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Design of large scale prosuming in Universities: The solar energy vision of the TUC campus

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ABSTRACT

The current paper presents the main steps in the design of large-scale photovoltaic (PV) power generation plants in University campuses towards their energy independence. As an example is used the campus of the Technical University of Crete as a base case to describe the design.

Today the insular power system of Crete is based on oil fuel by 75%. Solar electricity is designed and discussed in this report.

For this scope, the energy consumption figures of the buildings within the campus are analyzed. In parallel, a feasibility study of the PV energy generation is conducted revealing their potential contributions and applicability.

The resultant electrical energy generation design satisfies the project objective by utilizing alternative energy sources and reducing the greenhouse gas emissions of the campus. The results obtained are satisfactory being both technically and economically feasible.

To conclude, these designs proposed in this project can be the first steps towards a 100% green energy campus and get even more tempting with relevant technological improvements in the future.

1. Introduction

Solar energy is a resource with both scalability and technology maturity to meet constantly rising global demand for power generation. Amongst solar power technologies, photovoltaic (PV) technology has experienced rapid growth and is expected to continue its key role in creating sustainable energy future [1,2].

A significant number of universities globally are planning relevant investments, in order to improve their sustainability in short- and medium-term. To further enhance this approach, support policies have been introduced in several countries, while in some cases PV energy generation for self-consumption can be profitable without subsidies [3–5]. In this paper, the term self-consumption is used to refer to the total PV electricity generation that is consumed directly or within a limited timeframe by the owner of the PV system [4]. Although several studies have already investigated the feasibility and economic aspects of creating large-scale PV power plants (Table 1), limited research [11,12] has been published on the planning and design of these installations in University campuses towards their energy independence. The main aim of this paper is to propose a standard procedure for the design of large-scale grid-connected PV installations on University campuses. In this framework, the campus of the Technical University of Crete (TUC) is selected in order to validate the developed procedure through the design of a 2 MWp grid-connected PV system. Moreover, this study also explains the significance of self-consumption in countries, such as in Greece, where there are no incentives for electricity fed into the grid.

Abbreviations: AC, alternating current (A); CO_{2e}, tons of equivalent carbon dioxide; DC, direct current (A); E_{AC}, AC energy output (kWh or MWh); $E_{AC,m}$, monthly total AC energy output (kWh or MWh); $E_{AC,y}$, annual total AC energy output (kWh or MWh); E_{DC}, DC energy output (kWh or MWh); $E_{DC,y}$, annual total DC energy output (kWh or MWh); $E_{DC,m}$, monthly total DC energy output (kWh or MWh); H, total solar irradiation-insolation on a horizontal surface (W/m^2); $\overline{H}$, monthly average total solar irradiation-insolation on a horizontal surface (kWh/m^2); $\overline{H}_Y$, annual total solar irradiation-insolation on a horizontal surface (kWh/m^2); H_T, total in plane solar irradiation-insolation (kWh/m^2); $\bar{H}_T$, monthly average daily total in plane solar irradiation-insolation (kWh/m^2); $\bar{\boldsymbol{H}}_{T,Y}$, annual total in plane solar irradiation-insolation (kWh/m^2); IEC, international electrotechnical commission; K_T, clearness index; $\bar{K}_T$, monthly average daily clearness index; MPP, maximum power point; $P_{pv,rated}$, PV rated power (kW$_p$); PR, performance ratio (%); PV, photovoltaic; STC, standard test condition; T, temperature (°C); T_α, ambient temperature (°C); $T_{\alpha,m}$, monthly average value of ambient temperature (°C); TUC, Technical University of Crete; Y_A, array yield (kWh/kW$_p$) or (h).

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Table 1
Summary of previous similar studies.

Case Study	Objective	Reference
University of Jaen Campus, Spain	Feasibility evaluation of large-scale PV systems through economic and cost analysis of several PVGCS on buildings.	[3,6]
Aachen-Hörn, Germany	Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial application	[7]
Nordsømøllen, Denmark	Calculation of the optimal configuration of large PV plants based on minimization of the levelized cost of the generated electricity (LCOE)	[8]
Spain	Consideration of Large-scale PV Self-consumption effects on the Aggregated Consumption	[9]
University of New Haven (UNH) Campus, United States	Investigation of the economic feasibility of campus-wide photovoltaic systems in New England	[10]

For this purpose:

- the energy consumption data were gathered and analyzed;
- the solar potential of the campus was evaluated;
- the suitable sites for the PV systems, according to the space requirements were identified;
- the performance of the system was simulated using solar PV planning and simulation software packages such as PVSyst;

The obtained knowledge provides safe estimates and information about the suitability of PV technology and potential improvements in order to create new installations in campuses.

2. State-of-the-art

Taking into account their multidimensional mission, many universities have not only been incorporating environmental education into their system, but also encouraging on-campus sustainability life experiences [13], such as renewable energy self-production. As the campuses include areas which are typically large, horizontal and usually free of shading, they constitute favorable fields of solar applications. A literature review of grid-connected PV systems into campuses exposed a continuous increase in total installed capacity. Typical cases of universities, which are currently utilizing PV panels on their campuses are summarized in Table 2, up to 28 MWp installed in Arizona. Several other plants are already operating or under construction.

3. Methodology

The design of a large-scale grid-connected PV system is a complex process that requires significant technical experience and knowledge. There are many adjustments that need to be made in order to reach the optimum balance between energy performance and cost, especially in self-consumption estimates. In this section, a standard design procedure and critical issues that need to be considered are outlined.

The development process of the PV project would include the following steps (Fig. 1);

- Obtain the energy consumption data in the campus
- Assessment of the solar potential and identification of the suitable sites for PV integration, taking into account the basic constraints (available area, land use, topography, local climate conditions, grid connection characteristics, accessibility, module soiling, etc.)
- PV system design
  - -Technology selection
  - -Arrangement and Shading
  - -Electrical configuration
- Energy analysis of the selected areas

3.1. Energy consumption

The first step throughout the design procedure was to gather the data related to the energy consumption in the campus. Specifically, the first thing done in order to derive as much information as possible was to check the facility manager's annual reports, which provide information such as building description, total useful floor area, main heating fuel, annual energy consumption, electricity bills, instantaneous power demand, etc. Also, more detailed information could be acquired from the real-time metering website of the university, which contains every possible reading related to the campus electricity consumption. [25].

This extended data gathering was crucial to clarify the energy saving potential, the type of the energy demand to be covered – especially the power needs, and the fluctuations (due to the seasonality and the day-to-day use).

3.2. Assessment of the solar potential and identification of the suitable areas for PV integration

3.2.1. Assessment of the solar potential

Obviously, the solar irradiation is the most important parameter for PV systems, affecting directly their energy output and efficiency [12]. This parameter is influenced by a significant number of factors such as geographical latitude of the given location, the season of the year, time of the day, clearness of the atmosphere, orientation and surface inclination, etc. [26]. Therefore the examination of the local solar irradiation levels is crucial for a successful design.

A common source of solar irradiation data for the given location can be obtained by the PV geographical information system (PVGIS) developed by the European Commission's Joint Research Centre (JRC-PVGIS). Another useful source is the experimental data of the area [27] and long-term weather data (period: 1958–2001) reported in an official technical guide of the Technical Chamber of Greece (TOTEE) [28].

In addition, it should be noted that, when assessing the solar potential at a site, care must be taken to minimize any shading that will reduce the irradiation actually received by the modules. Avoiding shading is critical as even small areas of shade may significantly impair the output of a module or string of modules.

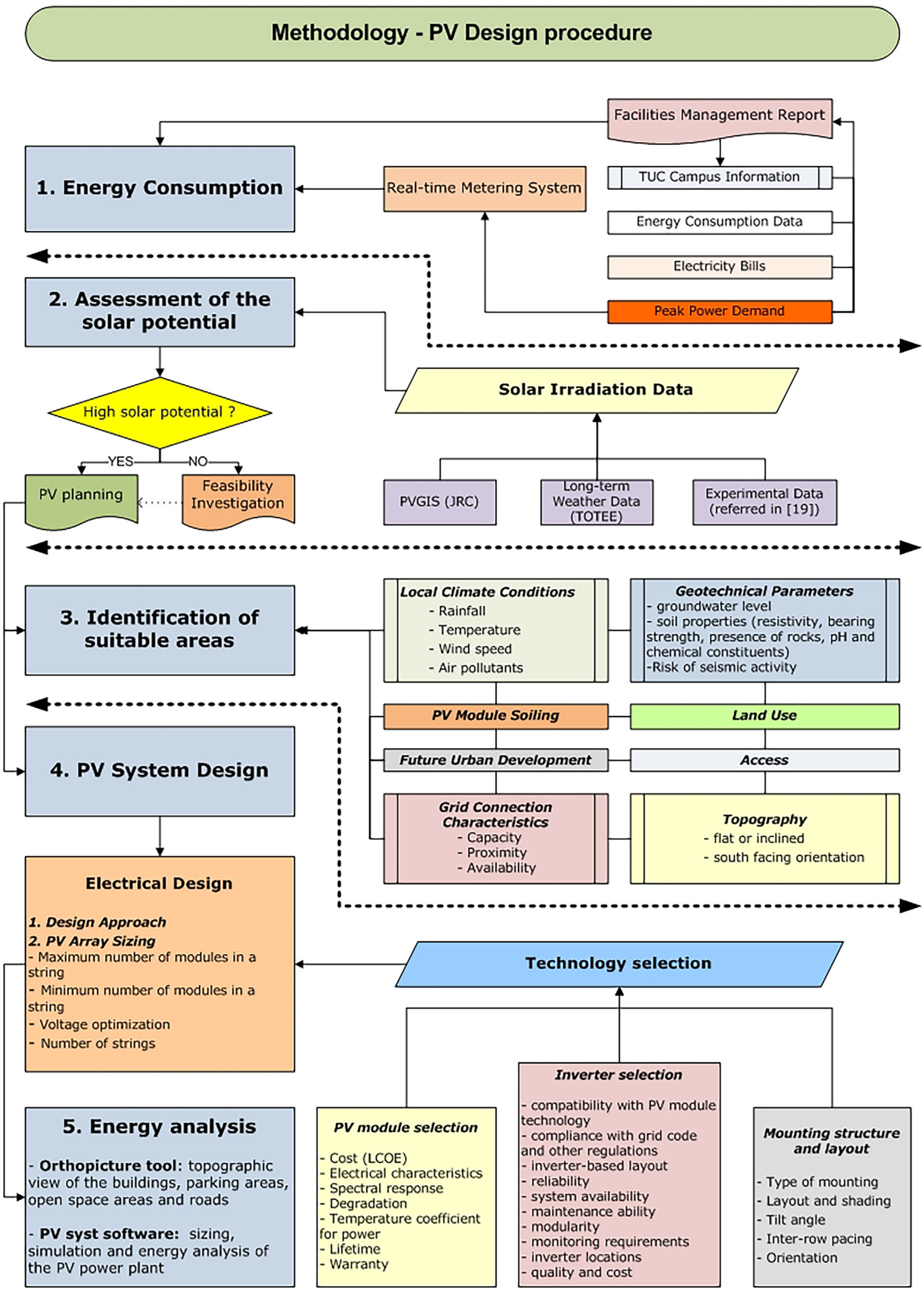

Fig. 1. Overall presentation of the methodology adopted.

Table 2
Summary of the existing, under construction or planned large-scale grid-connected PV systems on campuses.

Institution name	Country	$\bar{H}$[a]	Total capacity	Status	Ref.
		kWh/m²/d	kWp		
The University of Arizona	USA	5.88	28,095	installed	[14]
Arizona State University	USA	5.84	23,567	installed	[14]
Rutgers, the State University of New Jersey	USA	4.07	17,417	installed	[14]
Mount St. Mary's University	USA	4.09	17,400	installed	[14]
Colorado State University	USA	4.46	6754	installed	[14]
California State University, Fullerton	USA	5.38	6000	installed	[14]
West Hills Community College District	USA	5.51	6000	installed	[14]
United States Air Force Academy	USA	4.91	5150	installed	[14]
Arizona Western College	USA	6.07	4616	installed	[14]
Yale University	USA	4.01	1250	planned	[15]
Cornell University	USA	3.70	2000	under construction	[16]
Oregon University	USA	4.75	2000	installed	[17]
University of Murcia	Spain	5.04	2750	installed	[18]
Jaen University	Spain	5.11	200	installed	[19]
Hashemite University	Jordan	5.72	5000	under construction	[20]
TU Delft	Netherlands	3.07	1200	under construction	[21]
University of Queensland	Australia	5.50	1220	installed	[22]

[a] The National Solar Radiation Database (NSRDB) [23] and Photovoltaic Geographical Information System (PVGIS) [24] were used to provide solar radiation information.

3.2.2. Identification of study areas

The selection of the proper area is a critical part of creating a feasible solar PV plant. There are no precise rules for site identification, since capable PV installations have been developed in locations that may seem inappropriate at first sight. In general, the siting process should determine the limitations and the impact of the selections on the cost of the energy output. The main factors, except for solar potential, to be evaluated include: local climate conditions; local climate conditions; geotechnical parameters; accessibility; land use; PV module soiling; grid-connection characteristics [3,11,29,31,32].

3.2.2.1. Local climate conditions. The local climate should not be characterized by extreme weather conditions that will increase the risk of damage or non-operating periods of a PV system. In the present work, weather events to be investigated include:

- Flooding—May increases the risk of erosion of support structure and bases, depending on geotechnical aspects.
- High wind speeds—The risk of a high wind event out of the plant specifications is to be estimated. Typically, areas characterized by high average wind speeds should be avoided [29].
- Temperature The performance of PV systems is significantly influenced by increasing temperature. Hence, in places with a high solar potential and warm climate, alternative mitigation options should be examined during the design and technology selection. For example, it is preferable to choose PV technology with a low-temperature coefficient of power [27,30]. Moreover, cooling of PV modules during operation could be an alternative option that can result in a better overall conversion efficiency. Recently, integration of Photovoltaic (PV) and phase change materials (PCMs) system concept for thermal regulation was investigated by the staff of the Renewable and Sustainable Energy Systems Laboratory (ReSEL), Technical University of Crete (TUC), in order to assess its performance under actual Mediterranean climate conditions on the island of Crete [30].

3.2.2.2. Geotechnical parameters. The ideal position must be flat (slopes <3%) on a slight south-facing slope (orientation south, southeast, southwest). This topography simplifies the PV installation and reduces the cost of technical configurations for land leveling. Otherwise, complex mounting structures can be manufactured with additional cost. [29,31,32]

A geotechnical survey of the area is required in order to be taken the correct design decisions. The scope is to evaluate the ground status and to ensure that the mounting structures will have adequate bases. Standard practices dictate that boreholes or trial pits should be made to investigate: the groundwater level; the soil properties (resistivity, bearing strength, presence of rocks, pH and chemical constituents, etc.). Moreover, the geotechnical study has to evaluate the risk of seismic activity and the erosion and flooding. [29,31]

3.2.2.3. Accessibility. A suitable area should allow access for vehicles to deliver PV system parts and construction materials. Sometimes this means an improvement of existing roads or building of new ones. Moreover, it should be noted that the closer the selected area is to the main access road (<1 km, 1–2 km), the lower the cost of the investment. In addition, the selected area should be in a secure location where the possibility of vandalism or damage from wildlife is minimised, and the easy access of security and maintenance staff is ensured. [4,29,31,32]

3.2.2.4. Land use. A land with low value (e.g. an area without vegetation or dry-land herbaceous crops) and limited use estimation for the next generation period (30 years) is characterized as ideal to erect PV systems. In cases that the land is not owned by the University, the cost of purchase or lease, as well as the additional expenses, should be taken into account. [29,31]

3.2.2.5. Module soiling. If the PV modules are soiled by particulates, then the performance of the PV plant may be reduced, so it is important to take into account the site-specific environmental conditions, such as:

- Dust particles from transport and building activities;
- The abundance of birds due to the ensuing module soiling from its droppings.

In addition, soiling of PV modules may require an appropriate maintenance and cleaning plan at the site location. [33,34]

3.2.2.6. Grid connection and communication. Commonly, the long-term viability of grid connection mainly depends on capacity,

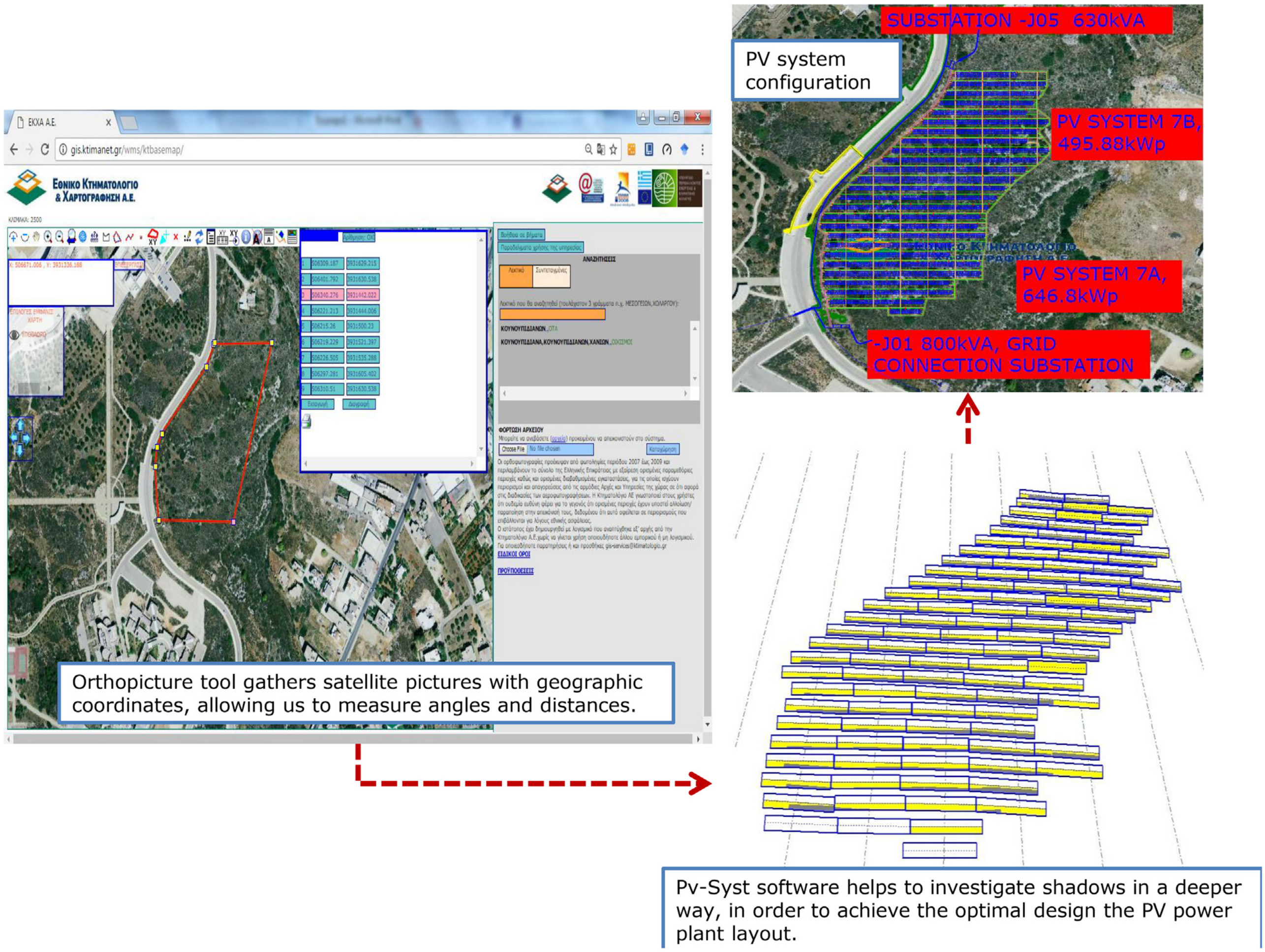

Fig. 2. Combining orthopicture tool and PV-Syst^{TM}.

availability and proximity. These factors should be investigated very early, as the cost is significantly increased if the site is later found to be inappropriate for grid connection (distance to substations >10 km) [11,29,32].

- Capacity—The capability of the grid to accept the power output of a PV plant is determined by the existing infrastructure and current use of the local electrical grid. Specifically, the rating of overhead lines, cables and transformers plays a key role in estimating the connection capacity available. In cases where the local electrical grid is incapable of allowing connected, the peak power export should be reduced to the acceptable limits of the grid or the whole grid to be upgraded to allow the desired export capacity (i.e. by using smart grids).
- Proximity—The distance between the selected site and the grid connection point increases highly the interconnection. Besides, a higher connection voltage implies an increased cost of equipment such as transformers, as well as upgraded cable specifications. Additionally, since modern PV systems offer significant data network connectivity capabilities in order to ensure data acquisition and control, telecom infrastructure facilities have to be easily accessible. Hence, selected areas should be in positions where the cost of grid connection has a slight impact on the economic performance of the project.
- Availability—The grid availability level describes the percentage of time that the grid can receive the generated output of the PV plant. Its effect on the project may be essentially undesirable, since the annual energy yield may be significantly reduced if the grid is saturated for long periods.

Finally, in order to assess the PV generation capabilities of the TUC campus, it was necessary to identify the available areas across the campus, taking into account its future building development [3,11,29,31].

3.3. Photovoltaic system design

The design and planning stages include all decisions to be taken on the dimensioning of the PV system as well as the selection and matching of the different components (PV modules, inverters and other equipment). Hence, an in-depth investigation of the main design aspects should be conducted in order to ensure the optimum performance of the PV system during its total life cycle [11,29,35].

3.3.1. Technology selection

3.3.1.1. PV modules. Although tests and certifications for efficiency, durability and reliability of commercial PV modules in accordance with international standards have already been conducted, there are differentiations on their operational performance under real field conditions. Consequently, in order to select a PV technology, a range of variables should be evaluated. Specifically, the following key aspects should be considered [11,29,33,35]:

- Cost—The aim to minimize the levelised cost of electricity (LCOE) should imply the determination of the most cost efficient solution

Fig. 3. Depiction of the Technical University of Crete Campus.

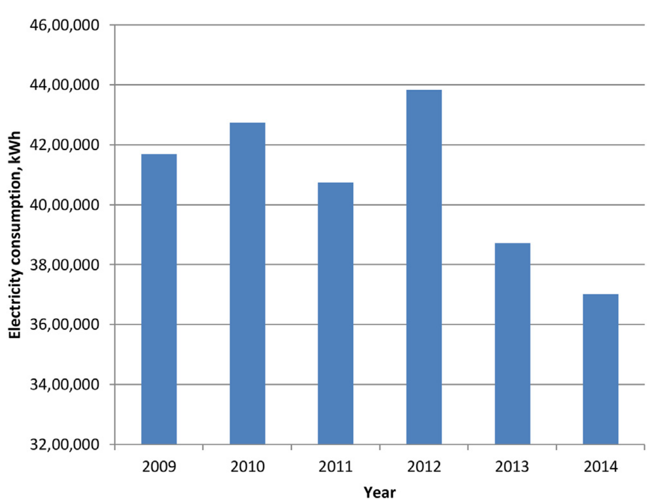

Fig. 4. Total annual electricity consumption during the last six years.

for the operational period. It is, therefore, critical to investigate high efficient PV module types which would require low maintenance costs [3,6,8,36].

- Electrical characteristics—In order to select the PV technology, information can be obtained from its' electrical characteristics at standard test conditions (STC), such as the open circuit voltage (V_{OC}), the short circuit current (I_{SC}), the MPP voltage (V_{MPP}), the current (I_{MPP}), the power (P_{MPP}), the efficiency (n) and the relevant temperature coefficients. Although these electrical parameters do not predict accurately the actual PV performance, their values could form strong indications for the adaptation of the selected technology to a specific environment, e.g. warm climate conditions [11,27,35].
- Spectral response—As the separate PV technologies have a different spectral response, the site-specific light conditions should also be taken into account in order to choose a well-suited module.
- Degradation—Factors affecting the degradation rate of the PV module include the quality of manufacture materials, the manufacturing process and the quality of fitting of cells into the module. Therefore, the degradation attributes and long-term stability of PV modules should be fully understandable before the final selection. Moreover, the results from tests of modules under real-field conditions, which can be found in scientific journals, could be usable [37].
- Warranty—The warranty period could be a criterion for discrimination between commercial PV modules, which is to be taken into account together with the power guarantee. These guarantees differ between manufacturers, but a standard power warranty designates that the PV modules will deliver 90% of the initial nominal value after 10 years and 80% after 25 years.
- Lifetime—High-quality PV modules with the suitable International Electrotechnical Commission (IEC) certification have a design life more than 25 years. After 30 years, the degradation rate may be significantly increased [11,29].

3.3.1.2. Inverter. Inverters convert DC power from the PV modules to AC power, appropriate for supply to the grid, but they can also carry out a sequence of operations to maximise the energy output of a PV plant. There are two main categories of inverters: central inverters and string inverters. Hence, different solar PV module technologies and design approaches may fit different inverter classes. In order to establish optimum performance and lifetime,

Fig. 5. Instantaneous electricity power demand across the campus during a typical working day [http://www.tuc.gr/3879.html].

attention in the matching of PV modules and inverters is required. The main factors to study when selecting inverters include compatibility with the PV module technology, compliance with grid code and other regulations, inverter-based layout, reliability, system availability, maintenance ability, modularity, monitoring requirements, inverter locations, quality and cost [11,29,35].

3.3.1.3. Mounting structures. PV modules should be mounted on stable structures, which help to remain correctly oriented and provides them with structural support and protection. Mounting structures may be either fixed or on tracking systems. As fixed tilt mounting systems are simpler, cheaper and with lower maintenance requirements than tracking ones, they are usually preferred. Usually, mounting structures are manufactured from steel or aluminium. A high-quality mounting structure is expected:

- To be tested in order to ensure the mounting designs fulfill the site-specific load conditions;
- To achieve the desired technical specifications and field adjustments (e.g. tilt angle, placement of bases);
- To minimize tools and technical knowledge required for installation;
- To satisfy the special features described in the PV module manufacturer's installation manual.

In general terms, good quality structures from reliable manufacturers can be characterized as a low-cost and limited-risk option. Otherwise, custom-designed structures may be used as a solution to specific challenges or to reduce costs. Furthermore, the topography of the site and soil information gathered during the geotechnical survey will influence the choice of foundation type. [11,29]

3.3.1.3.1. Layout and shading. The layout of the PV power plant and the distance recommended between rows of mounting structures should be selected in accordance with the site-specific conditions, taking into account the constraints related to the available space of the selected area, as well as geological and topographical matters. The aim of the layout design is to minimize cost while achieving the maximum energy yield from the PV power plant. This should include:

- Designing row spacing to reduce shading losses;

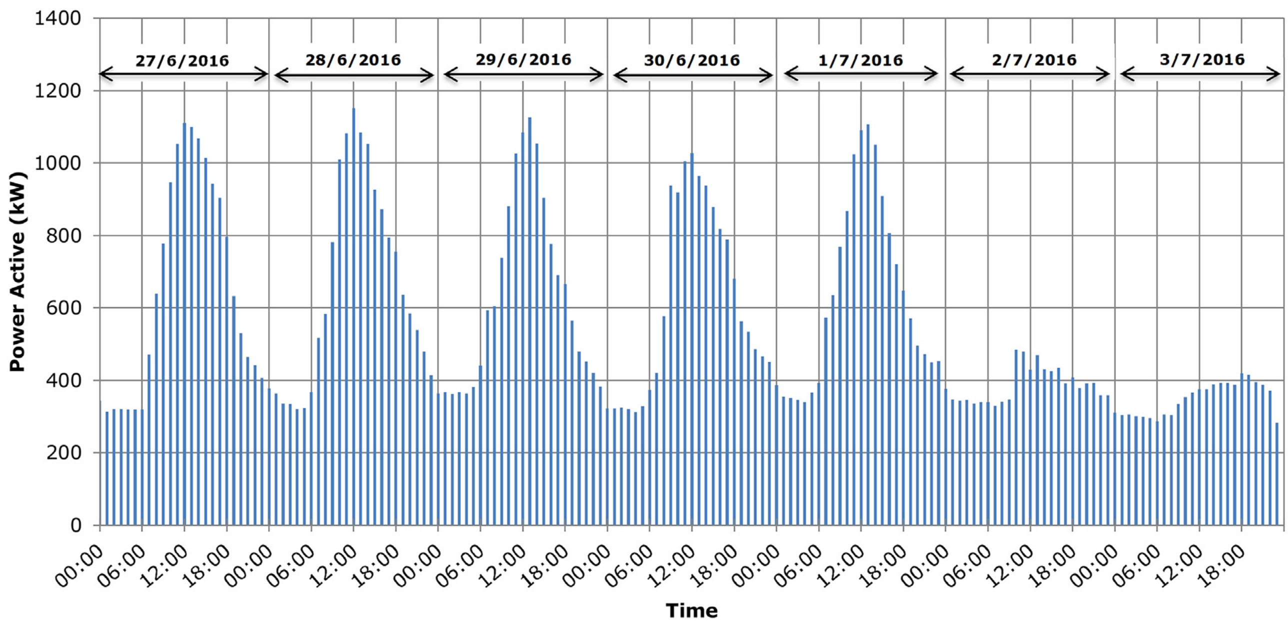

Fig. 6. Power vs time (typical working week).

- Designing the configuration to minimize electrical losses;
- Planning access and enough space between rows to allow moving for maintenance purposes;
- Choosing a tilt angle and orientation that maximizes the annual energy yield according to the latitude of the site, the distribution of solar resource on a yearly basis, as well as the seasonality of the power demand;

Computer simulation software could assist in the optimal design the PV power plant layout. This software includes suitable mathematical formulas which describe the movement of the sun throughout the year for any location on earth, plotting its altitude and azimuth angle on a sun-path diagram. This information is correspondingly used to compute the shading percentage and simulate the ensuing energy losses associated with various configurations of the tilt angle, orientation and row spacing [11,29].

3.3.1.3.2. Tilt angle. The optimal tilt angle that yields the maximum of the total annual incident irradiation on the PV module surface has to be determined in every location. For fixed systems, the optimum tilt angle could be theoretically calculated from the latitude of the site. However, adjustments are required to account for:

- Soiling—Higher tilt angles experience lower soiling losses, because of the natural cleaning of PV modules by the flow of rainwater.
- Shading—A tilted surface in a higher angle provides more shading on its behind surface. Consequently, a suitable option is to decrease the tilt angle, as it is usually effective in order to prevent inter-row shading.
- Seasonal irradiation distribution—In some cases, the seasonal particularities could determine the annual energy generation. So, it may be beneficial the tilt angle adjustment capability to avoid losses.

3.3.1.3.3. Inter-row spacing. The choice of row spacing is a compromise to reduce inter-row shading while keeping the area of the PV power plant within reasonable limits, reducing cable runs and conserving ohmic losses within low limits. Inter-row shading cannot be avoided: at the beginning and end of the day, the shadow lengths are considerably longer. For many locations, a typical design rule is to space the modules in such a way that there is no shading at solar noon on the winter solstice (December 21st in the northern hemisphere). If the annual loss due to shading is less than 1%, then the row spacing may be considered acceptable. Energy yield simulations can be performed to estimate losses due to shading, and to reach an economic optimization that also counts the cost of land if required.

3.3.1.3.4. Orientation. In the northern hemisphere, the orientation that maximizes the total annual energy yield is true south. The effect of tilt angle and orientation on energy yield production can be effectively modeled using simulation software [11,29].

3.3.1.4. Electrical configuration.

3.3.1.4.1. PV array sizing. The design of a PV array is based on the inverter specifications and the system architecture. Moreover, safety requirements, inverter voltage limits and national regulations also need to be taken into account [11,35,38].

- A maximum number of modules in a string – This is determined by the maximum DC voltage input of the inverter ($V_{MAX,DC,inverter}$) to which the string will be connected. This voltage value should not be exceeded, since crossing the limit can decrease the inverter's operational lifetime or switch the device off. The highest module voltage that can appear in operation is the open-circuit voltage in the coldest daytime temperatures (for Europe use − 10 °C) at the selected location. The maximum number of modules in a string may, therefore, be calculated using the formula:

$$V_{OC,ARRAY(-10)} < V_{MAX,DC,inverter} \quad [1]$$

- A minimum number of modules in a string – This should conserve the system voltage within the MPP range of the inverter. If the string voltage falls below the minimum MPP inverter voltage ($V_{MPP,MIN}$), then the system will noticeably underperform. In the worst scenario, the inverter may be rendered out of order. The lowest expected module voltage appears during the highest operating temperature conditions. Hence, the minimum number of modules in a string is calculated using the formula:

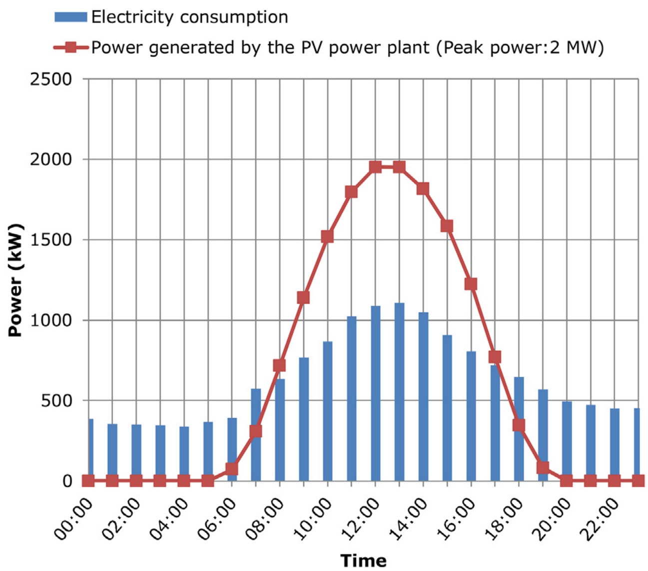

Fig. 7. Daily electricity consumption and expected PV energy generation profile (1/7/2016).

$$V_{MPP,MIN} \leq V_{MPP,ARRAY(NOCT)} \leq V_{MPP,MAX} \quad [2]$$

- Voltage optimization – As the inverter efficiency depends on the operating voltage, it is required to optimize the design by fitting the array operating voltage and inverter optimum voltage as close as possible. This will require voltage dependency graphs of inverter efficiency.
- A number of strings – The maximum number of strings allowed in a PV array is related to the maximum PV array current and the maximum inverter current. Generally, this limit should not be surpassed as it causes inverter underperformance [11,29,35].

3.3.1.5. Energy analysis of the selected areas. After the first step of potential areas' definition, an energy analysis of the selected zones is required in order to estimate the corresponding electricity generation. This investigation is being supported by the use of two different tools:

- The orthopicture tool, which will be used in order to determine an accurate topographic view of the buildings, parking areas, open space areas and other elements, such as roads, etc., of the campus. It gathers under the same visual environment real pictures integrating the related geometric properties, allowing us to measure angles and distances.
- Shading effect and energy estimation tool: A PC software package (such as PVSyst software), which is commercially available for the study, sizing, simulation and data analysis of complete PV power plants should be used. It contains also an extensive database of meteorological data for different locations, system components and their technical specifications, and estimates the electricity generated by PV systems.

Combining the orthopicture tool and the preliminary distribution of the PV modules, it is possible to design completely and simulate a PV power plant, and then the annual PV electricity generation in a specific location can be obtained. The PV syst software usually allows us to create the scene of the buildings, the PV system and its surroundings, as it is shown in Fig. 2. In this method, we can approximate the PV system energy generation taking into account possible shades between them. The acquisition of the dimensions of the area under study, through the orthopicture tool, it has allowed us to quantify the energy losses caused by different shadows (surroundings or self-shading). [3]

Table 3
TUC Building stock.

Time period	Building surface delivery m^2
1990–1995	23,206
1996–2000	6308
2001–2005	6497
2006–2010	14,031
2011–2015	5737
Total	55,779

3.4. Case study

TUC campus (Fig. 3) is located close to the city of Chania, Southern Greece (latitude: 35°31′N, altitude: 24°04′E) and the solar potential on in this area is favorable for the installation of PV systems, both in the ground or building integrated. TUC building infrastructure sums up to approximately 56.000 m^2, mostly consisting of offices, classrooms and laboratories. Other facilities also exist mostly related to student welfare like canteens, a restaurant, storage facilities, student dormitories etc.

During a recent survey the space usage mixture was as follows:

- Classrooms: ~14%,
- Offices: ~38%,
- Meeting rooms: ~2.5%
- Labs: ~29.5%
- Other: ~16%

Building facilities construction begun in late 80's and continues until now. Most recent building facilities were delivered in 2015. Table 3 summarizes building delivery distribution as per their surface in the relevant time brackets.

The energy consumption profile of the above-mentioned buildings varies significantly. Older buildings have relatively poor construction specifications in terms of electromechanical equipment, glazing and BEMS integration.

National energy regulation was introduced in 2011 but that was after the construction study of the buildings delivered in the 2011–2015 bracket, so eventually TUC's buildings do not necessarily comply with these regulations. However, the administration of the TUC has developed a **Strategic Plan for Sustainable Development** in order to contribute essentially to the environmental protection, which:

- is a "living" document that will continuously change during its implementation;
- it will have measurable results;
- it will promote the University to become an "open laboratory" on research and technology for sustainable development and
- it will contribute to the well-being of the academic community and the society as a whole.

The Strategic Plan outlines the Strategy for Research Development, the actions for the Green University and Environmental Policies and the Social Policies and Societal Outreach.

The Green University Initiative identifies actions on energy, water, paper consumption, recycling and green transportation. The most prominent action on the Green University Initiative has been the **reduction of energy consumption.**

Additionally, there were already installed seventeen (17) online energy metering devices to determine energy consumption in real time, monitor the energy use of various buildings and activities and

Fig. 8. Monthly distribution of electricity consumption.

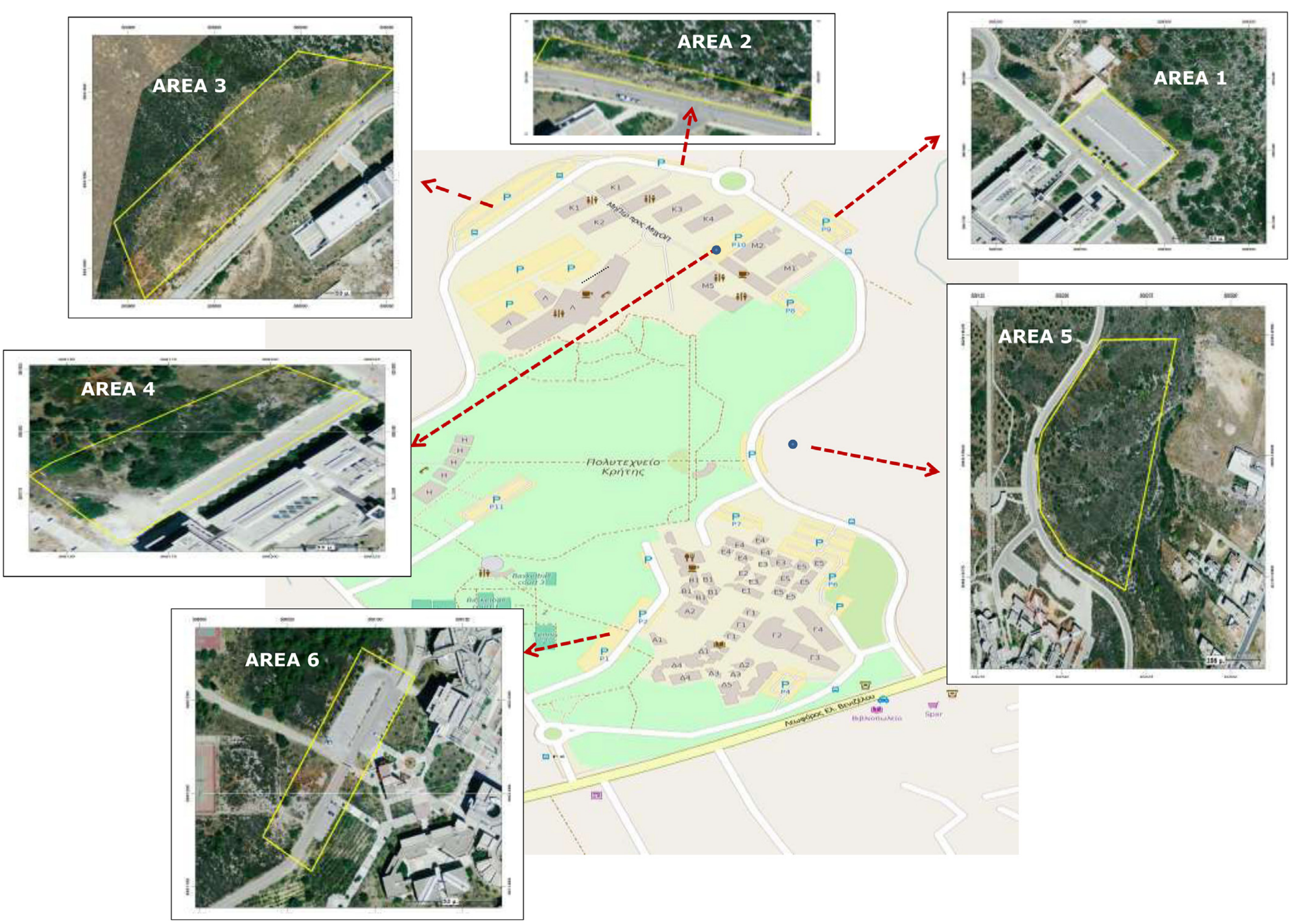

Fig. 9. Selected areas for PV integration.

Fig. 10. Simplified layout of the grid connected PV systems of the project.

use these data to develop strategies that would lead us in achieving our ultimate objective of 80% reduction in energy cost and campus sustainability.

4. Results and discussion

4.1. Energy consumption

According to the registered data from the facilities' management reports, 3700 MWh were consumed in the campus in 2014. This means that 423 kW of power have to be generated in order to meet the demand. Following to this relatively considerable consumption, 2405 ts CO_{2e} emissions[1] were produced that year.

In Fig. 4, total annual electricity consumption during the last six (6) years is depicted. The results show that in 2013 and 2014, the needs for electricity were significantly reduced, as a result of the implemented energy saving policies. However, this is far from the scope that the campus becomes green.

Real-time data acquired from the relative website of the university, show the spatial distribution of electric power demand across the campus during a typical working day (Fig. 5).

By looking at the power vs time plots for campus facilities (Fig. 6), it was found that the peak-demand time period lies between 8:00 am and 6:00 pm in working days while it is noticeably lower on weekends. Fig. 7 illustrates a sample curve, which combines the daily electricity consumption and PV energy generation in a typical summer day (1/7/2016).

Fig. 8 shows the monthly electricity consumption in the university over a four-year monitoring period. It was found that the university consumes the maximum monthly amount of electricity in February and in July, as a result of the higher heating and cooling demands during the final exam periods.

4.2. Local meteorological data

The climate of Chania can be characterized as temperate Mediterranean and particularly dry with sunlight 70% of the year.

Specifically, the long-term annual average value of irradiation on a horizontal surface is estimated more than 5.20 kWh/m^2/d or 1900 kWh/m^2/y for the selected site, using PVGIS. However, a corresponding value of 4.65 kWh/m^2/d is recorded as slightly lower in related experimental results, published recently [27]. Nevertheless, both these values indicate an excellent solar potential of the site.

[1] Based on emission of 0.65 kg CO_2/kWh, ec.europa.eu/clima.

Table 4
Monthly average daily solar insolation on a horizontal surface ($\bar{H}$), ambient temperature during daytime (Tα,m) and clearness index ($\bar{K}_T$). [19].

Month	1st monitored period (June 2010-May 2011)			2nd monitored period (June 2011- May 2012)			TOTEE (Long term average. monitored period: 1958–2001)		
	$\bar{H}$ kWh/m²/d	$\bar{K}_T$	$T_{\alpha,m}$ °C	$\bar{H}$ kWh/m²/d	$\bar{K}_T$	$T_{\alpha,m}$ °C	$\bar{H}$ kWh/m²/d	$\bar{K}_T$	$T_{\alpha,m}$ °C
June	7.35	0.64	25.9	7.20	0.62	25.1	7.33	0.63	25.8
July	7.56	0.67	28.2	7.53	0.67	28.1	7.26	0.64	27.6
August	6.72	0.65	29.3	6.72	0.65	27.1	6.61	0.64	27.3
September	5.37	0.61	26.1	5.32	0.61	25.9	5.37	0.61	24.6
October	3.26	0.47	22.1	3.37	0.49	19.3	3.58	0.52	20.7
November	2.97	0.57	20.4	2.01	0.39	14.4	2.60	0.50	17.5
December	2.09	0.46	16.8	2.18	0.48	14.6	1.90	0.42	14.5
January	2.21	0.44	13.9	1.94	0.39	11.0	2.21	0.40	12.9
February	2.53	0.40	13.5	2.64	0.41	11.8	2.58	0.45	13.2
March	3.62	0.44	14.4	4.52	0.55	15.1	4.00	0.49	14.6
April	5.06	0.51	15.9	6.16	0.62	19.0	5.57	0.56	17.7
May	6.39	0.58	20.1	7.10	0.64	21.7	6.84	0.62	21.5
Annual average	4.59	0.54	20.5	4.72	0.54	19.4	4.65	0.54	19.8

Table 5
Potential PV areas in the TUC campus.

Potential PV areas	Characteristic	Size (m²)	Suitability
Area 1	Parking lot	2200	Suitable
Area 2	Parking lot	650	Suitable
Area 3	Parking lot	7500	Suitable
Area 4	Parking lot	2000	Suitable
Area 5	Open field	24,000	Suitable
Area 6	Parking lot	3200	Suitable

The warmest months are July and August when the monthly average temperature value (during daylight hours) is equal to 27.6 °C and 27.3 °C respectively. Table 4 summarizes the monthly average daily solar insolation on a horizontal surface ($\bar{H}$), ambient temperature during daytime (Tα, m) and clearness index ($\bar{K}_T$).

4.3. Identification of available area for PV integration

The main objective of the project is the integration of a large-scale PV system into the university campus for self-consumption. The system should be designed to produce a significant share of the electricity demand of the University, which is estimated to be around 4000 MWh/year.

Six areas were identified as suitable for PV installations (Fig. 9) according to the criteria set out. These areas include open space places, which are characterized by: low – land value; flat topography; vehicles' accessibility; availability; suitability as regards the geotechnical characteristics; grid connection capability and extensibility; ensuring safe operation; etc. Moreover, the proposed sites meet the safety requirements for students, personnel and facilities in case of an accident, fire or unstable situation. Table 5 summarizes the potential PV areas based on their characteristics and sizes.

4.4. PV system final design

4.4.1. Design approach

The PV power plant will consist of eight (8) PV systems completely embedded in TUC campus in different mounting structures. Its peak power output is determined for multi-crystalline PV modules. In Fig. 10 a simplified layout of the PV systems is shown.

The installation will consist of 8206 multi-crystalline silicon PV modules (Day4Energy 60MC-I 245W), covering a total area of 13,950.20 m² with an installed capacity of 2.01 MWp. In this project, PV modules will be typically arranged in 4 parallel strings, 22 per string, and connected to three phase inverters (Refusol 020K-SCI) in order to convert the DC to AC. Each module has a nominal power of 245 Wp and includes 60 p-Si cells, with an efficiency of 15% under STC. In addition, the selected PV modules are certified to protect from the damaging effects of moisture and salt-mist. In this sense, these PV modules are ideal for integration in coastal areas, such as Chania. The inverter has a rated maximum efficiency of 98.7% and a maximum AC power of 20 kW. However, appropriate adjustments of the PV power plant components are expected in order to ensure its optimal operation. The PV module and string inverter technical specifications are summarized in Table 6.

4.4.2. PV array sizing

In order to design a PV system, the inverter specifications and the system's architecture aspects need to be taken into account. Specifically, the maximum and the minimum number of PV modules per string should be defined, as well as the number of strings per inverter. In this case, the following conditions need to be met:

1) $V_{OC\ ARRAY(-10)} < V_{MAX} \Rightarrow V_{OC\ ARRAY(-10)} < 1000V$
2) $V_{MPP\,\min} \leq V_{MPPARRAY(NOCT)} \leq V_{MPP\,\max} \Rightarrow 490V \leq V_{MPPARRAY(NOCT)} \leq 850V$
3) $I_{SCARRAY(70)} < I_{\max} \Rightarrow I_{SCARRAY(70)} < 41.5A$
4) $P_{MPPARRAY} < P_{MAX} \Rightarrow P_{MPPARRAY} < 22.3kW$

In accordance with the technical requirements, acceptable PV array size options include:

1) 4 strings of 20 modules (4 × 20 × 245 Wp=19.6 kWp)
2) 4 strings of 21 modules (4 × 21 × 245 Wp=20.58 kWp)
3) 4 strings of 22 modules (4 × 22 × 245 Wp=21.56 kWp)

To optimize system performance, the average operating voltage of the system should be matched to the maximum output voltage of the inverter (610 V) as much time as possible. Therefore, the array voltage distribution of each PV array sizing approach was simulated and evaluated using PVsyst software.

The obtained results (Fig. 11) show the optimum array design to consist of 4 strings of 22 PV modules each. The initial spike in all array voltage distributions depicted concerns a number of yearly hours, where the PV array output voltage is below the V_{MPPmin} threshold (490 V) at Nominal Operating Cell Temperature conditions, set as a design parameter to the PVsyst simulation tool.

4.4.3. PV design procedure example

PV system 7A: This PV system will include 30 string inverters, so the total power of the system under STC is to be:

$$P_{MPP}(7A) = 30 \times 4 \times 22 \times 245Wp = 646,000Wp$$

PV system 7B: The PV system consists of 495.88 kWp PV modules and 23 string-inverters of 20 kW:

$$P_{MPP}(7B) = 23 \times 4 \times 22 \times 245Wp = 495,880Wp$$

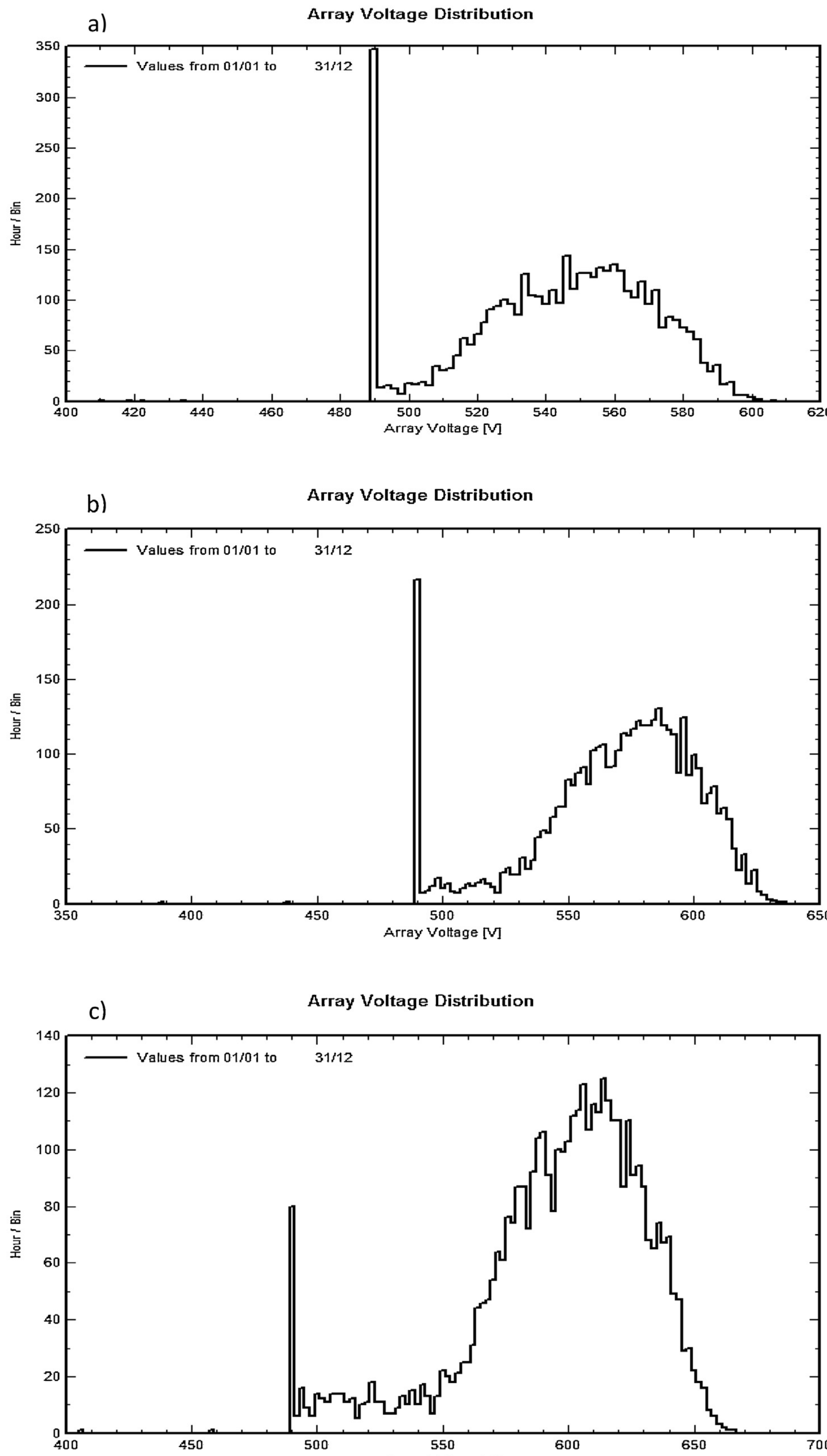

Fig. 11. Array voltage distribution for different PV array size (a) 4 strings of 20 modules, (b) 4 strings of 21 modules, and (c) 4 strings of 22 modules.

Table 6
PV module and string inverter technical specifications.

PV module* (nominal values)		String Inverter	
Parameter	value	Parameter	value
Nominal power (Wp)	245	Input (DC)	
Open-circuit voltage – V_{OC} (V)	30.29	Maximum DC power (kW)	24
Short-circuit current – I_{SC} (A)	8.08	Maximum DC voltage (V)	1000
Voltage at point of maximum power – V_{MPP} (V)	37.32	PV – voltage range at MPP (V)	490–850
Current at point of maximum power – I_{MPP} (A)	8.57	Maximum input current (A)	41.5
Module efficiency – η_m (%)	15	Output (AC)	
NOCT (°C)	42.3	Rated AC power (kVA)	20
Temperature coefficient		Maximum AC power (kW)	20
Open-circuit voltage – αV_{OC} (V/K)	−0.10	Maximum output current (A)	3 × 29.2
Short-circuit current – αI_{SC} (mA/K)	+2.67	Nominal AC voltage/range (V)	400/320–460
Power – βP_{MPP} (%/K)	−0.44	AC grid frequency/range (Hz)	50/60
		Power factor (cos ϕ)	1
		Efficiency	
		Max. efficiency (%)	98.7
		Euro-eta (%)	98.5
		General data	
		Dimensions (W/H/D) in mm	535/601/277
		Weight (kg)	41.5
		Operating temperature range (°C)	−25/+55
		Cooling concept	Natural convection

* The electrical data applies under standard test conditions (STCs): irradiation 1000 W/m^2 with light spectrum AM 1.5 and a cell temperature of 25 °C. The rated electrical characteristics are subject to a manufacturing tolerance of – 5%/+10%. NOCT conditions: irradiation of 800 W/m^2, ambient temperature of 20 °C and wind speed of 1 m/s.

The final design considerations are calculated, as:

1) $V_{OCARRAY(-10)} < V_{MAX} \Rightarrow 907.6V < 1,000V$
2) $V_{MPP\min} \leq V_{MPPARRAY(NOCT)} \leq V_{MPP\max} \Rightarrow 490V \leq 613V \leq 850V$
3) $I_{SCARRAY(70)} < I_{\max} \Rightarrow 34.69V < 41.5A$
4) $P_{MPPARRAY} < P_{MAX} \Rightarrow 21.56kWp < 22.3kWp$

4.4.4. Layout and shading

The PV systems 7A and 7 B (fig. 12) are to be integrated into an open space, which is close to the Medium-Voltage central substation. In order to ensure maintenance vehicle accessibility and systems' safe operation, a protection zone from the main access road was determined.

The general layout of the PV systems and the distance chosen between rows of mounting structures were designated to take into account the following requirements:

- The PV modules should be installed in a way that there is no shading at solar noon on the winter solstice (December 21st in the northern hemisphere)
- Fixed mounting systems keep the rows of modules at a fixed tilt angle while facing a fixed angle of orientation. Hence, the optimal positioning of the modules yields the maximum annual energy output.

The choice of row spacing is a compromise chosen to reduce inter-row shading while keeping the area of the PV systems within reasonable limits. As the selected site is on a slight northeast slope, the row spacing was defined as 7.3 m. As the effect of shading is more significant than a slight deviation from the true south and optimal tilt angle, the following assumptions were investigated:

1. Ideal orientation (tilt angle: 30°, azimuth angle: 0°)
2. To reduce shadows (tilt angle: 25°, azimuth angle: 0°)
3. For the sequence of the slope (tilt angle: 30°, azimuth angle: 15°)
4. For the sequence of the slope and reduce shading. (tilt angle: 30°, azimuth angle: 15°)

Table 7
Optimization of the PV arrays' tilt angle and orientation (Simulation results).

Tilt (°)	Azimuth (°)	$Y_{A\,(kWh/kWp)}$	PR (%)
30	0	1634	79.0
25	**0**	**1649**	**79.5**
30	15	1621	78.4
25	15	1638	79.2

The predicted values of the annual average array yield ($Y_{A,y}$) and performance ratio (PR) for each assumption are shown in Table 7. The maximum value of 1649 kWh/kWp was observed at a fixed tilt angle of 25°, facing true south.

4.4.5. Energy analysis of the PV systems 7A & 7B

According to the simulation results (Table 8) using PVsyst software, the total energy to be generated (AC) and fed into the grid is estimated at 1,898.8 MWh. This is about 47% of campus's annual electricity consumption or 1,234.2 CO_{2e} ts. The electricity for the corresponding DC generated from PV arrays is computed equal to 1,946.474 MWh. As the internal grid and inverter losses are computed lower than 2.5%, the PV array sizing could be characterized as optimal. Taking into account the proportionality of PV systems' 7A & 7B, the energy output is expected close to 1,074.77 and 823,99 MWh/y, respectively.

Moreover, the range of the monthly total production of DC energy ($E_{DC,m}$) is calculated to be from 98.99 MWh (December) and 220.22 MWh (July). Correspondingly, the estimated minimum ($E_{AC,m,min}$) and the maximum ($E_{AC,m,max}$) monthly total of AC energy output equals to 96.36 MWh (December) and 214.97 MWh (July) during a typical year. Consequently, it should be noted that the obtained results imply the necessity of forming an appropriate framework that could meet completely and continuously the

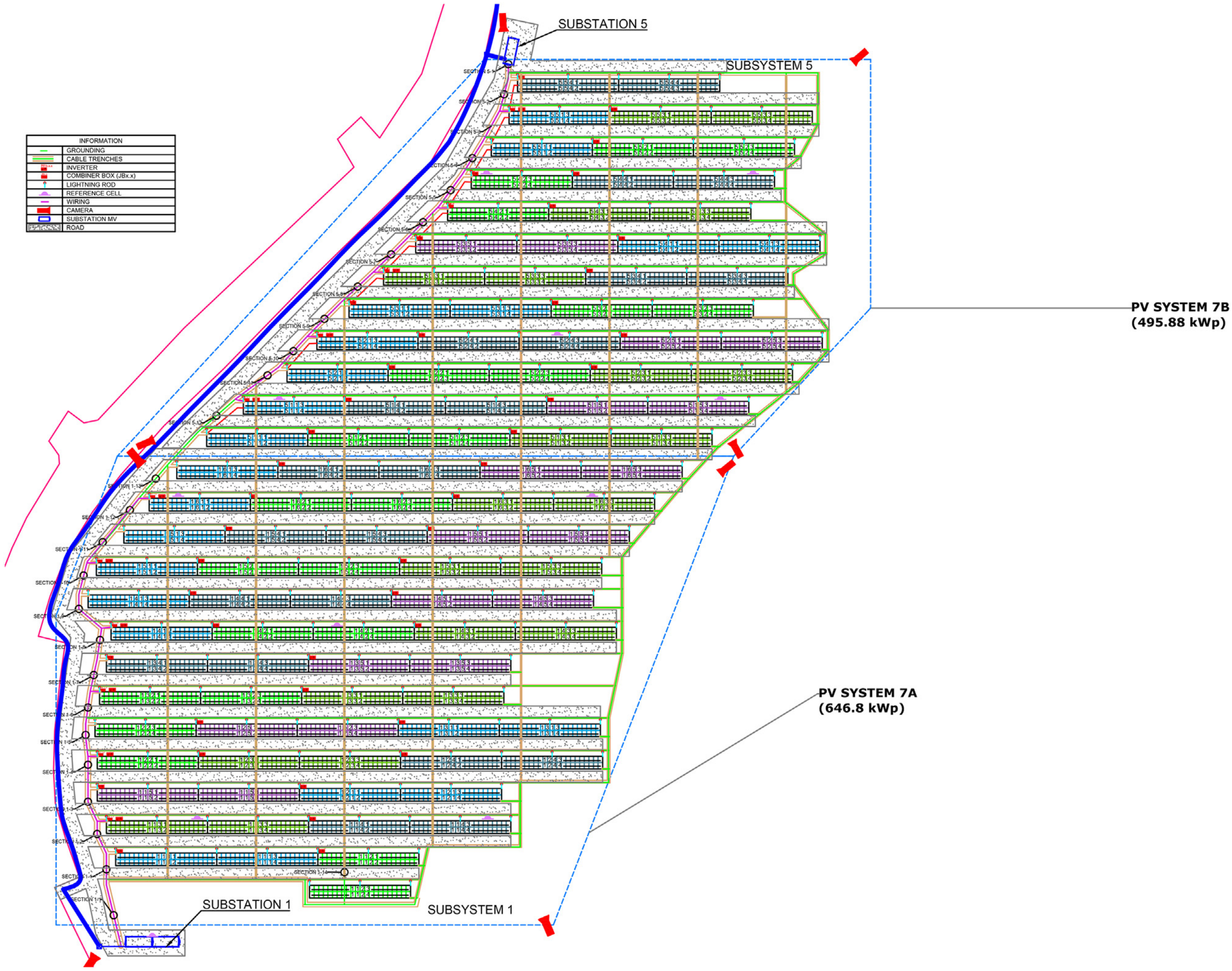

Fig. 12. PV system 7A & 7 B ground plan.

Table 8
Monthly total estimated PV system energy output in MWh, horizontal insolation ($\bar{H}$) and in plane insolation ($\bar{H}_T$).

	$\bar{H}$	T_α	$\bar{H}_T$	$E_{DC.m}$	$E_{AC.m}$
	kWh/m²/d	°C	kWh/m²/d	MWh	MWh
January	73.2	10.90	96.8	100.44	97.76
February	85.7	10.90	103.1	105.92	103.11
March	140.4	12.40	156.8	160.85	157.02
April	181.5	15.10	181.2	182.67	178.23
May	226.9	19.60	209.1	206.97	202.11
June	251.1	23.80	221.9	213.95	208.82
July	257.3	26.30	231.5	220.22	214.97
August	234.1	26.20	228.4	218.06	212.83
September	173.1	23.20	187.4	182.12	177.76
October	122.1	19.50	146.2	145.35	141.79
November	83.1	15.70	110.2	110.92	107.99
December	74.1	12.50	96.1	98.98	96.36
Annual total	1,902.6	18.05	1,968.8	1,946.47	1,898.76

energy demands, such as net – metering, in order to achieve the aim of 100% green energy consumption.

5. Conclusions

The draft procedure developed important issues to be considered in the design of large-scale grid connected solar PV systems at University campuses. Significant steps are the assessment of the solar potential, the identification of suitable areas, the selection of PV system's components and finally the design of the layout of the grid-connected PV system.

In the design of a 2 MWp grid-connected PV power plant on TUC campus, the developed procedure was followed step-by-step. A reliable assessment of the various aspects was conducted and the gained experience is to be used to optimize the final design options. Moreover, the obtained methodology provides useful tools and education for engineering purposes.

Analysis of the simulation results shows that the first phase of the project (PV system 7A & 7B) when implemented, will supply about 1899 MWh electricity annually, which is about 47% of TUC campus's annual electricity consumption. The PV systems 7A& & 7 B also stands the opportunity of saving about 1234 CO_{2e} ts which would be emitted by the diesel-based thermal power plant to generate the corresponding power amount.

Within the current national electricity grid's conditions, the project can be considered as feasible under a net – metering scheme or other incentives. The payback is estimated 4.2 years and the LCOE equal to 11 c€/kWh.

The licensing with the Hellenic Electricity Distribution Network Operator S.A.to follow in the large scale presuming scheme is ongoing. TUC campus could be a lighthouse for other Education campuses in Mediterranean countries, combining energy and cost saving with a demonstration for educational and research purposes.

Moreover, this research case will be used as a demonstration to raise the level of awareness of the local/regional community towards renewable energy and towards sustainable efforts in general. Specifically, most people experienced in renewable energy inherently may alter their perceptions and expectations, and therefore long-term positive impacts are to be generated.

Further work could also investigate the funding tools for PV installations on campuses, in order to improve solar power integration in terms of feasibility. More specifically, the engagement of potential financiers (i.e. utility companies, ESCOs, local authorities or renewable energy organizations etc.) in the development of this project should be further examined. This will provide the University the opportunity for clean, renewable energy that will be exploited to match the demand of electricity, leaving, in parallel, the major initial cost to third-party owners.

In addition, the increase in net-load variability created by the intermittent nature of renewable energy resources implies the necessity of further investigation of reliable ways to manage energy demand and simultaneously to achieve higher levels of PV penetration. To this aim, an effective action plan, which will take into account the energy storage aspects, will allow very high levels of PV contribution to the electric power system.

Important notice

This article is dedicated to the memory of Dimitris Hasapis, a faithful servant of solar energy technologies.

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