

Project Deliverable Report

DELIVERABLE D1.1

SYNERGIES

WORK PACKAGE NUMBER: WP1

WORK PACKAGE TITLE: POTENTIALS OF THE SYNERGIES OF INNOVATIVE AND INTELLIGENT AGRIVOLTAIC SYSTEMS

TYPE: REPORT

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REGACE Action Information	
Action full title	Responsive Greenhouse Agrivoltaics System with CO ₂ Enrichment for Higher Yields
Action acronym	REGACE
Grant agreement number	101096056
Project Officer	Dr. Irene Pinedo
Project coordinator	Prof. Ibrahim Yehia
Project start date and duration	1 February 2023, 36 months
Project website	https://regaceproject.com/



Document Information

Deliverable Information	
Work package number	1
Work package title	POTENTIALS OF THE SYNERGIES OF INNOVATIVE AND INTELLIGENT AGRIVOLTAIC SYSTEMS
Deliverable number	1.1
Deliverable title	SYNERGIES
Description	Estimation of the synergetic potentials of intelligent PV greenhouse and Energy audit report
Lead beneficiary	University of Thessaly
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Revision number	1
Revision Date	28/07/2023
Status (Final (F), Draft (D), Revised Draft (RV))	F
Dissemination level (Public (PU), Restricted to other program participants (PP), Restricted to group specified by consortium (RE), Confidential for consortium members only (CO))	PU

Document History			
Revision	Date	Modification	Author
0.1	28/05/2023	Draft version	BAXEVANOU
1	27/07/2023	Final version for submission	BAXEVANOU

Approvals



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Executive Summary

The present deliverable, named ‘D.1.1 Synergies’, includes estimation of the synergetic potentials of intelligent PV greenhouse and Energy audit report and summarizes the findings of Work Package 1. Work package 1, titled ‘Potentials of the synergies of innovative and intelligent agrivoltaic systems’ is consisted by two subtasks named: Task 1.1 Synergies creation (with 3 months duration from February to April of 2023) with leader the University of Thessaly (UTH) and participation of all the project partners and Task 1.2 Energy audits (with 6 months duration from February to July 2023) with leader again UTH and participants the Humboldt University of Berlin (HU), University of Natural Resources and Life Sciences, Vienna (BOKU), Alzahrawy Society (AZS), (Bio-Gärtnerei Watzkendorf GmbH) BW and (Fattoria Solidale del Circeo) FSC. The deliverable has been compiled by the UTH team.

The deliverable is structured in 7 chapters. The first chapter includes the introduction where the synergies to be examined are defined as well as their use in the project. In the second chapter the used methodology is presented. In the chapter two details about the greenhouses subject to energy audit are given by partners’ country. The chapter four is devoted to energy synergies as arise by energy audits and literature review. The energy flows are initially presented by country and then summarized and compared with literature review results. In chapter five the spatial synergies along with material synergies and rest of energy synergies are presented in terms of primary data collected during the project and literature review data. In chapter six the visualization of energy and material flows as well as spatial distribution maps are presented. Finally in the chapter seven the WP1 conclusions are summarized.



1 Introduction

The main objective of the work package 1 is to reveal, mainly at a qualitative level, all the synergies that occur during the operation of a greenhouse and which will be accounted for the design of the appropriate bifacial Si photovoltaic (PV) system mounted on a tracking system located under the greenhouse canopy within the intelligent greenhouse and in relation to the urban environment.

Strictly speaking as **'synergy'** defined the *'combine action or operation'* while as **'synergism'** is defined the *'interaction of discrete agencies, agents or conditions such that the local effect is greater than the sum of the individual effects.'*

In our case the question is to investigate the potentials from synergies between the greenhouse production area and the intelligent PV system in terms of energy, space, supply and social impact. For that reason, the following synergies will be examined first in existing greenhouses.

- Energy flows / energetic synergies (light, heat, CO₂ enrichment)
- Spatial synergies (existing greenhouses and indoor PV construction)
- Material flows (water, nutrients, substrates)

These multidiscipline synergies initially will be investigated individually and then will be combined in a holistic approach visualized in flow charts with the simultaneous presentation of energy, spatial and material flows reduced to the greenhouse product unit.

Special attention will be given in the definition of energy flows. As far energy concern a deeper analysis is required in order not only to define the total energy consumption, but also: a) the type of consumed energy, b) its use (eg the distribution of consumed energy in various procedures in a greenhouse), c) the primary energy consumption (which give information for the real environmental footprint of greenhouse in terms of energy), d) the time profile of energy consumption, e) the dependence of the above by (i) cultivation, (ii) greenhouse construction, (iii) greenhouse operating strategy and (iv) by external climatic conditions. For that reason, the energy synergies will be addressed among others with energy audits too.



The aim of this investigation is to qualitatively ascertain these synergy potentials with regard to material and energy flows and social impact of the designed agrovoltaic system (acceptance, food production and electricity supply security, stability of grid). For that reason, the work package 1 results will be exploited in many levels and in many WPs of the project. In particular the WP1 finding will be used in the design of PV units in WP 3.1 and 3.2 as well as in the modelling of the operation of greenhouses equipped with PV in WP4.1 and 4.2 while with the results of these WPs the effect of the new designed PV system on the synergies of conventional greenhouse could be quantified in WP5. Furthermore, the WP1 finding will feed in WP6 mainly in order to assess the social impact of the designed agrovoltaic system.

Broadly speaking the WP1 finding will allow the examination of the proposed agrovoltaic system potential to contribute to the energy transition and to climate neutrality to mitigate the greatest contemporary challenges facing European societies.



2 Methodology

According to the proposal the aim of WP1 is to qualitatively ascertain relevant synergy potentials with regard to material and energy flows and social impact of bifacial PV systems mounted on the roof of a greenhouse.

The way the project has chosen to do this is by recording and representation of all usable material and energy flows. Thus, the present deliverable goal is the investigation and the description of these flows. Specifically, is about the flows concerning

- Energy flows / energetic synergies (light, heat, CO₂ enrichment)
- Spatial synergies (existing greenhouses and indoor PV construction)
- Material flows (water, nutrients, substrates)

And the visual representation of the results in a flow chart

The work packages results will feed WP4 with data about the energy flows inside the greenhouses and the WP6 for the assessment, among others, of social impact of the proposed system.

2.1 Used Methods

For the determination of the above-described synergies three methods were used

- a) Data collection through desk work (statistics and literature review)
- b) Questionnaires completing
- c) Energy audits

Table 2.1. Used methodologies per examined synergy

Examined synergy	Data collection through desk work	Questionnaire completing	Energy audits
Energy flows – thermal energy		✓	✓



Energy flows – electrical energy		✓	✓
Energy flows – light		✓	✓
Energy flows – CO ₂ enrichment		✓	
Spatial synergies	✓	✓	
Material flows – water	✓	✓	
Material flows – nutrients	✓	✓	
Material flows – substrates		✓	
Material flows – wastes		✓	

The questionnaire about all the examined flows, except spatial synergies, was incorporated in the template used for energy audits. For the spatial synergies an additional questionnaire was created and presented following.

2.2 Spatial synergies questionnaire

The spatial synergies questionnaire addresses to project partners that are involved in the present WP.

The research on spatial synergies has been done in two levels

- Specific greenhouses which are known directly by partners (either because they own and operated them, or because they worked with them or read about them)
- Statistics of their country or the European Union or other database and/or literature data

Thus, the questionnaire is composed by two parts. The part A concern specific greenhouses, which are known to the partners, that uses PV systems on their roofs while the second part concerns aggregated data for PVs on roofs collected by statistics if available.

Part A is consisted by one table where asked data about the greenhouse that already has PVs in the roof. The data concerns: greenhouse location, basic geometry characteristics, type of greenhouse use and cultivation, level of greenhouse automation and used



technology, and characteristics concerning PV (PV type, installed capacity, position of installation etc).

Part B is consisted by three tables. In the first the source of presented information is determined. The second Table includes information about the existing capacity of greenhouse in the referred country. The third Table is divided in 13 sub tables and include statistical and/or aggregated information about the characteristics of the greenhouses that host PV in their structures and the characteristics of these PVs.

2.3 Energy audits

2.3.1 What is the energy audit

The concept of energy audit has been initially developed in USA and adopted in many applications in Europe almost 20 years ago. For the energy audits conduction (for industry and buildings) was developed methodologies according to relative European Union Directives (from 93/76/EC to 2018/844/EU) [1, 2, 3, 4, 5]. Especially for the energy audits of conventional buildings this methodology was specified according to 2002/91/EC [9] directive supported by a number of European and International Norms. The case of industry energy audits has been addressed through European research and development projects like FP7 or Intelligent Energy and more recently Horizon2020, without to lead yet in specific Directive other that the 93/76/EC [1].

Energy audit is a systematic process that aims to: a) form a comprehensive view on the energy consumption profile of a building or system by identifying the factors that affect it, b) consider energy saving options taking into account the total cost of the product, c) provide a comprehensive proposal to the unit manager regarding the energy saving measures he can implement [6].

2.3.2 Energy audit procedure

An energy audit is consisted of two discrete phases. The first phase is an operational rating approach which means that the energy consumption is calculated directly using the data of energy bills and of the production data. From the first phase auditor acquire a general perspective about the greenhouse energy performance but an analysis is required in order to be able to: a) distribute the consumed energy among the different procedures



inside a greenhouse, b) allocate the most energy consuming activities, c) assess the efficiency of various procedures and finally d) suggest energy performance improvement measures. This analysis is realized in the second phase which is an asset rating approach [6].

In the present project WP1 focuses in the first phase of the energy audit and extend in part of the second phase eg until distribution of the consumed energy among different procedures inside the greenhouse, which is the objective of the WP1.

In the first step (site visit) auditor: (i) records the installed equipment which consumes energy, (ii) record the construction characteristics, (iii) records the basic characteristics of the surrounding area, (iv) interview the unit manage [6].

In the second step auditor should collect data that cannot be recorded by greenhouse inspection. Most of them are collected and delivered by the owner/manager after the interview or during it. These data include: (i) Construction plans of the chambers and plans of the area, (ii) Manuals and technical characteristics specifications of the equipment, (iii) Existing energy consumption measurements, (iv) Energy consumption invoices (v) Production data in annual base for the last three years, (vi) Local climatic data. Energy consumption invoices can have covered the financial data [6].

The data analysis phase is constituted by following steps: (a) elaboration of the collected data, (b) Calculation of energy indices, (c) identifying energy-intensive processes and low performing equipment. The last procedure will be analyzed with examples in section 2.3.5.

2.3.3 Site visit and data collection methodology

According to the proposal each partner should carry energy audits in the greenhouses that will be used in the project for experimentation. Nevertheless, it was suggested to extend the number of delivered energy audits in order to include commercial greenhouses from where valuable information about greenhouse synergies can be drawn. Two methods were used for the presentation of the collected data by each partner: a) free text, b) complete a template for energy audit. In the following table 2.2 the used method by country is presented.

Table 2.2. Used methodologies per examined synergy

Partner	Free text	Template
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Austria	✓	
Germany		✓
Greece		✓
Israel	✓	
Italy	✓	

2.3.4 Energy audit template presentation

In order to maintain uniformity in the collected data presentation and ease its elaboration a template for the energy audit recording was developed. In the template was incorporated fields regarding the rest examined synergies.

The energy audit template is consisted by 11 sections in order to gather information not only for the energy audit but for the other examined synergies too.

In the 1st section (Table 1) general information about the audited greenhouse are asked including greenhouse type, crop, basic geometry, location and communication details.

In the 2nd section (Table 2) operating data of the unit are included for: a) be able to calculate the theoretical energy demand (in WP1 and in details in WP4) and b) gather data for the synergies related to heat demand and light

In the 3rd section a free text with a greenhouse short description is required.

In the 4th section (Tables 4.1, 4.2 and 4.3) production, water, fertilization and substrate data are filled along with general information of produced waste biomass for the assessment of synergies related with material flows

Sections 1 to 4 contain preparatory information and the main body of energy audit is contained in the sections 5 to 11.

In the 5th section information is requested for the construction of the greenhouse (geometry, plans, construction materials of the structural elements and their thermophysical and optical properties – Tables 5.1 to 5.3). This information will be used for the calculation of theoretical energy demand (in WP1 and in details in WP4).

In the 6th section the installed electromechanical equipment is recorded. This information will be used for the energy audit (distribution of power and energy). As well as



information about synergies related to CO₂ enrichment may be included there. The installed equipment is categorized to 9 basic energy consuming procedures namely: Heating (9 sub tables), Cooling (8 sub tables), ventilation (3 sub tables), irrigation (2 sub tables), lighting (2 sub tables), refrigeration (2 sub tables), transport system and production sorting (3 sub tables), fertigation (2 sub tables), and a general subsection with other type of equipment like compressor, generator pair etc in 3 sub tables.

In the 7th section the existence of systems for local energy production is assessed for both the purposes of energy audit and the energy related synergies (6 sub tables).

The 8th section investigates the audited greenhouse automation level

In the 9th section the energy invoices are required (5 sub tables)

In the 10th section existing measurements concerning microclimate characteristics and energy consumption and/or local production are recorded

Finally in the 11th section local climate data are asked in order to be able to evaluate the real and theoretical energy consumption.

Thus, with the completing of this template the first part of the inspection is completed.

2.3.5 Data analysis phase

The data analysis is the most interesting part and requires combination of recording, gathered information (from the manager interview), calculations and literature data. The elaboration of collected data in order to calculate the total installed power, the total consumed energy, the distribution of installed power to different procedures, the calculation of power indices and the calculation of general energy consumption indices is straight forward. However, for the distribution of consumed energy it is required calculations and use of the energy consumption invoices time series in monthly base with the concept of base load. This procedure will be shortly described here with two examples of realized for the project energy audit.

After elaboration of three years data the basic yearly pattern is determined. This pattern along with analytical calculations about the theoretical energy consumption is used for the determination of operation hours of each individual device, with the assumption that each device operates at full load continually. As already said the electrical energy



consumption can be distinguished to the following procedures: (i) heating, (ii) cooling, (iii) ventilation, (iv) irrigation, (v) lighting, (vi) refrigeration, (vii) fertigation, (viii) transport system, (ix) other.

Usually from the manager interview we know information about the operation conditions of transport systems, refrigeration and other machines operation which however according to the literature are not the main power consumption points. Furthermore, with theoretical calculation of heating demand and the known power of heating production equipment the hours of operation of heating equipment can be calculated. Finally, the energy consumption for irrigation can be calculated theoretically by the water consumption [7] and from there the irrigation system operation time. It can also be considered that the operation time of fertigation system is the same with the operation time of irrigation system. Then the unknown operation hours concern the cooling system, the ventilation system and the lighting system. From the time series a base load (the lowest energy consumption usually achieved in autumn or spring months) can be determined that correspond to consumption independent of climatic conditions. The summer maximum corresponds to base load plus the cooling load and the winter maximum correspond to base load plus the lighting load. Thus, a system with three equations and three unknowns is produced that allow the operation time of equipment for cooling, ventilation and lighting. Of course, the above procedure each time is adapted to the characteristics of each examined greenhouse, the type of the crop and the information given by the manager. Before proceed to the presentation of two examples short information about the calculation of heating needs will be given. This calculation can be done in monthly base using the concept of representing day (according to ISO13790 [8]) with quite accuracy, while the calculation of cooling needs would require more hideous calculations in hourly base and are not considered adequate for the purposes of an energy audit.

In the Figure 2.1 the electrical consumption time series of a tomato cultivation greenhouse in Central Greece is presented constructed from four months' invoices. In the specific greenhouse energy is consumed for heating, cooling, ventilation and irrigation and fertigation. It should also account that the crop schedule is from January to September or October.



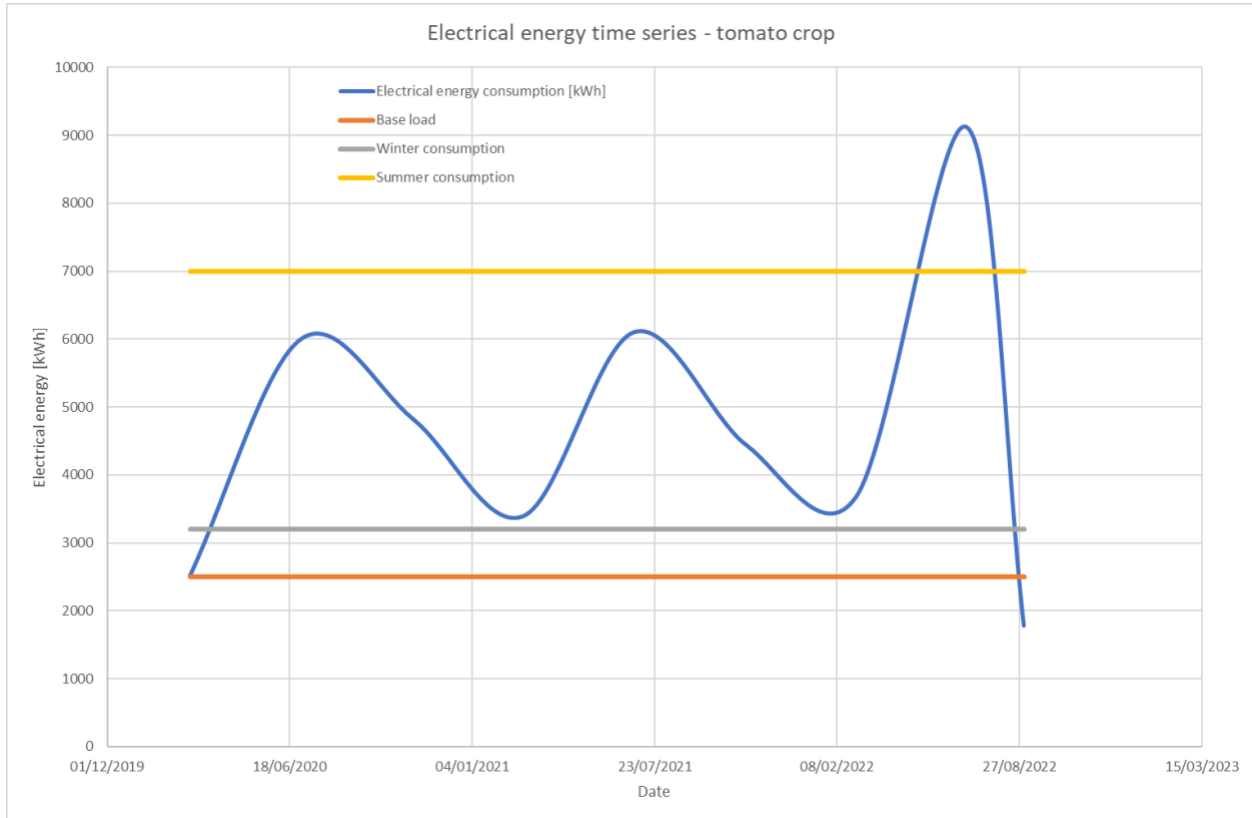


Figure 2.1. Electrical energy time series in a Tomato crop greenhouse in Greece

In this case the base load corresponds to fertigation and irrigation, the winter load corresponds to base load + heating and the summer load corresponds to base load + ventilation+ cooling.

A more complicated situation is presented in Figure 2.2 for a potted flowers greenhouse in the same location where the electrical energy invoices are available in monthly base. In this case the electrical energy is consumed for heating, ventilation, irrigation, fertigation, lighting, soil preparation and generator pair (the later tow referred as ‘other consumption’). The higher consumption appears during the winter and is attributed to lighting. So, the base load corresponds to May, September and October and concerns energy consumption for irrigation, fertigation and other consumption. The summer load (months June, July and August) in the base load the ventilation is added. In winter load corresponds the base load + heating + lighting. Finally, the months November, Mars and April and corresponds to the base load and half heating and lighting.



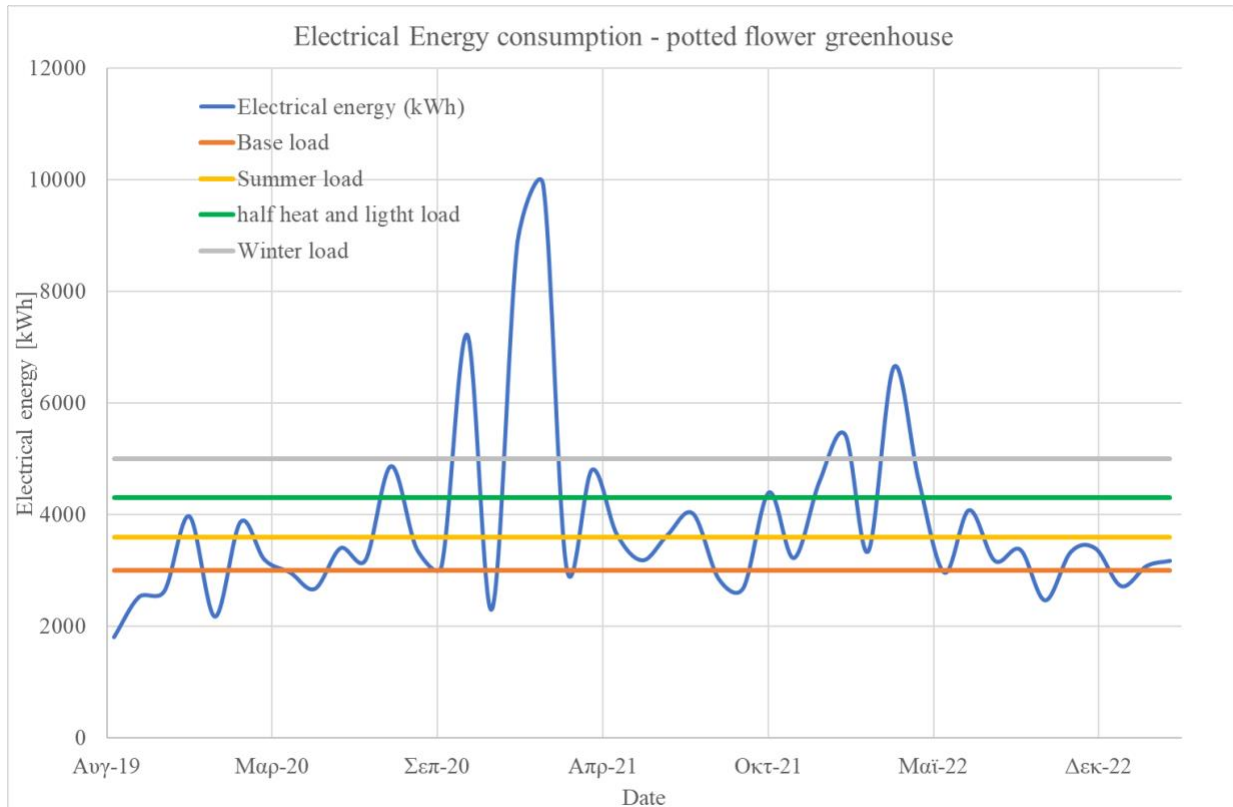


Figure 2.2 Electrical energy time series in a Potted flower crop greenhouse in Greece

2.4 Visual representation of the results

The results of energy and synergies' analysis will be visualized through creation of SANKEY diagrams where the energy and material flows reduced to greenhouse area will be presented for various types of greenhouses. In a chart the spatial distribution of existing greenhouses with PVs on their roof will be also presented.



3. Individual study cases

Energy audits were carried out in six (9) greenhouses, 4 in Greece, 3 in Israel, 1 in Austria and 1 in Germany. The basic characteristics of the audited greenhouses are presented in the Tables 3.1 to 3.9 and their position is noted in the chart of Figure 3.1. The three of them are experimental units which will be used in the project, the three are commercial units for which energy invoices are available and the other three are commercial units for which the energy invoices are not available. Three of the audited greenhouses have tomato crop, two of them potted flowers and one cucumber, the other three have bell peppers, peppers and cabbages.

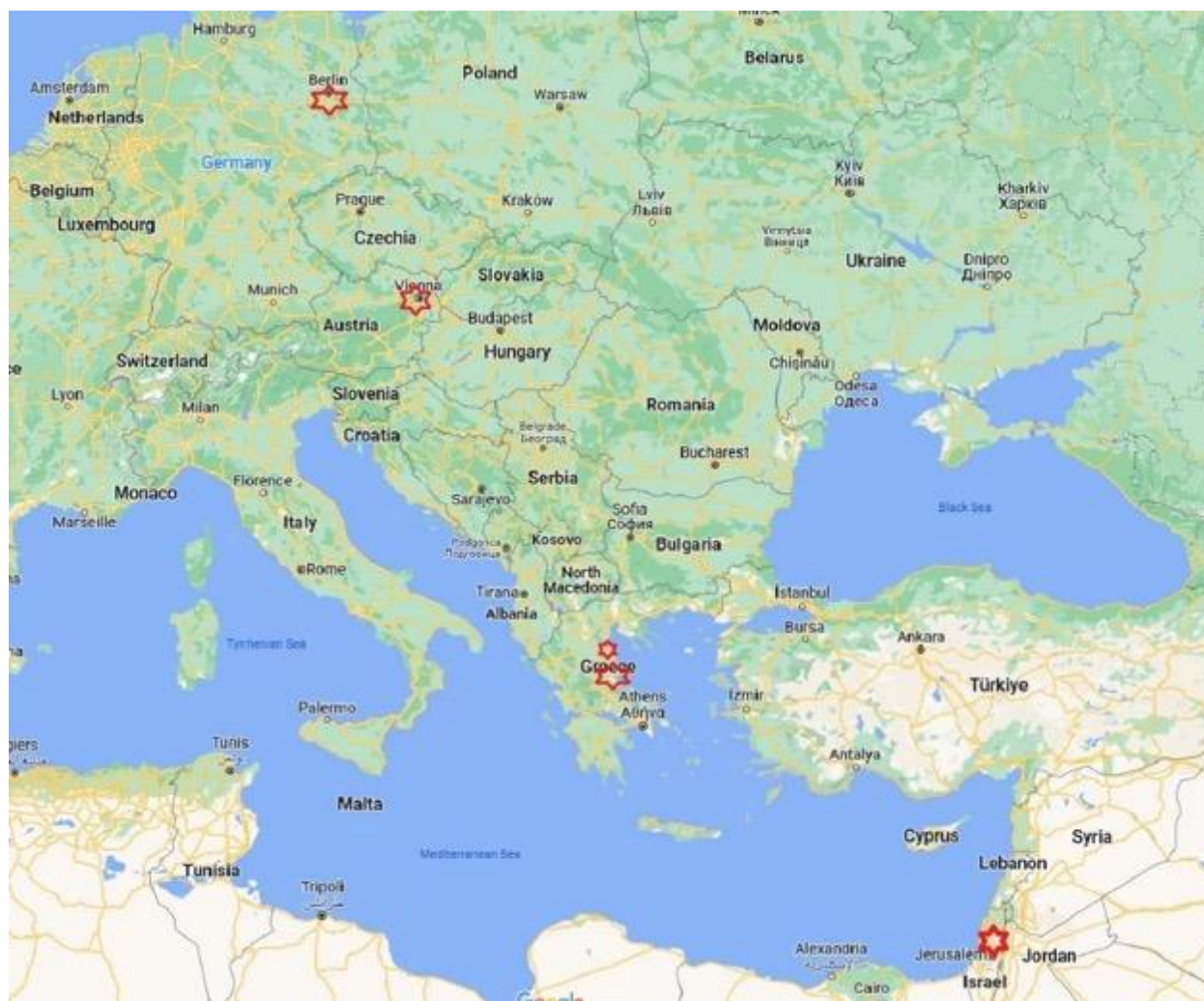


Figure 3.1 Energy audits spatial distribution

Table 3.1 Austrian Greenhouse general characteristics



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Greenhouse number	1 - Experimental Greenhouse (BOKU)
Greenhouse type	Temperate GH a) Pot cultivation b) Ebb-flow system (on tables)
Greenhouse crop	Basil, pepper, cucumber, tomato, strawberry
When was it constructed	2016/17
When was it renovated	no
Greenhouse location	48°14'12.6"N 16°20'08.1"E
Altitude of greenhouse location	238 [m]
Greenhouse ground area	79.38 [m ²]
Mean greenhouse heigh	3.925 [m]

Table 3.2. German greenhouse general characteristics

Greenhouse number	2 – Experimental greenhouse
Greenhouse type	hydroponic
Greenhouse crop	tomato, lettuce
When was it constructed	2010
When was it renovated	no
Greenhouse location	52°28'02''N, 13°17'56''E
Altitude of greenhouse location	44 m
Greenhouse ground area	307 m ²
Mean greenhouse heigh	6 m (side wall heigh)

Table 3.3 1st Greek greenhouse general characteristics

Greenhouse number	3 - Commercial
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Greenhouse type	Hydroponic, Gothic, multispan
Greenhouse crop	Cucumber
When was it constructed	2010
When was it renovated	2018, new (hanging) grow gutters
Greenhouse location	N 39° 54' 43'' E 22° 37' 21''
Altitude of greenhouse location	65 [m]
Greenhouse ground area	5040 [m ²]
Mean greenhouse height	Gutter 5 [m], top 7.35 [m]

Table 3.4 2nd Greek greenhouse general characteristics

Greenhouse number	4 – Commercial greenhouse
Greenhouse type	Arched, multispan
Greenhouse crop	Potted flowers
When was it constructed	2010
When was it renovated	2023, a new 1000 m ² compartment was added – not related with the audited part
Greenhouse location	N 39° 14' 14.56'' E 22° 43' 48.51''
Altitude of greenhouse location	70 [m]
Greenhouse ground area	8000 [m ²]
Mean greenhouse height	Gutter 4 [m], top (about) 6.2 [m]

Table 3.5 3rd Greek greenhouse general characteristics

Greenhouse number	5 – Commercial greenhouse
Greenhouse type	Arched roof, multispan greenhouse
Greenhouse crop	Tomato
When was it constructed	2011



When was it renovated	No
Greenhouse location	39° 15' 16.3'' N 22° 44' 19.18'' E
Altitude of greenhouse location	81 [m]
Greenhouse ground area	5000 [m ²]
Mean greenhouse height	3.5 m gutter, 6.1 m ridge

Table 3.6 4th Greek greenhouse general characteristics

Greenhouse number	6 – Experimental greenhouse
Greenhouse type	Gothic, multispans
Greenhouse crop	tomato
When was it constructed	2018
When was it renovated	No
Greenhouse location	39° 23' 41.14'' N 22° 45' 29.16'' E
Altitude of greenhouse location	85 [m]
Greenhouse ground area	800 [m ²]
Mean greenhouse height	Gutter 5 [m], top 7.35 [m]

Table 3.7 1st Israel greenhouse general characteristics

Greenhouse number	1
Greenhouse type	Soil
Greenhouse crop	Bell Peppers
When was it constructed	2020
When was it renovated	
Greenhouse location	Jatt
Altitude of greenhouse location	Jatt 32°23'58''N 35°02'12''E



Greenhouse ground area	10 donoms (1 hectare)
Mean greenhouse heigh	3.5 meters

Table 3.8 2nd Israel greenhouse general characteristics

Greenhouse number	2
Greenhouse type	Soil
Greenhouse crop	Peppers
When was it constructed	
When was it renovated	
Greenhouse location	Sde Yizhak
Altitude of greenhouse location	Sde Yizhak 32°24'14"N 34°59'40"E
Greenhouse ground area	50 donoms (5 hectare)
Mean greenhouse heigh	3.5 m

Table 3.9. 3rd Israel greenhouse general characteristics

Greenhouse number	3
Greenhouse type	Soil
Greenhouse crop	Cabbage
When was it constructed	The first one is in 1970 The last one is in 2016
When was it renovated	
Greenhouse location	Jatt
Altitude of greenhouse location	Jatt 32°23'58"N 35°02'12"E
Greenhouse ground area	195 donoms (10.5 hectare) of different greenhouses
Mean greenhouse heigh	3/ 3.5/4 m



4. Energy synergies

4.1 Austria

The energy synergies for Austria arises from energy audit in the experimental greenhouse used by University of Natural Resources and Life Sciences, Vienna and will be presented descriptively. The description concerns three chambers of the experimental facilities where Basil, pepper, cucumber, tomato, strawberry is cultivated as Pot and Ebb-flow systems. The transparent walls and the pitched roof are made of polycarbonate Thermoclear 2UV 16mm and it is ventilated by roof and side vents.

The audited chambers are heated by district heating system. A good half of Vienna's district heating comes from the combined heat and power plants, which are operated with natural gas. Combined heat and power plants are also used to cover peaks. The rest comes from industrial waste heat, waste incineration, biomass and geothermal and ambient heat. By 2040, district heating in Vienna is to be climate-neutral and completely free of natural gas. The district heating, the hot water, is distributed in Vienna via the interconnected network of Wiener Netze at high pressure and high temperatures. The heating starts working (in winter) when the temperature drops below a certain value. The temperature of the greenhouse in one point.



Figure 4.1. Location of audited experimental greenhouse



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The heat is distributed inside the greenhouse through hot water circulating inside pipes $\Phi 30$ in the roof and/or underfloor. This high pipe and underfloor system are also the heat emission system. There is no cooling system, when the temperature exceeds the predefined value the ventilation vents open, so there is no energy consumption for ventilation. Nevertheless, a house made misting system can be used for cooling. The other point of energy consumption concerns lighting with a 6.4 kW installed power. Fertigation and irrigation are carried by hand.

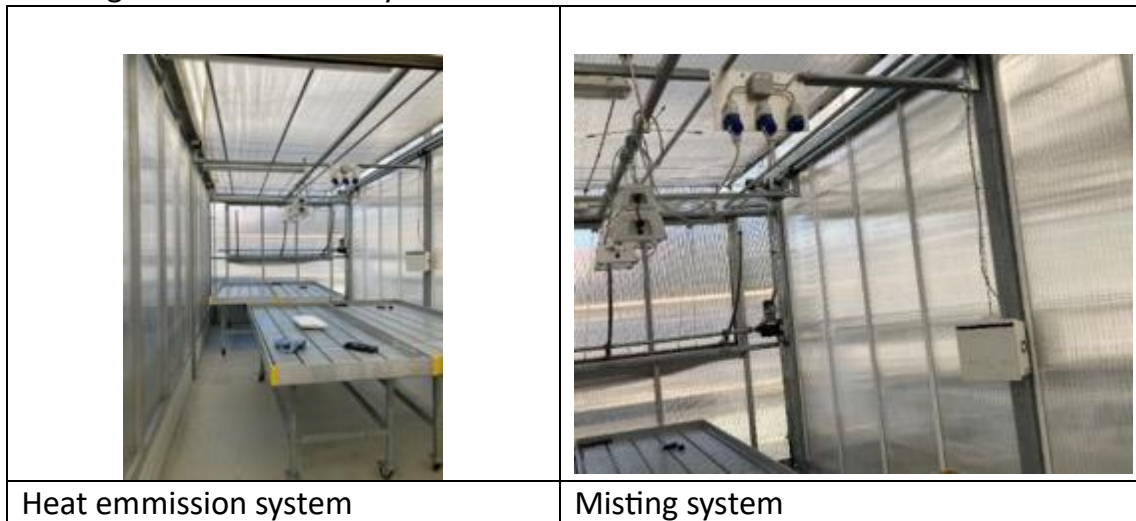


Figure 4.2. Heat emission system and cooling system

4.2 Germany

The energy synergies for Germany also arise from one energy audit carried out in the experimental greenhouse facility that will be used for the project by Humboldt-Universität Berlin. It is a tomato, lettuce experimental greenhouse of 307 m². It is a pitched roof greenhouse with glass roof and side walls.

The ZINEG greenhouse acted as solar collector, where 16 finned tube heat exchangers (4 per roof bar) were installed under the roof region. These were used for cooling processes, whereby sensible heat caused by transmitted solar energy and latent heat produced by plant transpiration were collected simultaneously. The total length of one finned tube was 21.4 m, which was separated into 125 galvanised fins per meter of tube. These dimensions lead to a total cooling surface of 684 m² resulting in a ratio of 2.23 in consideration of the total cooling surface and the ground area of the greenhouse. As coolant solution it was used water containing 31% glycol (v/v), which was pumped into



the finned tubes with a minimum flow temperature of 7 °C. For this cooling process and for heating processes, a system consisting of a reversible heat pump with 40 kW electrical power, 120 kW heating power and 100 kW cooling power, as well as one warm water tank (1 m³) and one cold water tank (1 m³) was connected to this pipe system. In this context, a maximum cooling capacity of 390 W m⁻² can be achieved. The cooling process in the solar collector greenhouse was started at a temperature of 22 °C followed by the ventilating at 29 °C to avoid plant damage. For the ventilation there are roof openings.

The specific electricity consumption ranges from 9 to 14 kWh/kg of produced vegetables.

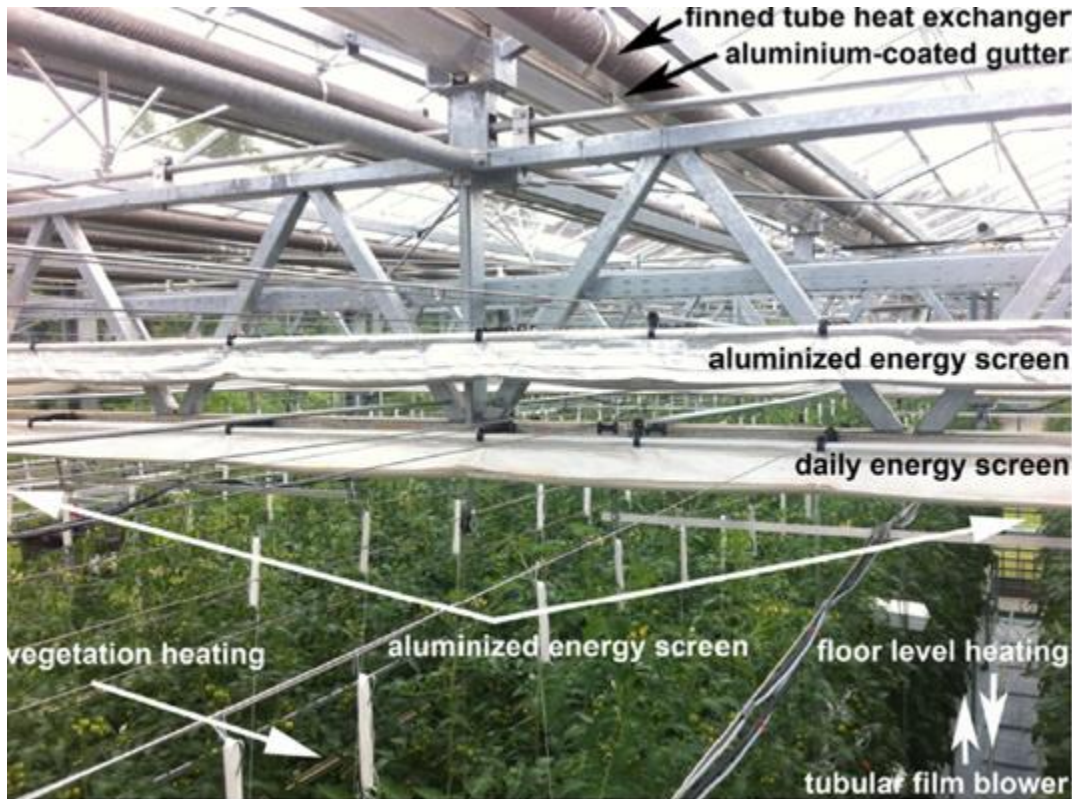


Figure 4.3. Heat and cooling system of ZINEG greenhouse

4.3 Greece

The energy synergies for Greece arise in total from energy audits and will be presented in terms of distribution pies of installed power and consumed energy as well as of installed power and consumed energy indices



As mentioned earlier four (4) energy audits were carried out in Greece in three (3) commercial and one (1) experimental greenhouse. The two greenhouses have tomato crops, one of the potted flowers and one of them cucumber.

4.3.1 Greenhouse installed power

In Figure 4.4 the installed power distribution is presented in terms of pies, for the four audited greenhouses

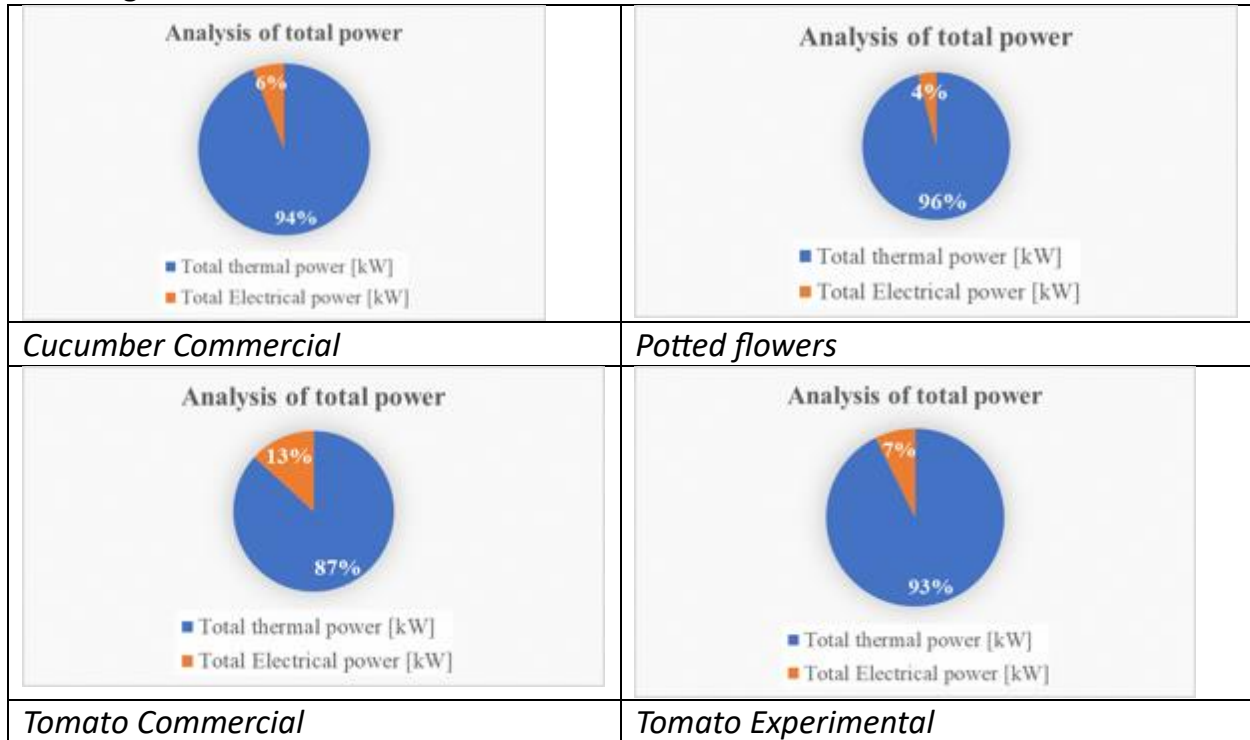


Figure 4.4. Total installed power distribution

All the audited greenhouse thermal energy represents most of the installed power.

In Figure 4.5 the thermal installed power distribution is presented and in Figure 4.6 the electrical installed power distribution is presented in terms of pies for the four audited greenhouse

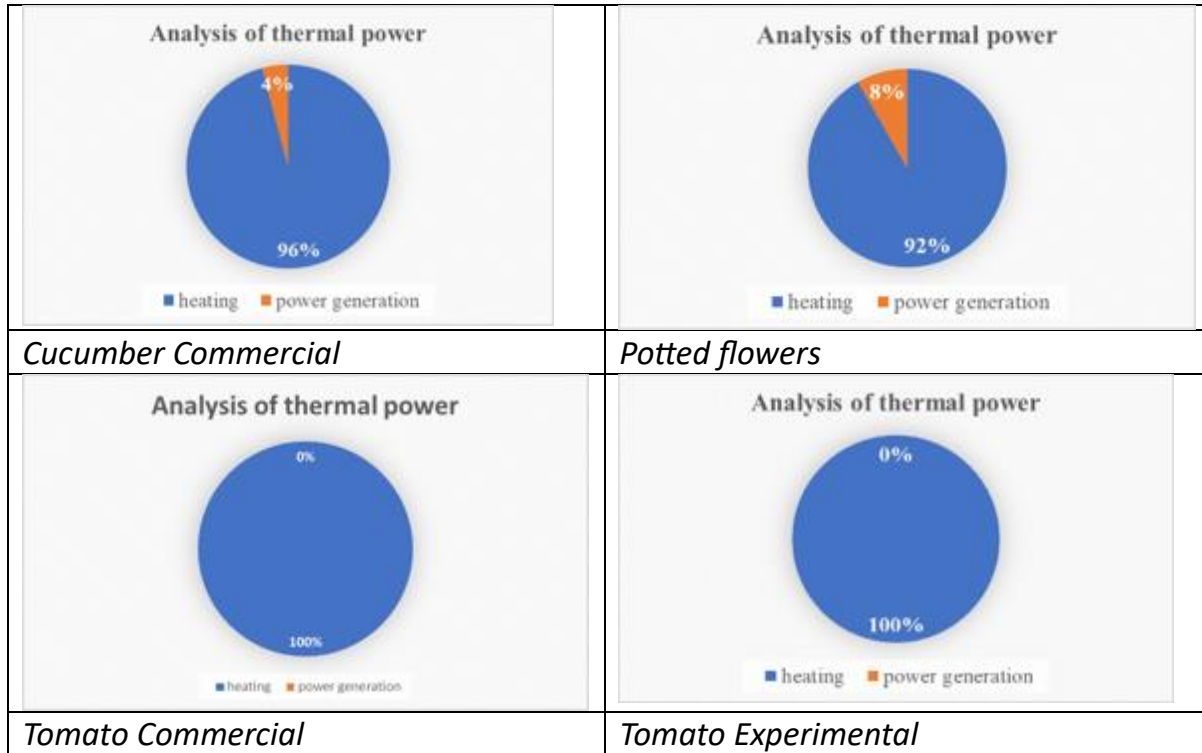
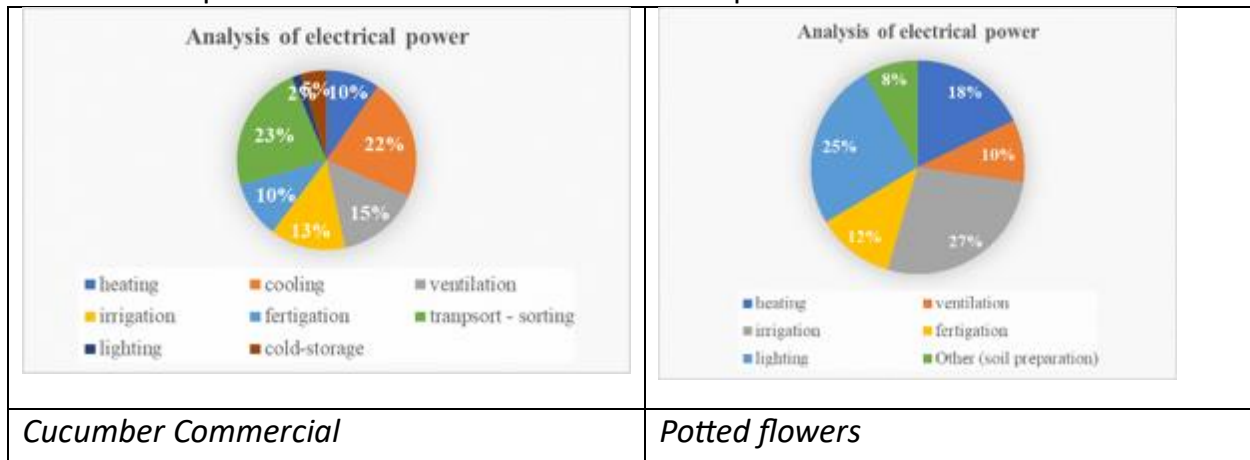


Figure 4.5. Thermal installed power distribution

And from the thermal installed power the biggest part concerns heating with a small contribution for power generation in a generator pair when it is considered that the cultivation is quite sensitive to risk loss of electrical power.



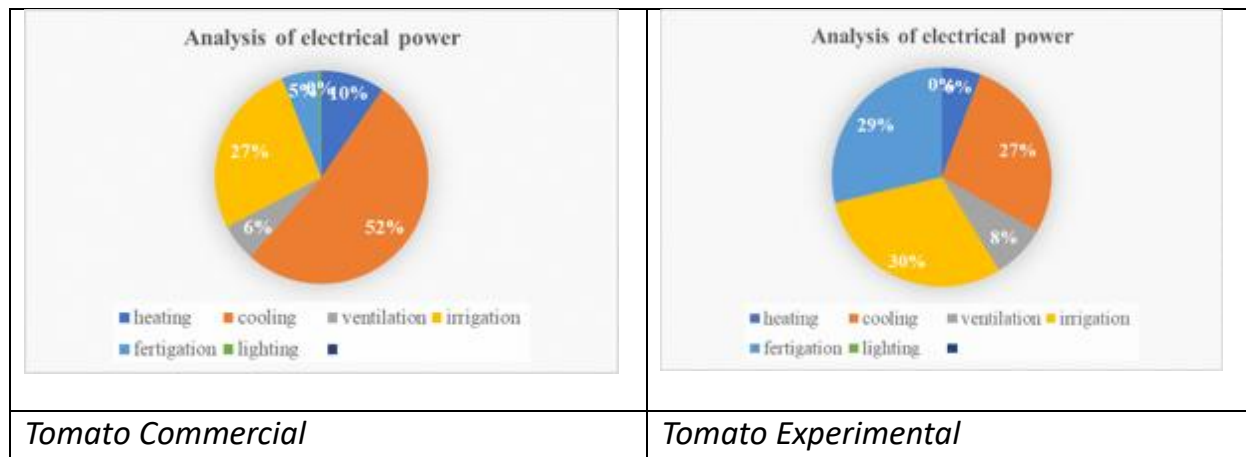


Figure 4.6. Electrical installed power distribution

In all the commercial greenhouses the fertigation represents the 10 – 12 % of the installed electrical power. The installed power for lighting is negligible except for the case of potted flowers greenhouse where it represents the 25% of the total installed electrical power. As far it concerns heating and cooling the vegetable production greenhouses have similar behavior while the potted flower greenhouse has no installed power for cooling but important installed power for heating. Installed power for ventilation ranges from 6 to 15%. While the installed power for irrigation is high enough in almost all the cases. It should be noted that usually this is due to drilling pumps which, however may serve other purposes too in the farm where the greenhouse is installed.

In the next Table 4.1 the installed power indices with respect to greenhouse area are presented. Specifically, the installed power is given in terms of kW per 100 m² area

Table 4.1. Installed power reduced to greenhouse area [kW/100m²]

Installed power	Cucumber	Potted flower	Tomato commercial	Tomato experimental
Total	35.80	21.44	4.46	28.38
Thermal	33.69	20.60	3.87	26.30
Electrical	2.10	0.84	0.59	2.08
Thermal Heating	32.31	18.90	3.87	26.30
Power generation	1.39	1.70	0.00	0.00
Electrical heating	0.20	0.15	0.04	0.12
Electrical cooling	0.46	0.00	0.23	0.57
Electrical ventilation	0.32	0.08	0.02	0.17
Electrical irrigation	0.29	0.23	0.11	0.62



Electrical fertigation	0.22	0.10	0.02	0.60
Electrical transport - sorting	0.49	0.00	0.00	0.00
Electrical lighting	0.04	0.21	0.00	0.00
Electrical cold-storage	0.10	0.07	0.00	0.00

This index is the only common for the four audited greenhouses. In terms of installed power per area the commercial and experimental greenhouses cannot be compared. The highest installed power is found in the cucumber greenhouse and it is attributed to the thermal power and to the power generation. However, the cucumber greenhouse is in North Greece (Macedonia) not close to the other three and their different requirements as far it concerns the internal microclimate conditions.

In the Tables 4.2, 4.3 and 4.4 the installed power indices with respect to the greenhouses' production are given. Table 4.2 present the installed power reduced to produced mass, Table 4.3 present the installed power reduced to produced pieces and in Table 4.4 the installed power is given in terms of produced volume (only for the potted flowers greenhouse).

Table 4.2. Installed power reduced to produced mass [kW/tn]

Installed power	Cucumber	Tomato commercial	Tomato experimental
Total	7.73	9.73	8.87
Thermal	7.28	8.44	8.22
Electrical	0.45	1.29	0.65
Thermal Heating	6.98	8.44	8.22
Power generation	0.30	0.00	0.00
Electrical heating	0.04	0.09	0.04
Electrical cooling	0.10	0.49	0.18
Electrical ventilation	0.07	0.05	0.05
Electrical irrigation	0.06	0.25	0.19
Electrical fertigation	0.05	0.05	0.19
Electrical transport - sorting	0.11	0.00	0.00
Electrical lighting	0.01	0.00	0.00
Electrical cold-storage	0.02	0.00	0.00



In terms of installed power per produced mass the three vegetable greenhouse are comparable and the average values can be considered representative of their needs.

Table 4.3. Installed power reduced to produced pieces [kW/1000pieces]

Installed power	Cucumber	Potted flower
Total	2.41	14.30
Thermal	2.26	13.73
Electrical	0.14	0.56
Thermal Heating	2.17	12.60
Power generation	0.09	1.13
Electrical heating	0.01	0.10
Electrical cooling	0.03	0.00
Electrical ventilation	0.02	0.05
Electrical irrigation	0.02	0.15
Electrical fertigation	0.01	0.07
Electrical transport - sorting	0.03	0.00
Electrical lighting	0.00	0.14
Electrical cold-storage	0.01	0.05

Cucumber and potted flower greenhouses cannot be compared since in the first case the piece is one cucumber while in the second case it is a flower in a flower pot of 2 – 3 l.

Table 4.4. Installed power reduced to produced volume [kW/m³]

Installed power	Potted flower
Total	8.64
Thermal	8.30
Electrical	0.34
Thermal Heating	7.61
Power generation	0.68
Electrical heating	0.06
Electrical cooling	0.00
Electrical ventilation	0.03
Electrical irrigation	0.09
Electrical fertigation	0.04
Electrical transport - sorting	0.00



Electrical lighting	0.09
Electrical cold-storage	0.03

4.3.2 Greenhouse consumed energy

In Figure 4.7 the total consumed energy is presented in terms of pies, for the three commercial audited greenhouses.

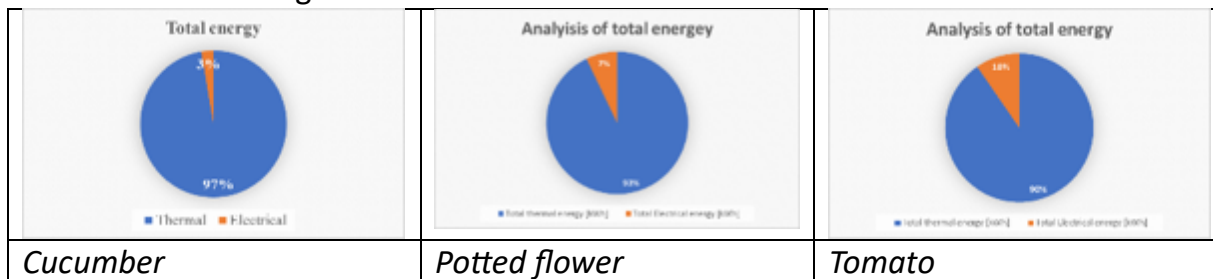


Figure 4.7. Total consumed energy distribution

However, the comparison of different types of energy does not always represent the real energy and environmental performance. For that reason, in the figure 4.8 is presented the distribution of primary energy.

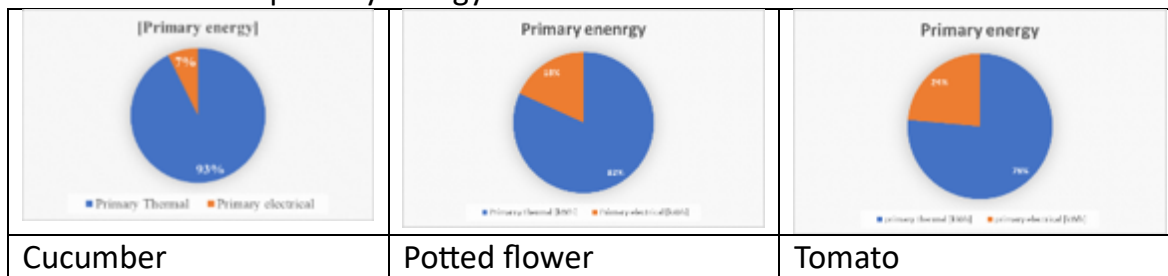


Figure 4.8. Primary consumed energy distribution

Although in terms of total energy consumption electrical energy seems negligible in terms of primary energy the electrical energy plays an important role which can reach the 25% of the total consumption. Since the energy consumption for heating depends on the energy demand as well as on the heating system efficiency the later was calculated (through comparison among the theoretically calculated energy demand and the real consumption arise from the energy invoices) for the four audited greenhouses and presented in the Table 4.5.

Table 4.5 Heating systems efficiency

Audited greenhouse	Heating system total efficiency
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Cucumber	26%
Potted flower	42%
Tomato commercial	65%
Tomato experimental	89%

From the above Table it comes out that greenhouses that use biomass have heating systems with very low efficiency degree. Thus, the picture arise from the Figure 4.5 should be calibrated to what thermal consumption should be if a 75% total heating efficiency could be achieved as presented in Table 4.6

Table 4.6. Corrected primary energy distribution

Audited greenhouse	Thermal energy [%]	Electrical energy [%]
Cucumber	65	35
Potted flower	66	34
Tomato commercial	69	31

Thus, it comes out that electrical primary energy accounts for the 1/3 of the total primary energy consumed in greenhouses.

Distribution of consumed electrical energy can be carried out only for the tomato commercial and the potted flowers greenhouses since for them electrical consumption time series is available. In Figure 4.9 the electrical energy distribution for these greenhouses is presented in terms of pies.

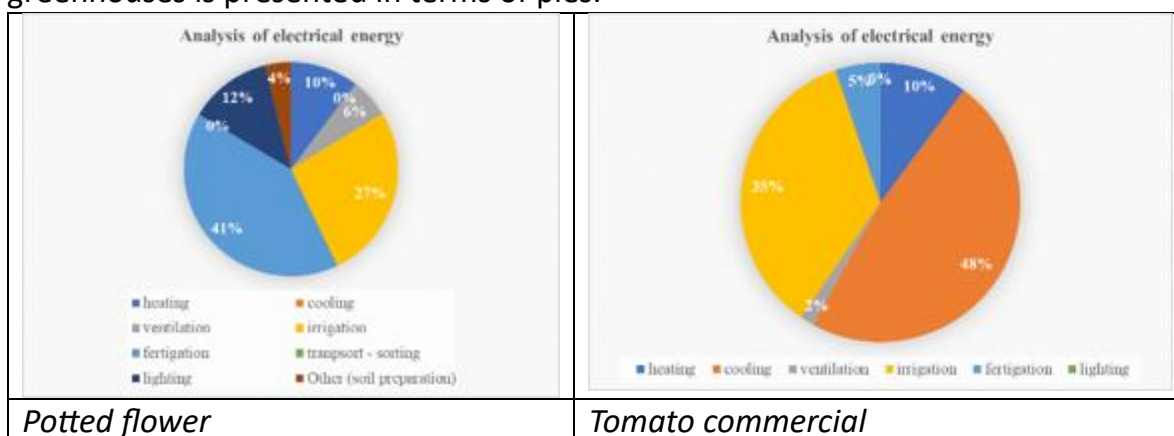


Figure 4.9. Electrical energy distribution



In both greenhouses the electrical energy consumed for heating is the 10%. In the tomato greenhouse cooling with 48% is the major power consumption process while in the potted flower greenhouse there is no such consumption and the need for cooling is covered by ventilation (representing the 6% of the consumption). In both irrigation accounts for the 1/3 of the total energy consumption. Fertigation system and lighting complete the energy consumption for the potted flower greenhouse while in the tomato greenhouse the fertigation accounts for the 5% of the total consumption and the consumption for lighting is negligible.

In the Table 4.7 the energy intensity in terms of total energy consumption is presented for the audited greenhouses with respect the greenhouse area

Table 4.7 Energy consumption indices per greenhouse area[kWh/m²]

Energy consumption	Cucumber	Potted flower	Tomato
Thermal	488.90	78.174	8.792
Electrical	13.38	5.998	0.935
Total Primary	527.71	95.567	11.504
Thermal Heating		77.868	8.792
Power generation		0.306	0.000
Electrical heating		0.618	0.095
Electrical cooling		0.000	0.447
Electrical ventilation		0.359	0.016
Electrical irrigation		1.594	0.328
Electrical fertigation		2.440	0.049
Electrical transport - sorting		0.000	0.000
Electrical lighting		0.751	0.000
Electrical cold-storage		0.236	0.000

The high thermal energy index of the cucumber greenhouse is due to: a) low efficiency of heating system (25%), b) high requirement for heating (design temperature 17-19o C. It should be reminded that in the case of potted flower the total heat efficiency is 42% and the required temperature 16o C, while in the tomato crop the total heat efficiency was 65% and the required temperature 10o C. Thus, the thermal energy index with respect the greenhouse area depends strongly on the cultivation type. More narrow is the range of the electrical energy index with respect the greenhouse area.



In the Table 4.8 the energy intensity is given in terms of produced volume and produced pieces for the potted flower greenhouse and in terms of produced mass for the tomato greenhouse

Table 4.8. Energy consumption indices per greenhouse production

Energy consumption	Potted flower [kWh/piece]	Potted flower [kWh/lt]	Tomato [kWh/kg]
Thermal	5.212	3.148	8.792
Electrical	0.400	0.242	0.935
Total Primary	6.371	3.848	11.504
Thermal Heating	5.191	3.136	8.792
Power generation	0.020	0.012	0.000
Electrical heating	0.041	0.025	0.095
Electrical cooling	0.000	0.000	0.447
Electrical ventilation	0.024	0.014	0.016
Electrical irrigation	0.106	0.064	0.328
Electrical fertigation	0.163	0.098	0.049
Electrical transport - sorting	0.000	0.000	0.000
Electrical lighting	0.050	0.030	0.000
Electrical cold-storage	0.016	0.010	0.000

4.4 Israel

The energy synergies for Israel arises from energy audit and will be presented descriptively.

The first audited greenhouse is a bell pepper soil type greenhouse of 1 hectare area with plastic roof and a yearly production of 150-160 tons per year in one growing season. the greenhouse has neither a heating system nor a cooling system, while the ventilation is done manually. To cool down the greenhouse they replace the cover from plastic to mesh. For the irrigation a standard drip system they use. Practically there is no other energy consumption system neither any automation.

The second audited greenhouse is a pepper soil type greenhouse of 5 hectares with plastic roof and side walls with a yearly production of 5 to 6 tons per year in one growing season.



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To cool the greenhouse during the summer the plastic cover is changed to net. They do not have heating system and they consume energy only for the operation of a standard drip irrigation system and for a cooling room for storage. No automation is applied.

The third audited greenhouse is a cabbage soil type greenhouse of 10.5 hectares with plastic roofs and side walls. In the greenhouse Cabbage, lettuce, mint, parsley, leafy greens are cultivated with a yearly production of 1000- 1500 tons per year in one growing season. No heating system is used while during the summer cooling is achieved by replacing the plastic cover with net and with two cooling units. A standard drip irrigation system; that is half automated, is used along with a man powered sprinkler irrigation.

4.5 Italy

The energy synergies from Italy arise from desk work and are presented as description of existing situation in Italy according to the literature, since their experimental greenhouse is still to be installed.

In Italy, the majority of greenhouses are typically not equipped with air temperature conditioning systems, either for heating during winter or cooling during summer. Due to the absence of such conditioning systems, the energy bills associated with heating and cooling are generally not significant for these structures. It is worth noting that while there are instances where heating and cooling systems are used in certain greenhouses, they are not as prevalent as in other countries with colder climates or specific crop requirements.

Based on the estimates made using the RICA database (Rete di Informazione Contabile Agricola – Network of agriculture accounting information), energy procurement costs for agricultural enterprises, including fossil fuel sources for fuel and combustion, represent over 20% of variable costs, with higher percentages for certain sectors such as livestock and grain production (around 30%), see Figure 4.10. Consequently, investments in energy efficiency and renewable energy production for self-consumption result in cost reductions that can significantly enhance agricultural profitability. A significant aspect to consider is the energy costs of agricultural enterprises for irrigation purposes.

For farms with irrigated crops, the costs related to energy for water lifting/distribution depend on the type of irrigation supply. The supply can occur through irrigation water



service providers (irrigation consortia) or self-supply (defined by the Italian Law in Article 6 of RD 1775/1933). Half of the irrigation withdrawals are from self-supply, 18% of the farms have a mixed supply method, while the remaining portion is attributed to the irrigation water service (SII – Servizio idrico di Irrigazione), provided collectively by irrigation consortia.

Farms associated with an SII pay a consortium fee to the irrigation consortia, which includes energy costs for water lifting from water bodies. On the other hand, farms that obtain water from on-site wells bear the entire supply costs.

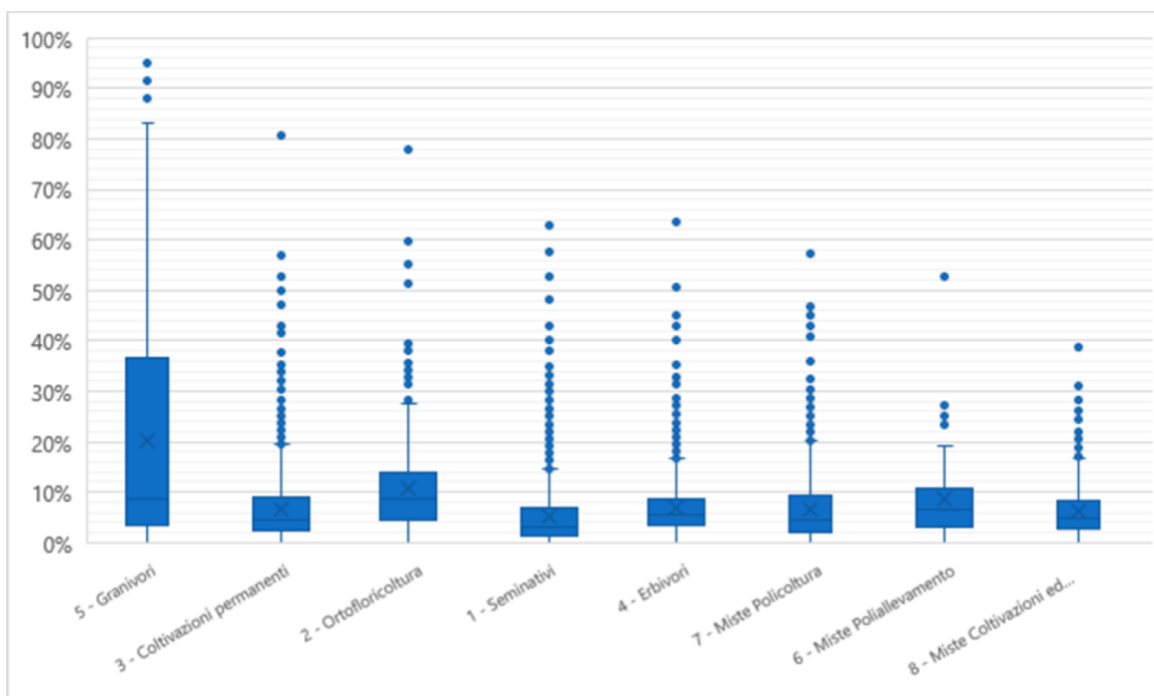


Figure 4.10: Energy cost impacts on total costs for agricultural enterprises (%). Granivori = Granivores. Coltivazioni permanenti =Permanent cops. Ortofloricoltura =horticulture. Seminativi = arable crops. Erbivori = Herbivores. Miste policoltura = Mixed Polycoltura. Miste Poliallevamento = Mixed livestock farming. Miste coltivazioni e allevamento= Mixed culture and livestock.



4.6 Total comparative presentation

As it comes out from the presented results the distribution of consumed energy among the various processes depends strongly on the crop and on the cultivation strategy. Thus, there is a wide range in the percentage at which each procedure participates in the final allocation. In the Table 4.10 the relevant energy audits are summarized and compared with values appear in the literature.

Table 4.10. Comparative presentation of procedures participation in final energy consumption in Greenhouses

s/n	Procedure	Energy audits	Literature [9]
1	Heating	78 – 93%	0 – 99%
2	Cooling	0 – 11%	
3	Ventilation	0.5%	
4	Irrigation	2 – 8%	1 – 19%
5	Fertigation	1 – 3%	1 – 27%
6	Pesticide		0 – 6%
7	Lighting	0 – 1%	1%
8	Other	0 - 0.5%	-

The energy audit results compare well with the literature values and can be considered reliable. As far it concerns the total energy intensity the audited tomato greenhouse compares well with low energy intensity cases from the literature mainly in countries around Mediterranean while the cucumber greenhouse compares with the high energy intensity cases.

Table 4.11. Comparative presentation of energy index kWh/m²

Case	Energy consumption per area [kWh/m ²]
Tomato energy audit	8.79
Cucumber energy audit	488.9
Potted Flower energy audit	78.17
Spain high energy intensity tomato [10]	386
Spain low energy intensity tomato [11]	5.58
Spain low energy intensity lettuce [11]	4.03
Spain low energy intensity peppers [11]	5.56



Spain low energy intensity beans [11]	4.31
Greece high energy intensity tomato [12]	237
Greece high energy intensity lettuce [13]	200
Greece high energy intensity flowers [14]	318
Greece low energy intensity tomato [15]	7.14
Greece low energy intensity cucumber [15]	6.9
Italy low energy consumption tomato [16]	3.49
Italy low energy consumption lettuce [16]	1.75
Netherlands tomato [15, 17] (average)	368
Netherlands cucumber [15]	398
Netherlands sweet pepper [15, 17] (average)	376
Germany tomato [15]	351
Germany cucumber [15]	362

Thus, the energy audits can be considered representative of greenhouses operating in Europe and their analysis can be used for energy flows visualization.



5. Spatial, material, other synergies

5.1 Spatial synergies

5.1.1 Greenhouses in Europe

In Europe greenhouses cover 276000 ha [18] with 144200 business operating in them [19]. The operating business are distributed across Europe as presented in the following Table 5.1.

Table 5.1 Greenhouse area and holdings across Europe

Country	Area [ha]	Holdings Fresh vegetables (including melons) and strawberries	Holdings Flowers and ornamental plants
Belgium	37,340	1,040	370
Bulgaria	244,860	5,810	260
Czechia	25,950	-	-
Denmark	37,380	270	410
Germany	282,160	2,160	3,900
Estonia	18,750	170	30
Ireland	139,560	110	60
Greece	703,590	8,460	680
Spain	944,300	19,130	2,600
France	463,710	9,700	4,760
Croatia	157,100	2,320	970
Italy	1,009,440	21,700	7,040
Cyprus	35,150	480	40
Latvia	80,720	310	50
Lithuania	171,730	9,590	430
Luxembourg	2,060	10	10
Hungary	453,090	12,710	2,030
Malta	9,000	290	20
Netherlands	65,790	1,520	2,610
Austria	139,610	810	740
Poland	1,421,560	13,790	2,870
Portugal	263,580	3,750	1,790
Romania	3,563,770	18,730	980



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Slovenia	72,280	490	170
Slovakia	22,050	160	40
Finland	54,230	850	620
Sweden	66,550	290	600
Norway	41,890	230	200
United Kingdom	182,180	1,370	1,250
North Macedonia	168,990	7,950	710

5.1.2 Installed photovoltaics in Europe

In the 2023 the installed PV capacity in Europe was almost 150 GW distributed among the European countries as presented in figure 5.1.

From them the 60% was installed on roof top in various types of buildings (residential, industrial, special buildings etc) [21]. However, this distribution is not uniform in all the countries. For instance, in Greece only the 15% of the installed capacity is cited on roof tops [22].





Figure 5.1 Distribution of installed PV capacity in Europe at 2019 [20]



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5.1.3 Greenhouse in Europe with installed photovoltaics

Farms active in the production of electricity from photovoltaics

According to the RICA sample data for 2019, 4% of agricultural enterprises produce and utilize energy from photovoltaic systems. These enterprises are typically medium to large-sized, with an average structural size of nearly 50 hectares and over 500 Adult Livestock Units (UBA). On average, 40% of the Used Agricultural Area (SAU) of these enterprises is self-owned.

In terms of production specialization, 90% of the enterprises with photovoltaic systems are represented by specialized farms, primarily engaged in permanent crops (18.9% of the RICA sample) and arable crops (18.4%), followed by livestock farming (11%).

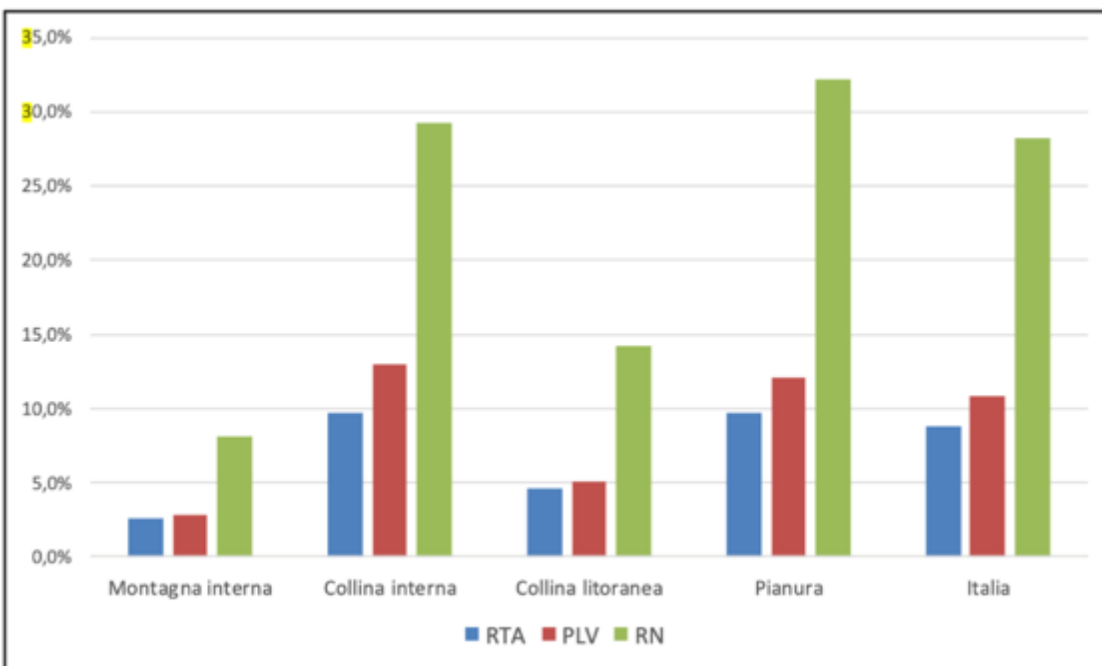


Figure 5.2 Percentage share of Renewable Energy revenues on Total Revenue (RTA), Gross Added Value (PLV), Value Added (VA), and Net Revenue (RN) in companies with photovoltaics. Montagna interna = Internal Mountain. Collina Interna= Internal hill. Collina litoranea = seaside hill. Pianura = . Plan.



Figure 5.25.2 illustrates the percentage share of revenue from renewable energy sales on various aspects, including total farm revenue (RTA), sellable production (PLV), value added (VA), and net farm income (RN). These percentages vary based on the altimetric range in which the farm operates. Nationally, the percentage contribution of renewable energy revenue is 8.8% of total revenue, 10.9% of gross farm output, 17.9% of value added, and 28.3% of net farm income. Analyzing the data based on altitude distribution, it is evident that the plain areas exhibit the highest percentage values, surpassing 32% in the case of net farm income. The inner hill areas follow with 29.2%. The lowest incidence of renewable energy revenue on net farm income is observed in the inner mountain areas, accounting for just over 8%.

These findings provide insights into the current utilization and economic impact of photovoltaic systems in the agricultural sector, highlighting the varying contributions of renewable energy revenue across different altimetric regions. Further exploration of these patterns can contribute to discussions on the role of agrivoltaics in sustainable agricultural practices, land use optimization, and the overall economic viability of renewable energy integration in the agricultural sector.

Self-consumption of Renewable Energy in Agricultural Enterprises.

Investments made by agricultural enterprises in renewable energy production, when appropriately sized, result in cost reductions that enhance agricultural profitability and improve competitiveness. The self-consumption of energy generated through agrivoltaic systems serves as a tool for enhancing operational efficiency within agricultural businesses. The National Recovery and Resilience Plan (PNRR) itself recognizes that the investment dedicated to the development of agrivoltaic installations contributes to the sustainability, not only environmentally but also economically, of the involved enterprises.

The investment envisaged by the PNRR aims to make the agricultural sector more competitive by reducing energy procurement costs, which currently account for over 20% of variable costs for many enterprises, with even higher figures observed in certain livestock and grain sectors. Additionally, this investment seeks to improve the climatic and environmental performance of agricultural operations. Setting a minimum self-consumption target for energy produced by agrivoltaic systems aligns with the aforementioned goals in terms of incentivizing such practices. In 2020, in Italy, photovoltaic self-consumption amounted to 4,735 GWh, representing 19.0% of the total production of photovoltaic systems and 46.0% of the production from systems that



engage in self-consumption. The highest level of self-consumption is recorded in July in absolute terms, while the highest self-consumption percentages are observed during the winter months.

In the residential sector, nearly all owners of photovoltaic systems engage in self-consumption. However, it is in the tertiary and industrial sectors where the highest percentages of self-consumption are observed. In the agricultural sector, there is a self-consumption rate of 15% of total production, which increases to 40% when considering only cases of self-consumption. It is important to note that the mentioned data primarily refers to traditional photovoltaic applications located on rooftops or ground-mounted systems within agricultural premises.

Installed PV on greenhouse roofs

However, the above are not related necessarily with PV installed on roofs of farms facilities and more over in greenhouse roofs. These PVs arrays are usually installed either on the roof of conventional and/or special farm buildings with opaque roof either in the ground around the farms. Actually, there are not available statistics about the existence of PVs on the roofs of greenhouses.

In the review paper [24] information about installed photovoltaics in commercial greenhouses is given and summarized in Table 5.2

Tables 5.2. Installed PV capacity in commercial greenhouses world wide [24]

s/n	Location	Installed capacity [kW]	Cultivation	Tracking existence
1	Abruzzo, Italy	800	Pasture, Tomato, water melon, wheat	Yes
2	Arizona, USA	-	Cabbage, chard, kale, tomato, onion	No
3	Montpellier, France	-	Cucumber, durum, wheat, French beans, lettuce	Partly
4	Santiago, Chile	-(Production 21437 kWh/year)	Various cabbage varieties (broccoli, cauliflower, kale)	No



5	Chiba, Japan	- (Production 35000 kWh/year)	Cabbage, cucumber, eggplant, peanut, tomato, taro, yam	
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Nevertheless, in some countries like Israel the issue of agrovoltaics installed in greenhouse roofs is more developed than in the rest world. In the Table 5.3 the installed PV capacity in Israel in commercial is presented.

Table 5.3 Installed PV capacity in Israel commercial greenhouses [23]

s/n	City	Installed capacity [kW]	Cultivation	Tracking existence
1	Gan Yashia	200	nursery	No
2	Kfar Haim	100	Ornamental plant nursery	yes
3	Kfar Haim	100	Covered vegetables	yes
4	Kfar Haim	62	Covered vegetables	no
5	Kfar Yedida	100	various vegetables	yes
6	chicory	-	chrysanthemums	yes

In some cases, the PVs on the roof are used for combined production of electricity and heat (PVT) as is the case of Kfar Yedida greenhouse.

The fact is that the majority of these installation concern experimental greenhouses. In the Table 5.4 indicatively PV installed in greenhouse cases are summarized

Table 5.4. Installed PV capacity in experimental greenhouses world-wide

s/n	Location	Installed capacity [kW]	Cultivation	Tracking existence
1	Matsue City/Japan [25]	0.098	-	No
2	Matsue City/Japan [26, 27]	0.720	Welsh Onions	No
3	Patra, Greece [28]	0.058	Lettuce	No
4	Kunming, Chine [29]	0.510	Lettuce	No
5	Sardinia, Italy [30]	68	Tomato	No



6	Thessaloniki, Greece [31]	4.4	Tomato	No
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5.2 Material synergies

The basic material flows in greenhouse include consumption of water, fertilizers and substrates for the production of the cultivated crop and waste biomass

5.2.1 Water

The water consumption depends on the type of crop, of the method of cultivation and of the greenhouse location. In the Table 5.5 the water consumption per greenhouse area and per production unit is given for different types of crops, different types of cultivation and different locations.

Table 5.5 Water synergies on greenhouse

Crop	Cultivation	Location	Water per greenhouse area [m³/m²]	Water per produced mass [m³/tn]	Water per produced pieces [m³/1000 pieces]	Water per produced volume [m³/m³]
Cucumber	Hydroponic	Greece	1.08	23.7	7.4	-
Potted flowers	Potted	Greece	1.6	-	106	64
Commercial Tomato	Hydroponic	Greece	0.41	75	-	-
Experimental Tomato	Hydroponic	Greece	1.3	40	-	-
Exp-Basil, pepper, cucumber, tomato, strawberry	Pot cultivation & Ebb-flow system	Austria	-	-	-	-



Experimental Tomato, lettuce	Hydroponic	Germany	1.63	36	-	-
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5.2.2 Fertilizers

The amount of use fertilizers depends on the crop and cultivation type. In the table 5.6 the fertilizers consumption is given in terms of greenhouse area and production characteristics

Table 5.6. Fertilizers synergies

Crop	Cultivation	Fertilizer per greenhouse area [kg/m²]	Fertilizer per produced mass [kg/tn]	Fertilizer per produced pieces	Fertilizer per produced volume
Cucumber	Hydroponic	-	-	-	-
Potted flowers	Potted	-	-	-	-
Commercial Tomato	Hydroponic	0.5	135	-	-
Experimental Tomato	Hydroponic	-	-	-	-
Exp-Basil, pepper, cucumber, tomato, strawberry	Pot cultivation & Ebb-flow system	-	-	-	-
Experimental Tomato, lettuce	Hydroponic	-	-	-	-

5.2.3 Substrates

Substrates are used in hydroponic cultivations and depend on the cultivated crop. In the Table 5.7 the used substrates per greenhouse areas and per production units

Table 5.7 Substrates synergies



Crop	Substrates per greenhouse area [slabs/m ²]	Substrates per produced mass [slabs/tn]	Substrates per produced pieces [slabs/1000 pieces]	Substrates per produced volume [slabs/m ³]
Cucumber	0.2	4.3	1.35	-
Potted flowers	0.03 [m ³ /m ²]	-	2 [m ³ /1000 pieces]	1.2 [m ³ /m ³]
Commercial Tomato	-	-	-	-
Experimental Tomato	0.4	12.8	-	-
Exp -Basil, pepper, cucumber, tomato, strawberry	-	-	-	-
Experimental Tomato, lettuce	3.1	70	-	-

5.2.4 Waste biomass

Depending on the general business plan of the greenhouse and on the cultivated crop it is possible to be create in site waste biomass that should be accounted on a general mass balance. In the Table 5.8 the produced biomass is presented in terms of greenhouse area and production units

Table 5.8. Waste biomass synergies

Crop	Waste biomass per greenhouse area [kg/m ²]	Waste biomass per produced mass [kg/tn]	Waste biomass per produced pieces [kg/1000 pieces]	Waste biomass per produced volume [kg/m ³]
Cucumber	9	195	61	-
Potted flowers	0.013	-	0.84	0.5



Commercial Tomato	-	-	-	-
Experimental Tomato	-	-	-	-
Exp -Basil, pepper, cucumber, tomato, strawberry	-	-	-	-
Experimental Tomato, lettuce	-	-	-	-

5.3 Other synergies

As already mentioned in the energy synergies chapter the final energy consumption depends on the required temperature and the required light for the crop growth. In order to complete the presentation and justification of the differences presented in energy consumption in the various greenhouses and in the possibility of installing photovoltaics on their roofs, the required temperature and lighting level for some of the crops under consideration are then presented indicatively

5.3.1 Temperature

On the Table 5.9 the required day and night temperatures are presented for various cultivations. Specifically, will be presented the designed temperatures and operating start temperatures of the heating system and the cooling system

Table 5.9 Required temperatures in greenhouses

Crop	Designed temperature	Temperature below which the heating operates	Temperature above which cooling operates [°C]
Cucumber	24	19 day/ 17 night	22 day/ 22 night
Potted flowers	23.5	16 day/ 16 night	20.5 day/ 22 night



Commercial Tomato	20	10	24
Experimental Tomato	23	18 day/ 14 night	25
Exp -Basil, pepper, cucumber, tomato, strawberry	18 - 16	18 day/ 12 night	26 (ventilation set point)
Experimental Tomato, lettuce	22	17	22

5.3.2 Light

Light is a crucial parameter for the crop growth. Nevertheless, in the majority of cultivations only the natural light is used. However, in some case the required light level is so high and so important that artificial light is used too consisting an important component of consumed energy. In the Table 5.10 the required light levels for various cultivations are presented.

Table 5.10 Required light levels

Crop	Required light level
Cucumber	No
Potted flowers	30000 [Lux]
Commercial Tomato	No
Experimental Tomato	No
Exp -Basil, pepper, cucumber, tomato, strawberry	Desired levels of natural lighting: 150 – 200 $\mu\text{mol}/\text{m}^2\text{s}$ Desired levels of artificial lighting: 100 $\mu\text{mol}/\text{m}^2\text{s}$
Experimental Tomato	No



6. Visualization of synergies

The energy, material and spatial synergies described in chapters 4 and 5 are summarized here and presented in terms of SANKEY flow charts and geographical distribution maps.

6.1 Visualization of energy flows

For the visualization of energy flows the audited greenhouse cases presented in chapter 4 are used since, as it was proven in section 4.6 they can be considered representative of the low energy intensity greenhouses. From the energy flows visualization, the energy losses and the useful energy distribution in the various procedures for the greenhouse operation are depicted.

In the Figure 6.1 the SANKEY diagram of energy flows for the potted flower greenhouse is presented while in the Figure 6.2 is presented the SANKEY diagram of energy flows of commercial tomato greenhouse. The energy flows are presented in terms of energy final consumption (and not in terms of primary energy).

The most impressive characteristic of SANKEY diagram for the potted flower greenhouse is the low efficiency of the heating system (losses higher than useful thermal energy), characteristic of heating systems based on biomass burning. Not only due to low efficiency of the biomass combustion but also due to system oversize and due to negligent use of the energy source (uninsulated distribution system and poorly maintained boilers). The second important characteristic is the energy consumption for artificial lighting due to the nature of the specific cultivation. The heat system efficiency of the tomato greenhouse is significantly higher than the flower greenhouse case mainly because it is a heating system based on oil fuel burning. Nevertheless, it is something that could be substantially improved.

In both cases the electrical energy consumption losses are due to the reactive power arising from motors operation and it is typical for industrial application.

So, in both cases it is clear that with proper management and sizing of the equipment it is possible to significantly reduce the consumption of thermal energy. However, the scope for saving electricity with corresponding interventions is limited. Therefore, they could, in principle, be considered privileged users of locally produced energy from photovoltaics.



Final Energy Consumption

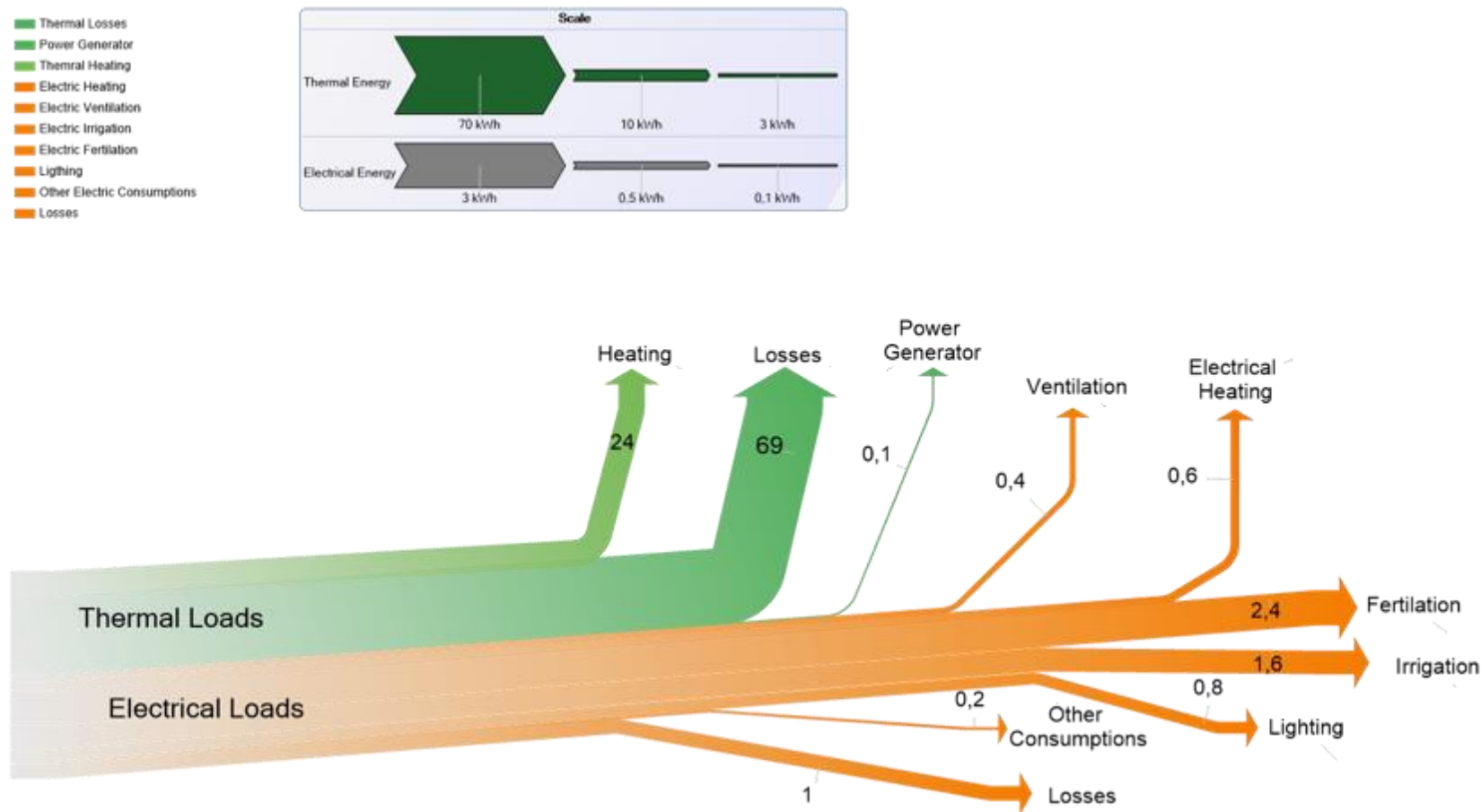


Figure.6.1 SANKEY diagram of energy flows for potted flower greenhouse

Final Energy Consumption

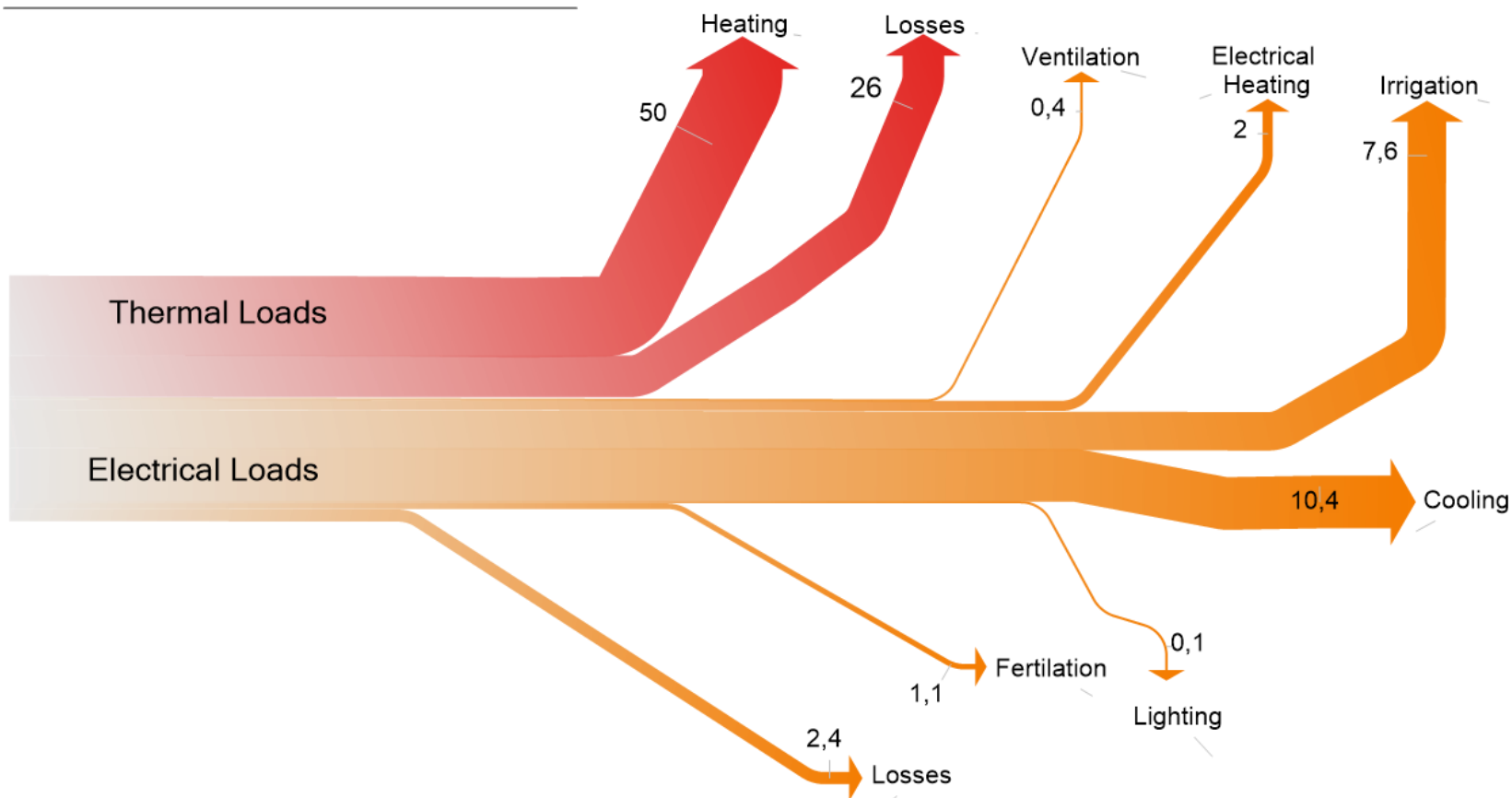


Figure 6.2 SNAKEY diagram of energy flows for tomato greenhouse

6.2 Visualization of material flows

For the visualization of material flows again the material and energy flows of the audited greenhouses will be analyzed as representative of the most common cases of commercial and experimental greenhouses. The visualization of material flows is also carried out with SANKEY diagrams where all the flows (energy inputs, material inputs, production and greenhouse requirements) are presented simultaneously giving all the necessary information in order to assess the greenhouse performance.

The energy and material flows are reduced to production unit. However, the reduction of flows to the production unit does not give information about the greenhouse productivity (eg low energy consumption could just lead to low greenhouse productivity because the equipment fail to achieve the designed internal microclimate). For that reason, for each presented greenhouse the basic characteristics of desired microclimate as well as the productivity in terms of production per greenhouse area are also given. Characteristic is the difference in productivity and eventually in all the flows among the experimental and the commercial tomato greenhouses.



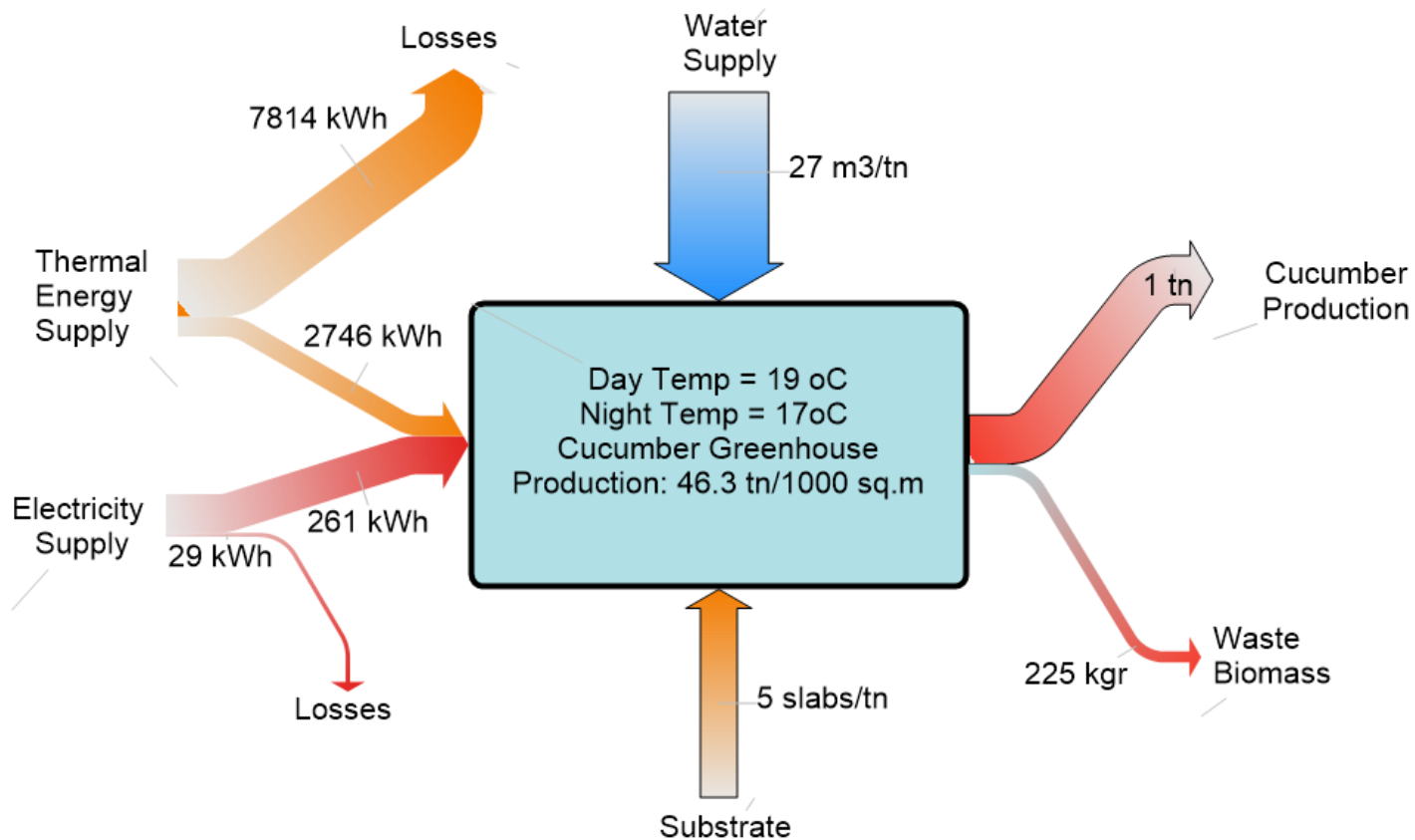


Figure 6.3 SANKEY diagram of energy and material flows for cucumber greenhouse

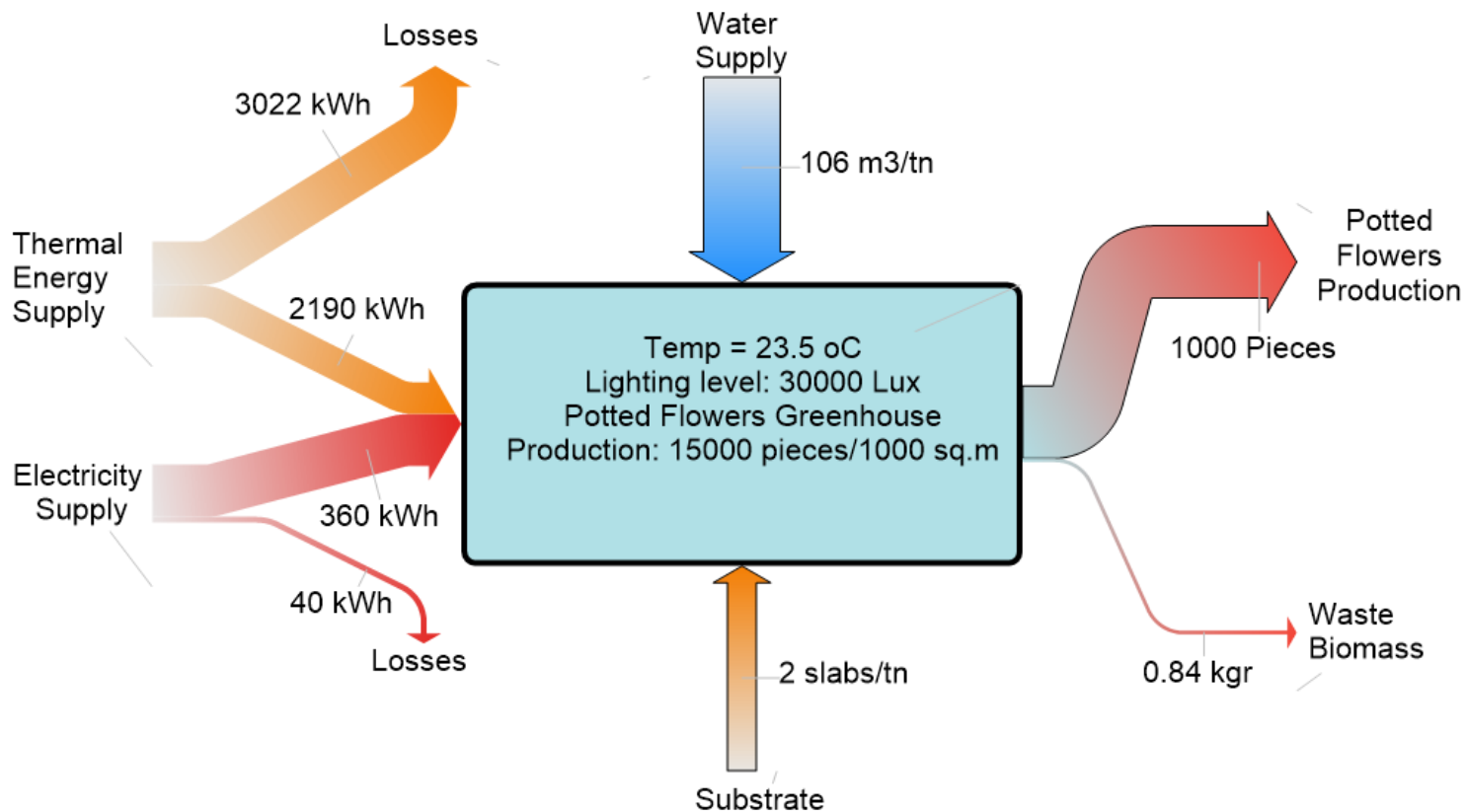


Figure 6.4 SANKEY diagram of energy and material flows for potted flower greenhouse

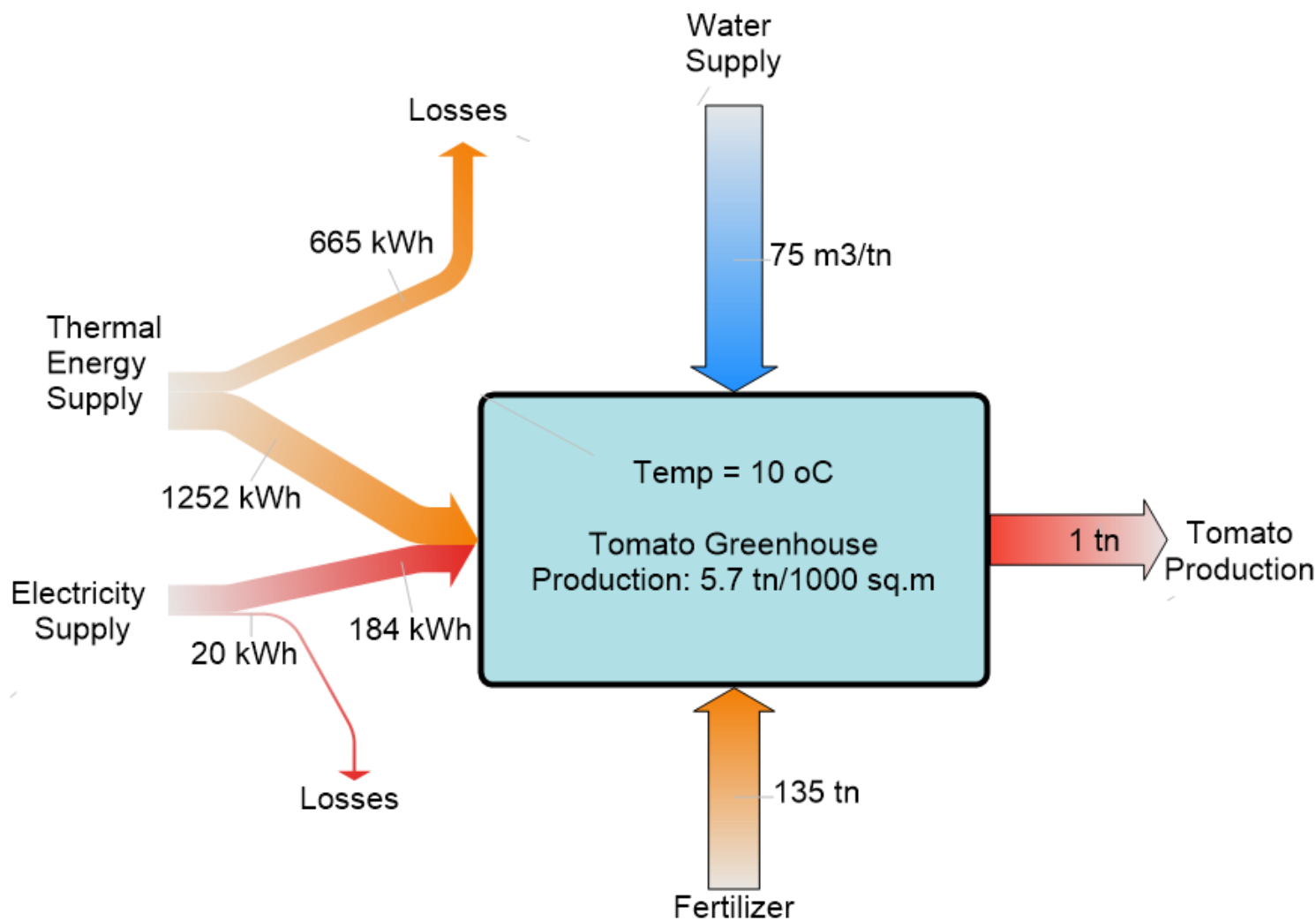


Figure 6.5 SANKEY diagram of energy and material flows for tomato greenhouse in Greece



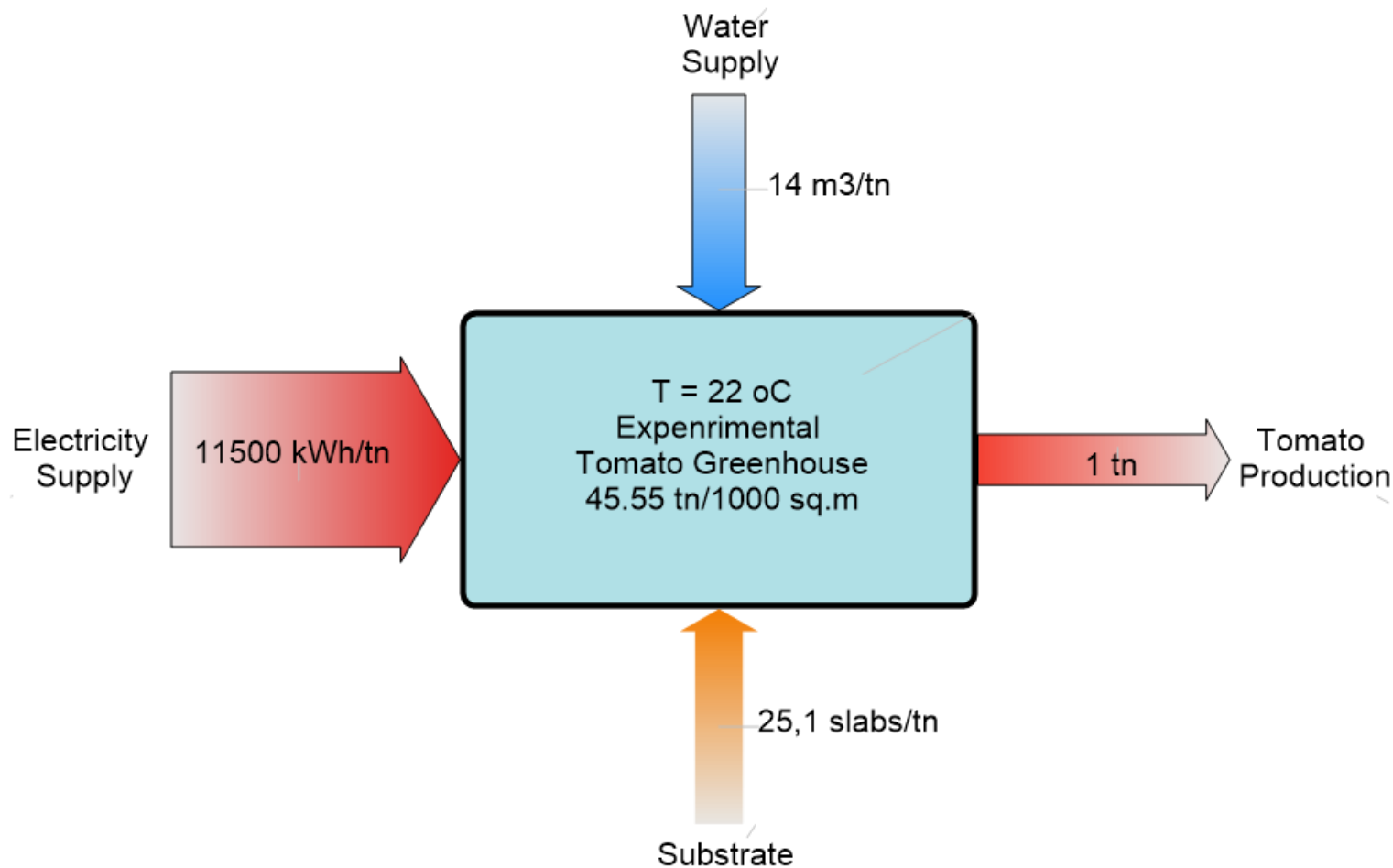
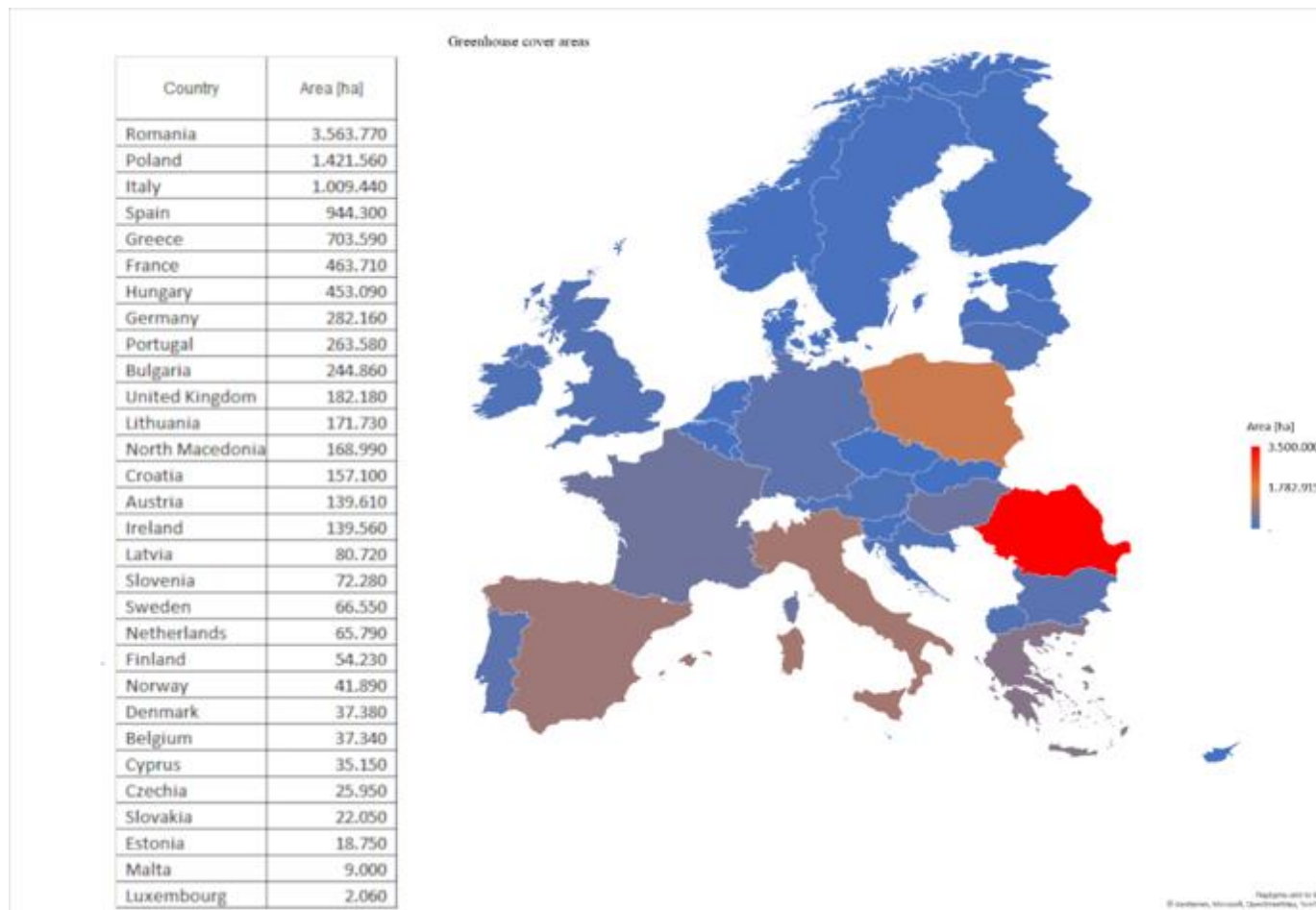


Figure 6.6 SNAKEY diagram of energy and material flows for tomato greenhouse in Germany

6.3 Visualization of spatial synergies

In the figure 6.7 the spatial distribution of greenhouse covered areas across the Europe is given.



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Figure 6.7 Distribution of greenhouses in Europe in terms of covered area



In the Figure 6.8 the spatial distribution of existing greenhouses with PVs in their roof are presented. With circle are denoted the commercial greenhouses while with rhombus are denoted the experimental greenhouses. The characteristic of all of them is that they are arranged around Mediterranean despite the fact that according to the Figure 6.7 it is clear that a large number of greenhouses are also installed at high latitudes.

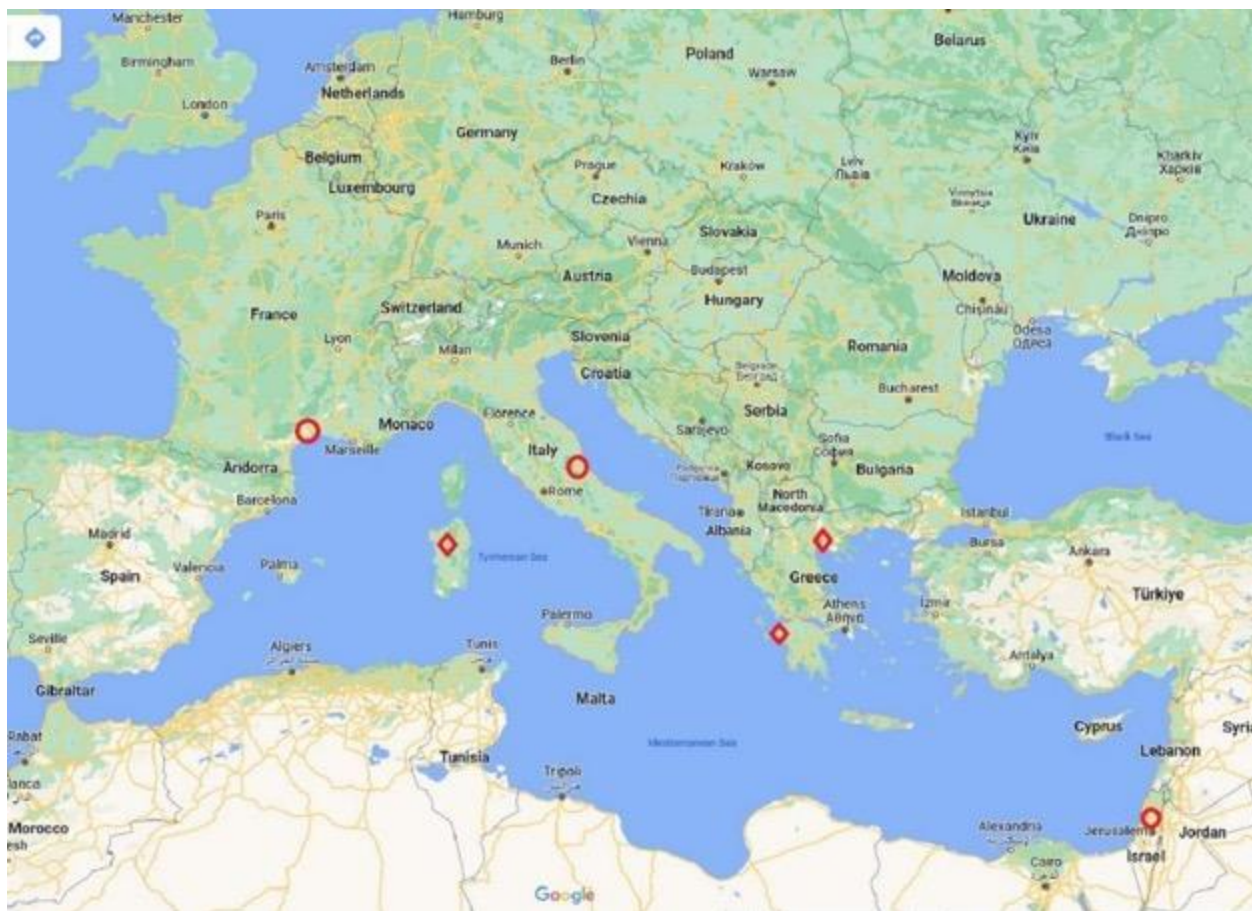


Figure 6.8 Distribution of PV installation in greenhouse roofs in Europe, Middle East and Mediterranean



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7 Conclusion

In the present deliverable the energy, material and spatial synergies in the greenhouse's operation were investigated through audits and literature review. Comparison of the of the primary data produced by the audits with bibliographic data demonstrated their validity and made it possible to use them to produce flow charts with generalized validity. Furthermore, the presented results will feed with data the WP4 for the simulation of greenhouses operation with PV on their roof.

Although the use of photovoltaics is widespread, with a large percentage (65% which corresponds to 97.5 GW) of them installed on roofs, their penetration in greenhouses is rudimentary. And this despite the fact that the surfaces of the existing greenhouses occupy a very large area of the order of 276000 hectares. Accounting literature data according to which the 40 - 50% of the greenhouse roofs can host photovoltaics without affecting the crop growth. This means that an area of more than 130000 hectares could be made available for the installation of photovoltaics without additional land use, while the energy produced by them could be used directly to cover the energy needs of the greenhouses themselves.

In fact, the surface area of greenhouses that could be safely covered by PV while maximizing both the yield of the crop and the PV depends on many factors such as the type of crop, the type of greenhouse, the automation and technology level of the cultivation and the geographical location. All the above factors determine on the one hand the allowed PV coverage (eg the coverage that will secure the desired environmental conditions mostly in terms of available light) and the local electrical energy consumption (off course with respect the local electrical energy purchase price).

For instance, a tomato greenhouse seems to be more adequate for installation of PV than a potted flower greenhouse where the requirement for light is increased.

Greenhouses are energy and water consumers. Although in terms of final energy consumption electrical energy represents a small percentage, in terms of primary energy (and consequently in environmental terms) electrical energy consumption accounts for the 25% of the total consumption. This contribution tends to increase due to introduction of automations and the increases use of heat pumps that allow a more precise management of greenhouse operation.



Finally, it is fact that up to now the use of PVs in commercial and experimental greenhouses is concentrated around Mediterranean although a big percentage of greenhouses operates in higher latitudes for two reasons: a) In these areas the cooling needs (that are served mainly by electrical energy) are higher, b) the solar lights is high enough to secure that even with the installation of PVs on the greenhouse roof the available radiation at the plants level remains at appropriate levels.

The above issues will be addressed by the project aiming at the study and development of PV system installed on the greenhouse roofs in a way that will allow the simultaneous maximization of energy production and cultivation depending on the type of cultivation and the available external solar radiation.



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