal with agri-technical aspects (such as: soil characterizations, pest control) or technical aspects of the marketing system (such as programming supply chains operations) were excluded.
7. Papers related to local food systems and global food systems. Papers that do not relate to the geographical dimension of the production and distribution system were excluded.
8. Papers that describe empirical research or meta-analysis of papers that describe empirical research. Papers that are not based on empirical research were excluded.

The following Figure details the process of paper collection and selection using the exclusion criteria. At the end, 92 papers were identified as relevant for the in-depth analysis.

[22] According to Koppen-Geiger climate classification.

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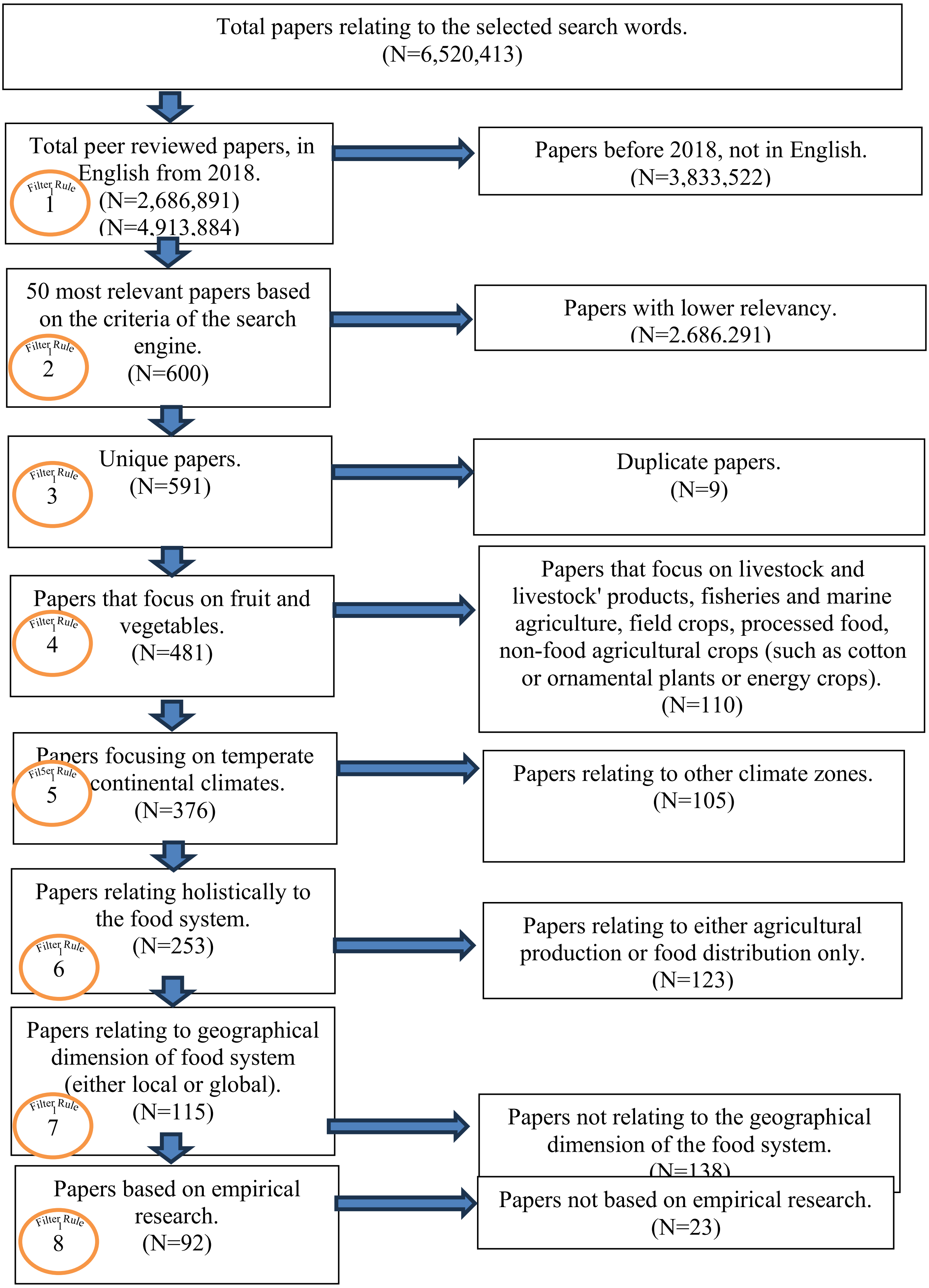

Figure 87 : Publications' collection and selection. N- the number of publications.

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Literature analysis

Two questions are addressed in the analysis:

1. What are the parameters of comparison of the sustainability of local versus global food systems?
2. Are local food systems more sustainable than global food systems? In what parameters are local food system more sustainable than global food systems?

Sustainability usually has three dimensions (or pillars): environmental, economic, and social. To tackle the 1st question, each pillar of sustainability was elaborated to include several sub-parameters of its manifestation within food systems.

The elaboration of sub-parameters, relied on the results of the European-wide project, GALMUR (Global and Local food chain Assessment: a Multidimensional performance-based approach). The GLAMUR research programme (2013-2016) investigated how the sustainability performance of food chains varied along the global-local continuum and aimed to answer the question: is local more sustainable than global, when it comes to food systems (GLAMUR, 2016; Brunori et al, 2016). GALMUR identified 24 attributes of food system sustainability. These attributes were crossed referenced with the main themes of the 92 papers in our database, to produce a list of 15 attributes for analysis. The following table presents the attributes.

Table 39: Attributes for analysis

No.	Pillar of sustainability	Attribute	Referred attribute of GALMUR project	Comments
11	Environment	Resource use	Resource use	
12	Environment	Climate change, energy and GHG emission	Pollution	Within the framework of GALMUR pollution includes GH gas
13	Environment	Food waste	Food waste	
14	Environment	Biodiversity	Biodiversity	
15	Environment	Technological innovation	Technological innovation	
21	Economic	Farmers' income, Profitability, Fair Trade	Creation and distribution of added value	Within the framework of GALMUR- fair trade is classified under "ethical"
22	Economic	Local economy, employment, multiplier effect	Economic development	
23	Economic	Food prices	Affordability	
24	Economic	Marketing (Consumer behavior)	Consumer behavior	Within the framework of GALMUR- classified under "social"

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25	Economic	Supply / value chain	Resilience	Supply chains are usually examined in reference to resilience
26	Economic	Efficiency	Efficiency	
31	Social	Food security, nutrition, health, food safety	Food security	
			Nutrition	
			Food safety	Within the framework of GALMUR-Classified under "health"
32	Social	Community (low-income households, immigrates, social inclusion, urban agriculture, community identity, civic agriculture)	Connection	
35	Social	Responsibility, Traceability, Governance	Responsibility	Within the framework of GALMUR-classified under "ethical" and "health"
			Traceability	
			Governance	
36	Social	Information and communication	Information and communication	

Each of the publications in the dataset was read by two reviewers and categorized into one of the 15 attributes that reflect the main theme of the article. In some of the articles, a second attribute and a third attribute were also identified, reflecting less central themes that the publications relate to.

After the classification of the articles' themes, an analysis was conducted in order to identify the main attributes in the discourse on the local or global food system.

The third stage of the analysis included, for each of the articles, an identification of the conclusion it reached on the question of the local versus global food systems. The articles were analyzed and categorized according to the factors in the following table.

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Table 40: factors for classification of the publications' findings, regarding local versus global food system

Global food system is better than local
Local food system is better than global
The local food system is considered better as an agenda and not as a research question
The question of what is better, local or global food system, is not examined
There is no conclusive finding on what is better, local or global

In the fourth stage, the five main themes in the discussion about the local versus the global food system were examined to identify, for these themes, which is better – the local or the global?

The main themes in the discourse over local versus global food systems

The main sustainability aspect in light of which local and global food systems are examined is economic: 50% of the publications in the database tackle economic themes such as the resilience of supply chains, consumer preferences, the development of the local economy, and fair trade. The second sustainability aspect is social: 30% of the publications in the database deal with social themes, such as food security, nutrition, health, community, governance etc. The issue of local and global food systems has been examined less from an environmental perspective: only 20% of the publications in the dataset deal with environmental impacts of the food system, such as energy and climate change, waste or biodiversity.

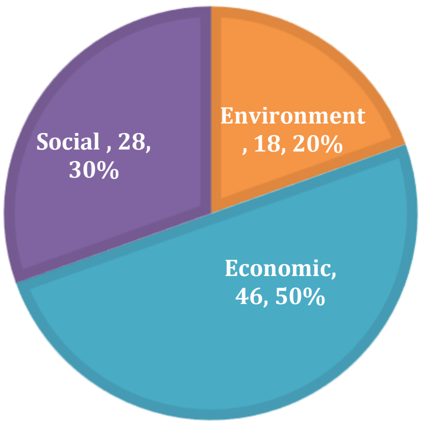

Figure 88: The main sustainability aspect in light of which local and global food systems are examined. Source: literature survey. Number of publications and % of all publications. N=92.

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Figure **89**: detailed attributes of sustainability in light of which local and global food systems are examined. Source: literature survey. Number of publications. N=92.

In the economic pillar, the attribute "supply / value chain resilience" is the most studied, with 12 publications (13% of the publications in the database). The second most addressed attribute is also economic: "marketing, consumer behavior" with 11 publications (12% of the publications in the database).

In the social pillar, the attribute "responsibility, traceability, governance" is the most studied, with 11 publications (12% of the publications in the database). The second most addressed attribute in the social pillar is "food security, nutrition, health, food safety" with 9 publications (10% of the publications in the database).

In the environmental pillar, the attribute "climate change, energy and GHG emission" is the most studied, with 9 publications (10% of the publications in the database). This is the only attribute in which energy plays a role in evaluating local against global food systems. As can be seen, energy is not the most important attribute in the discourse regarding local and global food systems. It ranks 5th out of 15 attributes in our database, in terms of the number of publications relating to it.

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What is more sustainable – a local or a global food system?

The question in the heading cannot be given a simple "yes or no" answer, as the local can be more sustainable than the global for some attributes and less sustainable in other attributes (GALMUR, 2016; Brunori et al., 2016).

The following presents the analysis of the 5 most central attributes in the discourse over local or global food systems, as identified in the literature study (see previous paragraph).

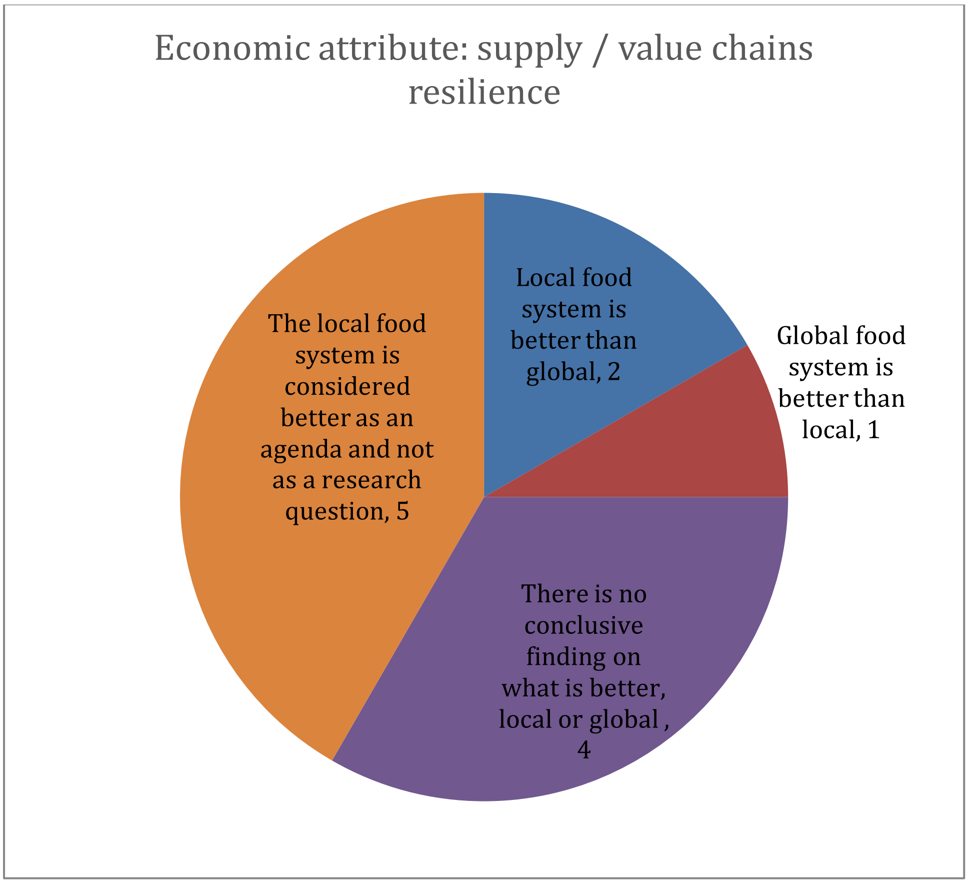

Figure 90: the economic attribute "supply chains resilience" – what is better: local or global food systems? N=12

From the perspective of the economic attribute "supply/ value chain resilience" there seems to be no conclusive evidence as to what is preferable: local or global food systems. Most of the publications dealing with this attribute (5 publications) take the position of preferring local food systems as an agenda and not as a research question. 4 publications did not reach a conclusive conclusion. Only 2 find local food systems to be better, and one finds global food systems to be better in strengthening the resilience of food supply chains.

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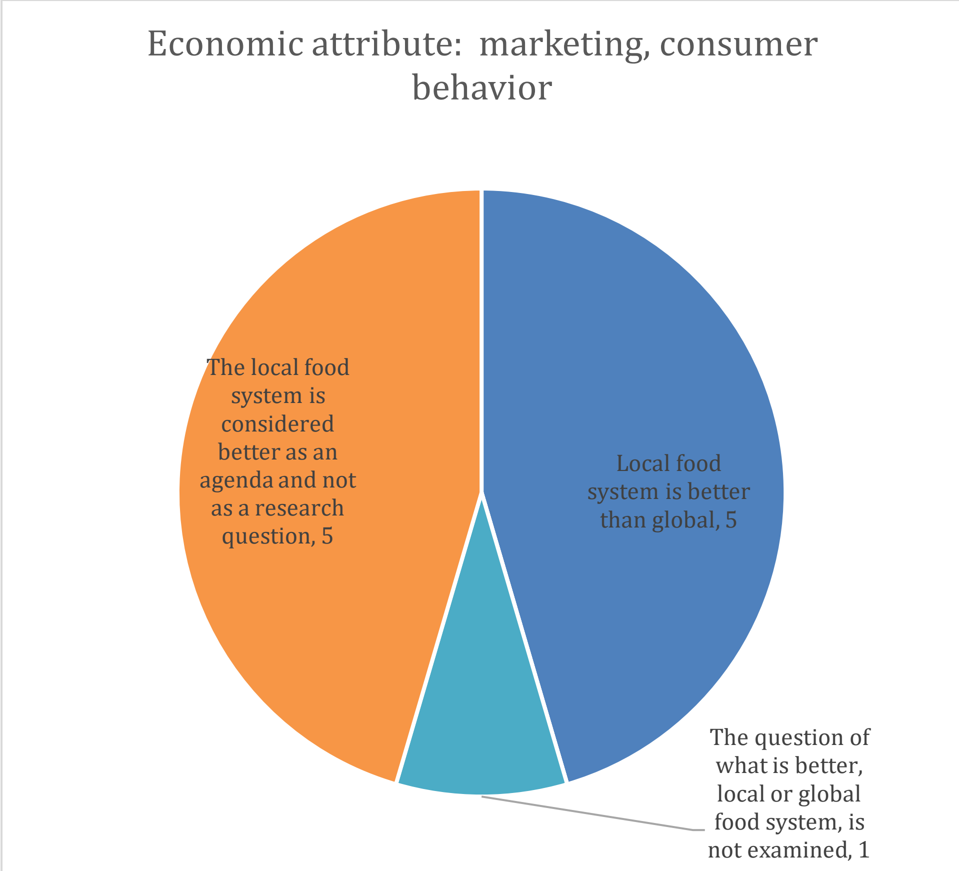

Figure 91: the economic attribute "marketing, consumer behavior" – what is better: local or global food systems? N=11

From the perspective of the economic attribute "marketing, consumer behavior" consumers prefer local food to food derived from the global food system (imported food). Some publications show that consumers are willing to pay more for local food. However, many publications dealing with this attribute assume that the local food system is better as an agenda and not a research question (5 publications) or don't deal with the question at all.

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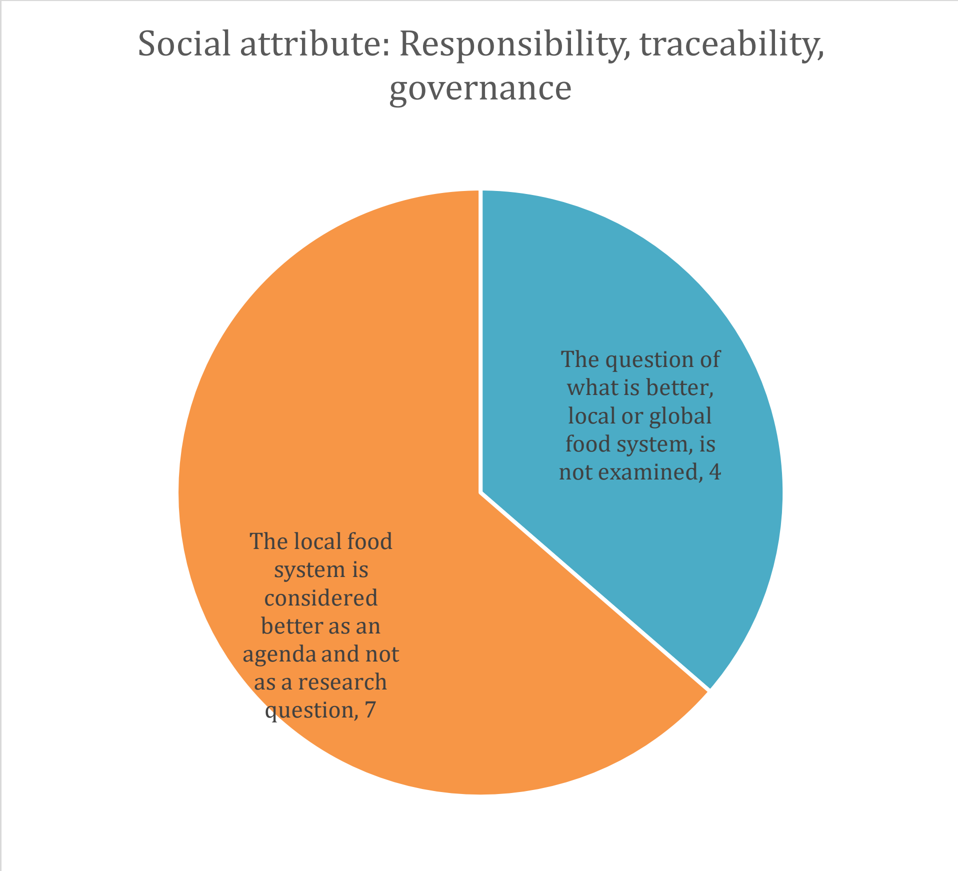

Figure 92: the social attribute "Responsibility, traceability, governance" – what is better: local or global food systems? N=11

From the perspective of the social attribute "Responsibility, traceability, governance" – there is no answer in the literature as to whether local or global food system perform better. Most of the publications consider the local food system to be better as an agenda, and in other publications – the question is not examined.

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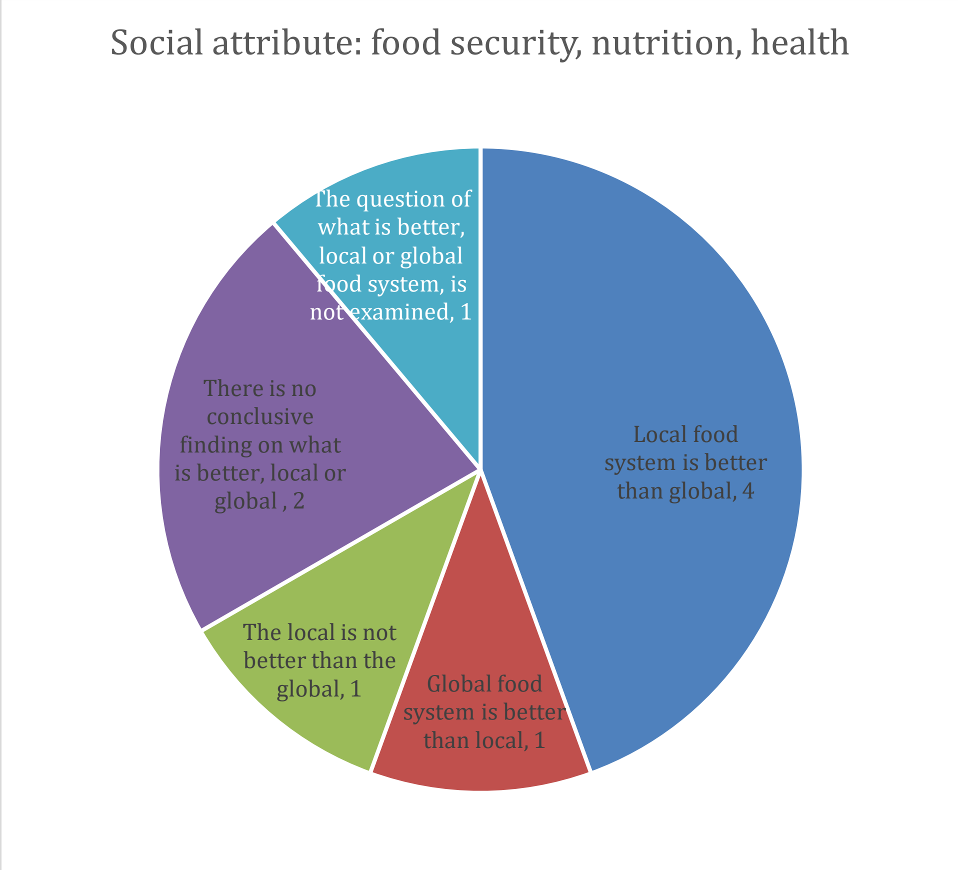

Figure 93: the social attribute "food security, nutrition, health" – what is better: local or global food systems? N=**9**

From the perspective of the social attribute "food security, nutrition, health" –it has been found by 44% of the publications (4 out of 9) that a local food system contributes more to food security and healthy diets than the global food system.

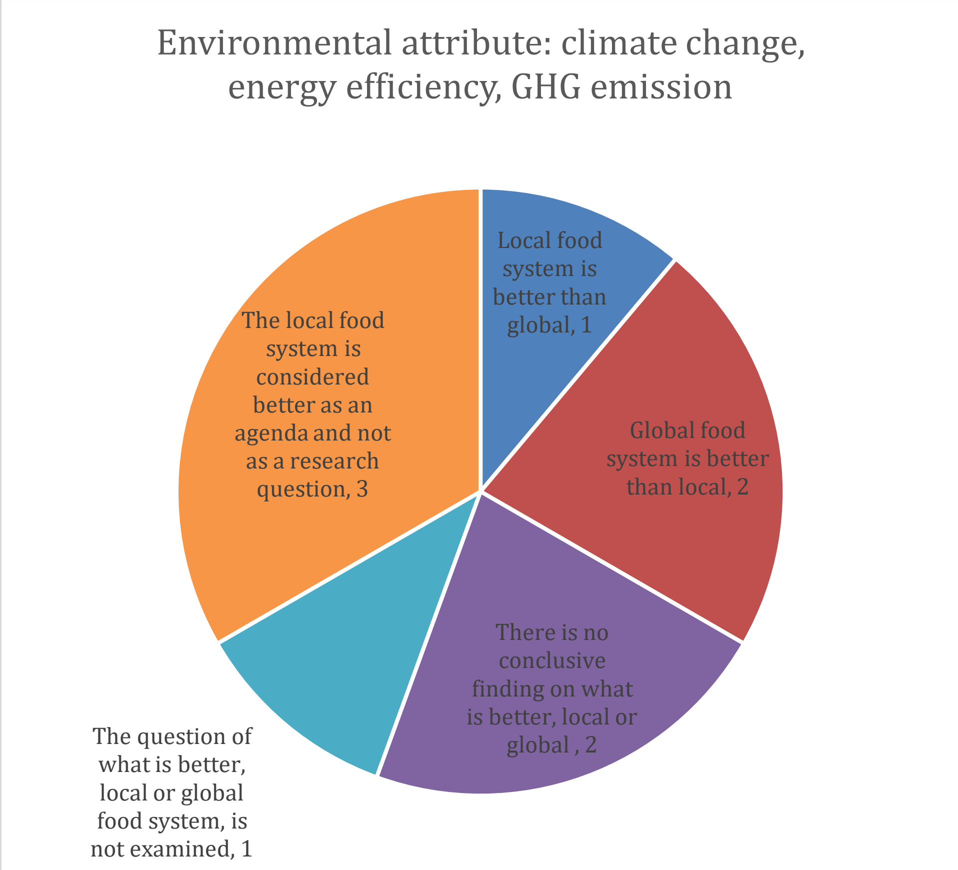

Figure 94: the environmental attribute "Climate change, energy efficiency and GHG emission" – what is better: local or global food systems? N=9

From the perspective of the environmental attribute "Climate change, energy efficiency and GHG emission" there seems to be no conclusive evidence as to what is preferable: local or global food systems. some of the publications dealing with this attribute (3 publications out of 9) take the position of preferring local food systems as an agenda and not as a research question. 2 publications did not reach a conclusive conclusion. 2 publications find global food systems to be more energy efficient and have less impact on climate change, and one finds local food systems to be better in climate protection.

In conclusion, it seems that there is no definitive answer to whether a local food system is more sustainable than a global one. It seems that reducing energy use, emissions, and increasing climate protection can sometimes be fulfilled better by the global food system than by a local food system. On the other hand, consumers prefer locally produced food to imported food, and food security can be reached better when local food production is strengthened.

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Annex 5: Trends in trade of greenhouse vegetables

The following table presents the local production, local consumption and % of imports in major greenhouse vegetables in the partner countries. The vegetables that were studied are the vegetables that were grown in the research greenhouses of REGACE. The data was retrieved from FAOSTAT and relates to 2023.
As can be seen, the partner countries can be divided into two groups:

- Countries that import about 15% or less of the local consumption of greenhouse vegetables: Israel, Greece and Italy.
- Countries that import about 75% or more of the local consumption of greenhouse vegetables: Germany and Austria.

The countries that have warmer climates – also import a smaller share of the vegetables that are consumed by their population.

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Table 12: Main greenhouse vegetables, local production (tons), local consumption (tons), % import of local consumption in the partner countries, 2023

	Israel			Greece			Italy		
Crop	local production	local consumption	% import of local consumption	local production	local consumption	% import of local consumption	local production	local consumption	% import of local consumption
bell pepper and chilies	117,760	88,348	8.4%	108,400	95,880	6.8%	227,510	296,402	27.5%
Cucumber	88,863	102,836	13.6%	115,710	50,882	1.9%	66,330	82,232	27.1%
Eggplant	43,447	44,084	1.4%	41,420	41,007	5.5%	317,980	345,794	9.7%
lettuce	13,428	13,763	2.4%	47,670	52,750	14.3%	660,270	669,569	18.7%
Zucchini, squash, pumpkin	6,354	12,817	51.3%	48,260	48,299	5.6%	560,630	575,443	7.8%
Tomato	324,684	355,590	8.7%	753,150	742,379	3.5%	6,016,050	6,077,491	2.3%
Average			14.3%			6.3%			15.5%

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	Austria			Germany		
Crop	local production	local consumption	% import of local consumption	local production	local consumption	% import of local consumption
bell pepper and chilies	13,480	43,677	161.3%	16,160	390,222	99.3%
Cucumber	43,430	63,500	52.7%	267,140	804,796	71.9%
Eggplant	1,240	5,129	178.7%		56,048	102.6%
lettuce	47,420	78,213	44.4%	211,680	410,426	58.8%
Zucchini, squash, pumpkin	27,900	43,658	53.0%	149,680	255,897	44.7%
Tomato	56,950	95,753	90.2%	101,060	744,611	88.7%
Average			96.7%			77.7%

Data source: FAOSTAT

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The following table presents the trends in trade of 3 main greenhouse vegetables in the partner countries.

Table 42: Trends in trade of 3 main greenhouse vegetables in the partner countries, 2023

Importing country	Crop	The main country from which it is imported	How much is imported from that country, tons
Austria	bell peppers	Turkey	43,087
Austria	cucumbers	Germany	11,819
Austria	tomatoes	Turkey	49,580
Germany	bell peppers	Spain	210,875
Germany	cucumbers	Spain	258,563
Germany	tomatoes	Netherlands	310,494
Israel	bell peppers	Jordan	5,094
Israel	cucumbers	Jordan	10,211
Israel	tomatoes	Turkey	27,778
Italy	bell peppers	Spain	53,438
Italy	cucumbers	Spain	9,832
Italy	tomatoes	Netherlands	64,801
Greece	bell peppers	Netherlands	2,063
Greece	cucumbers	Bulgaria	361
Greece	tomatoes	turkey	11,278

Source: FAOSTAT, retrieved 20 August 2025

The analysis of the potential impact of REGACE technology on the energy efficiency of the food system assumes that the existing food system is based on a one-way movement of vegetables grown in relatively warm countries and exported to colder countries. However, the food system is based on a more complex matrix of movement[23]:

- Vegetables are imported from warm climate countries to other warm climate countries. For example, Greece and Israel import tomatoes from Turkey; Italy imports bell peppers and cucumbers from Spain.
- In some cases, vegetables are imported from cold climate countries to other cold climate countries. For example, Austria imports cucumbers from Germany, and Germany imports tomatoes from the Netherlands.
- In some other cases, vegetables are exported from cold- climate countries into warmer climate countries. For example: Greece imports bell peppers from the Netherlands and Italy imports tomatoes from the Netherlands.

[23] The data in the next points was retrieved from FAO statistical data base, and relates to the main country from which the crop is imported, and the year 2023.

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In conclusion, it is difficult to say that REGACE's technology reduces the use of energy in transporting food from warm countries to colder countries. It can contribute to reducing the emissions of energy in greenhouses, in all the countries where they are used.

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