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A methodology exploiting geographical information systems to site a photovoltaic park inside a sustainable community

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This paper describes a methodology for applying geographical information systems (GIS) tools to site a photovoltaic (PV) park inside a sustainable community, in order, not only to meet all siting restrictions, such as environmental protection, but also to operate a PV park more efficiently reducing the shading effect erection and cabling cost. Additionally, the PV operation impact on the grid is investigated, integrating GIS maps into power systems analysis software, such as the PowerWorld® Simulator. In other words, this paper also stresses the importance of GIS for the design, installation and monitoring of power systems. A case study considering the Campus of the Technical University of Crete has been performed showing that siting properly a PV installation meeting 20% of the demand can gain significant savings in both peak and regular energy demands, especially on peak summer days.

Keywords: geographical information systems; sustainable communities; renewable energy sources; power system analysis software; photovoltaics; distribution grid

1. Introduction

Significant interest is noted in many countries all over the world, including Greece (Ayeridis 2011), to support the establishment of sustainable communities. In such communities, among other actions, increased penetration of renewable energy sources (RES) installations is foreseen. Since photovoltaics (PVs) are much easier to install than other RES, without the need for extensive measurement campaigns, they are expected to be part of almost every plan for the creation of sustainable communities. PVs in such communities can be installed not only as part of buildings, e.g. roof or walls, but also in available empty spaces, very close however to inhabited areas. In the latter case, competing land uses within the community, such as private land, plantation, recreational activities and requirements for additional building activity should be taken into account before selecting the most suitable location for installing PVs. Additional constraints include shading avoidance and the reduction of both erection and electric interconnection works. Since in many communities of this kind there is only one point of common coupling (PCC) with the upstream network, characterised as a typical weak interconnection, the impact on the voltage profile within the community may be significant. Therefore, the siting methodology should also take into account the potential impact of each of the proposed locations on the internal grid of the community, selecting the most favourable one.

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Geographical information systems (GIS) enable the management of spatial data and associated properties. Generally, they are able to integrate, store, adapt, analyse and present geographically referenced information. In a general sense, GIS tools are 'smart map tools', allowing users to capture a summary of the real world, construct interactive spatial or descriptive questions, analyse and adapt spatial data, etc. (Ramachandra and Shruthi 2007).

GIS are widely used nowadays in many diverse aspects, including natural resources planning, marketing activities and so on. GIS have greatly helped in creating RES potential maps both for regional and international areas (Šúri, Huld, and Dunlop 2005; Tsoutsos et al. 2009). The solar potential assessment of buildings within an urban area, in order to evaluate the rooftop PVs penetration, has been also discussed by Bergamasco and Asinari (2011). The GIS map projection offers an efficient data model to evaluate energy indices and building energy characteristics (Fabbria, Zuppiroli, and Ambrogio 2012). GIS are suggested as a significant tool in Sustainable Engineering planning (Roseland 2005).

GIS tools have been also extensively used in Power System studies, including analysis, operation and planning of power systems. Mapping of electricity networks (transmission and distribution) has been one of the major applications of GIS in the power system industry, increasing its reliability. Using GIS, the entire electrical network of a region can be overlaid on a satellite image or a vector-based map, providing ability to zoom, resize and scroll (Meehan, Brook, and Wyland 2012). Thus, efficient management of assets, much quicker faults identification and effective expansion of networks under constraints can be achieved.

For example, zones of influence or exclusion zones can be precisely defined by using some GIS tools (Erase, Union, etc.), and subsequently the route of the transmission lines in the proposed area can be easily drawn (Ormsby, Napoleon, and Burke 2004; Routsis 2011). Combination of mapping electricity networks, RES potential, existing infrastructure, e.g. roads, along with mapping constraints, can assist in both efficient siting of additional RES installations and maximisation of the corresponding benefits (Hatziargyriou et al. 2007). GIS tools are often combined with commercial power system analysis software, such as the PowerWorld® simulator, as described in Section 4 of this paper.

Based on these characteristics, the use of GIS for siting PVs within a sustainable community can be an ideal solution for meeting all the requirements described above. The scope of this paper is to present a methodology, using GIS software, for designing a PV installation specified to meet a predetermined percentage of the local demand. A special type of such a community is a University Campus. The implementation of a sustainable campus can provide additional benefits for educational and research activities. Such actions are not uncommon, either in the USA, where the Sustainable Campus (2012) initiative promotes energy efficiency and RES utilisation within Campuses, or in Europe, such as the TU Delft (2012) Green Campus action. More and more universities and colleges have invested on RES, as recent reports describe it (Phillips 2008) as part of either their efforts in cost and emissions reduction or their research activities (Kozman, Reynolds, and Lee 2011). Recently, the Administration of the Technical University of Crete (TUC) has adopted a similar initiative for energy saving and RES power production in the University Campus.

In this case study, it is assumed that 20% of the TUC Campus electricity demand is met by PVs. The most appropriate installation area, in terms of PV production and minimisation of erection works is suggested. Additionally, the impact on the distribution grid within the campus is also studied. For the purpose of this study, the ArcGIS® 10 for desktop PC is used, which is a complete system for designing and managing solutions through the application of geographical knowledge. The ArcGIS® Desktop is available in three versions, each intended to meet the needs of many different users. Each version includes a set of applications, such as ArcMap, ArcCatalog, ArcToolbox, ModelBuilder.

The structure of the paper is as follows: in Section 2, an outline of the methodology is provided while information on the consumption of the Campus is presented in Section 3. Sizing of the PV installation is computed in Section 4. Based on this sizing, the procedure to identify the most appropriate location to place an entire PV park as a single installation (not distributed on the buildings), by the use of GIS tools, is described in Section 5. In Section 6, the feature of GIS to interface with various network simulation programs, such as the PowerWorld® Simulator, is exploited, in order not only to study the load flow within the Campus and evaluate the PV impact, but also to propose the most appropriate cabling and the most favourable position from the network losses point of view. Conclusions are drawn in Section 7.

2. Methodological steps

The steps followed for siting a PV inside a sustainable community are summarised below and are described in detail in the following sections. An illustrative flow chart for this methodology is shown in Figure 1.

(1) *Sizing of the PV installation*. It is based on the solar radiation potential and the desired production level. If the latter is a fraction of the demand, as in this case study, the monthly demand of the campus should be also known. It is strongly advised that at least some energy efficiency measures are taken into account. Thus, either the RES fraction will be increased or the installed capacity for the same fraction will be decreased.
(2) *Determination of the most appropriate site(s) for installation within the community*. The procedure in Step 1 can provide information not only for the electrical but also for the physical sizing of the installation. Such information should be combined with the digital map of the community along with user-defined constraints, like areas to be excluded, distances from obstacles or contour lines, exploiting some GIS features as described in Section 5. If a GIS map for the area under study is not available, a GIS map can be built using the map of the campus, on which the contours, the roads, the buildings and other land uses can be digitised manually. Topographic information from CAD files or other available sources could be very useful. Compatibility with other urban-planning features and layers is desirable but not mandatory for such a study. Thus, the most appropriate area or areas for installation can be defined, as described in Section 5.
(3) *Assessment of distribution system impact*. Having the most appropriate sites for installation resulted in Step 2 above, analysis of the distribution system impact is performed. This is essential, in order to identify the most economical cross-section of the interconnection cable, complying also with the technical regulations. If more than one candidate areas for PV installation within the campus exist, this step identifies the most suitable one, based, for example, on the annual production losses minimisation.

3. General information about the site under consideration

The Campus of this case study is located at Akrotiri peninsula, 7 km northeast of the city of Chania, Crete, Greece and extends over an area of 2.9 km^2. Within the Campus, four out of the five Academic Schools, given in Table 1, administrative buildings, the library, the main restaurant and the student dormitories are located.

Based on consumption measurements, the annual electricity consumption of the Campus reaches 4.13 GWh, corresponding to 0.89% of the annual electricity consumption of the Chania city substation. A large portion of this amount is consumed for heating and cooling since electricity-driven air conditioners are used for cooling in all buildings and electricity-driven heating is used

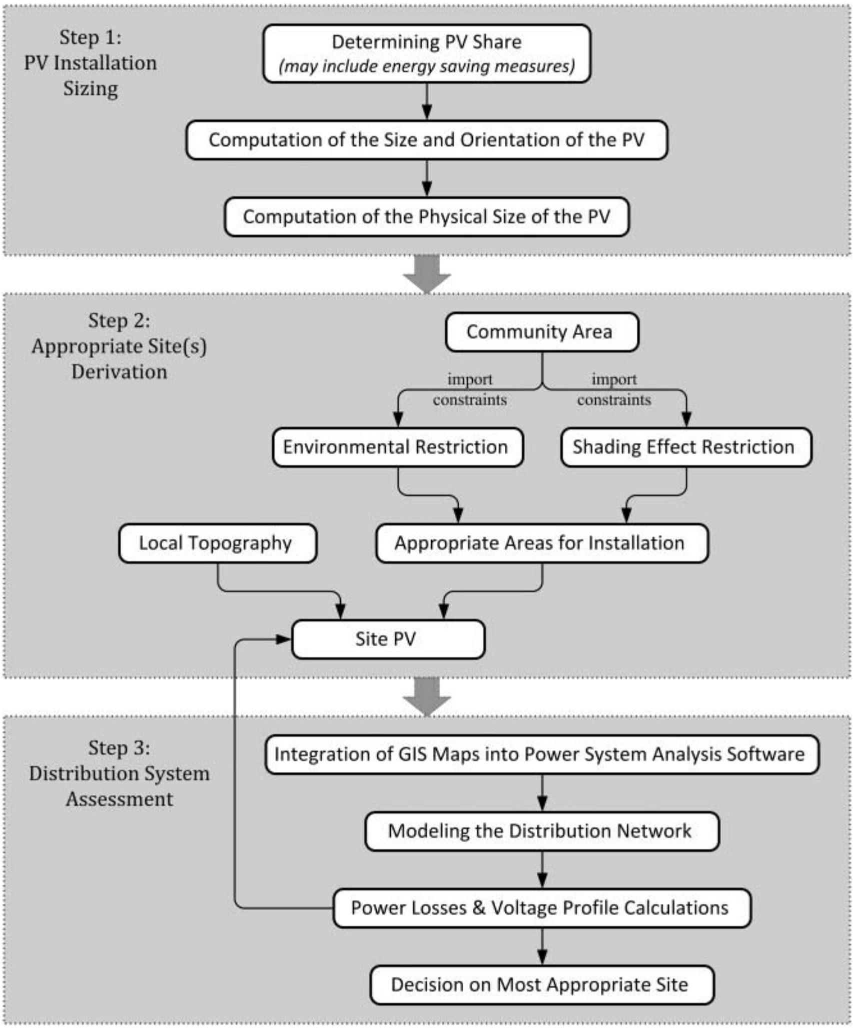

Figure 1. The methodology flow chart.

Table 1. The buildings in the TUC Campus with their electrical heating/cooling capacity.

Abbr.	Description	Electrical capacity for heating/cooling
DPEM	Department of Production Engineering and Management	402 kW
ECE	Department of Electronic & Computer Engineering	570 kW
ENVENG	Department of Environmental Engineering	100 kW
MRED	Department of Mineral Resources Engineering	250 kW
DOR	Student Dormitories	–
RESTAU	The restaurant & Library complex	20 kW

in half of them (Pafilis 2011). The installed capacity of electrical cooling/heating per building complex is also given in Table 1.

It is estimated that approximately 902.2 MWh annually are consumed for heating and cooling purposes, representing, 21.83% of the Campus electricity consumption. For the ECE building, during a hot morning in September 2012 with high humidity and temperature, cooling accounted

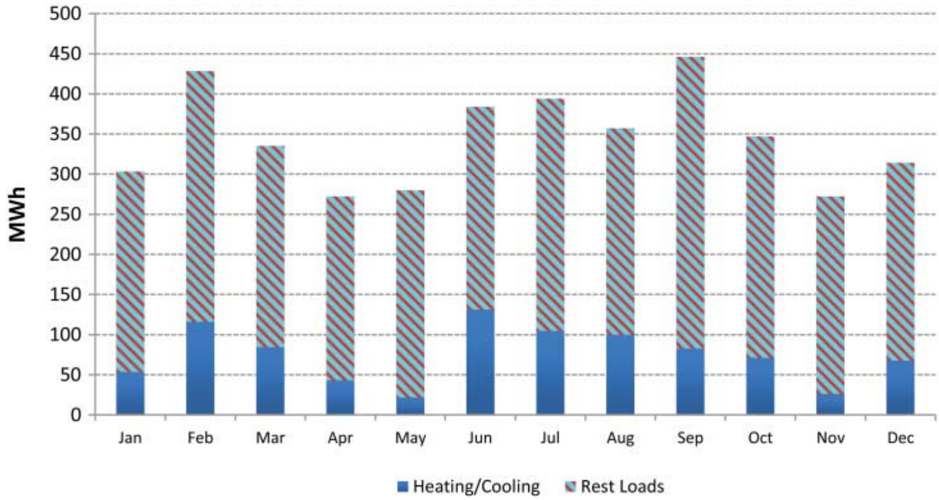

Figure 2. The electricity demand (MWh) of TUC as allocated to end-uses.

for 71.3% of the demand (Vavouranakis 2012). Increased demand is strongly correlated to the heating/cooling demand and occupancy in the buildings. Figure 2 shows the heating/cooling portion of the demand for each month. It can be seen that during February, September, June and July, due to increased educational activity (e.g. exams and classes) and increased heating/cooling needs, the demand is much higher compared with April, May and November when external conditions are milder. Low consumption in August is due to summer vacations.

4. Sizing of the PV park

Fulfilling the Commitments of Greece for the Kyoto Protocol, under the Directive 2001/77/EC, 20% of the annual demand should be produced by RES. Under this objective, the simulation of such a penetration scenario for the TUC Campus using PVs is proposed here. Based on actual measurements performed within the Campus (Papadakis, Koutroulis, and Kalaitzakis 2005), the wind potential is not very favourable but the solar potential, as in the whole Crete, is very high. The average daily solar irradiance is estimated at 4.74 kWh/m^2, reaching an average of 7.3 kWh/m^2 during the summer period, when the cooling demand is rather high.

The appropriate sizing and orientation of the solar park was computed using the HOMER® software, a simple but powerful tool for designing PV installations. Based on the electricity consumption mentioned above and the solar radiation data from the Campus, the behaviour of a grid-connected PV park is simulated, comprising crystalline panels of 13.5% efficiency and DC/AC converters with 93% efficiency, under various installation angles. Taking into account the above data, an installed capacity of 455 kW, with 31.5° inclination angle, φ, with respect to the horizontal level, 0° azimuth angle and 39% ground reflectance, e.g. light-coloured sand is sufficient to produce 826 MWh annually and thus meet the requirements as shown in Figure 3.

Regarding the space required for the installation and assuming that the installed capacity consists of 2600 modules of 175 W peak-power each, the park splits into two partitions of 1300 modules each. Erection of the panels depends on the inclination angle with respect to the horizontal level, φ, and the slope of the terrain selected, δ. Details such as the installation PV height, H_p, and the land length required, L_p are illustrated in Figure 4.

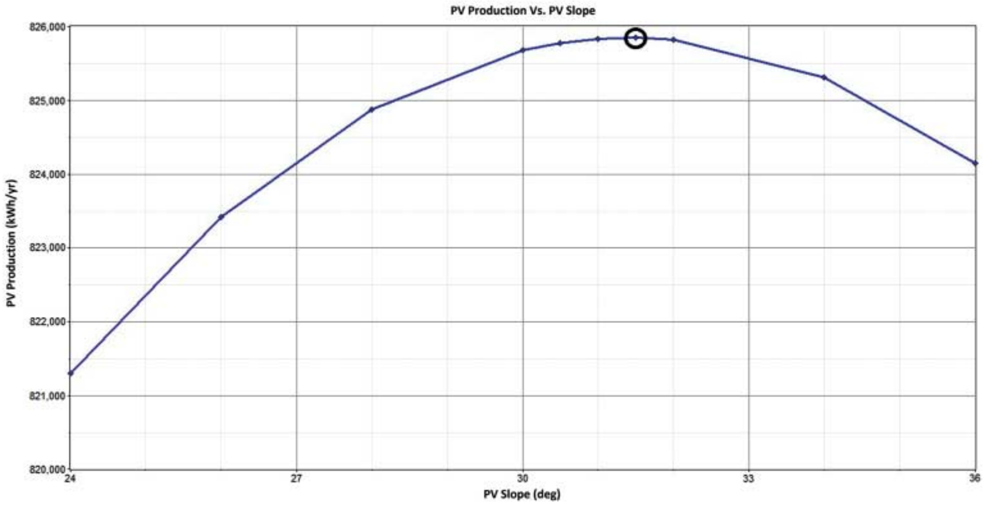

Figure 3. Selection of the optimum slope based on HOMER® simulations.

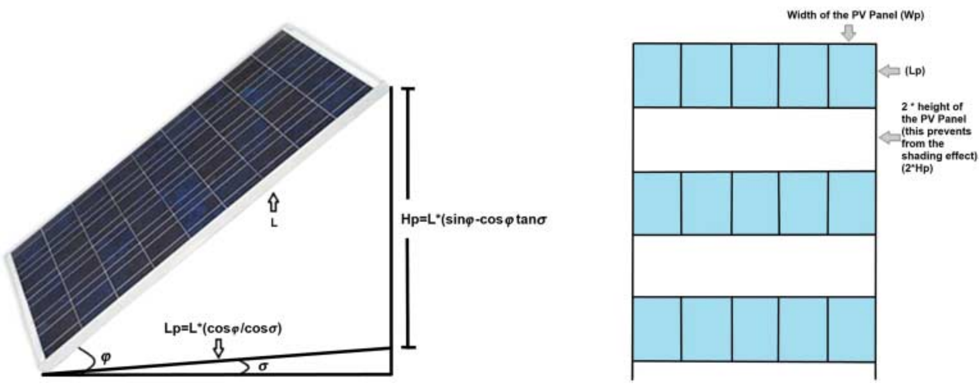

Figure 4. The dimensions of the PV panel (left) and the layout of the PV park (right).

Each partition consists of 65 parallel rows of 20 modules each, in series. In order to avoid shading between the parallel rows, the minimum distance between two successive rows is considered to be equal to $2 \times H_p$. Therefore, each partition's width is $20 \times W_p$ and its length is $65 \times (L_p + 2 \times H_p)$ (as described in Equations (1) and (2)). Between these two partitions, a 2 m width corridor is assumed. A typical layout of the park is also shown in Figure 4.

$$\text{Width} = 2 \cdot (20 \cdot W_p) + 2, \tag{1}$$

$$\text{Length} = 65 \cdot (L_p + 2 \cdot H_p). \tag{2}$$

Based on Equations (1) and (2), the dimensions of the PV park, when the slope angle is $\delta = 0°$ and $\varphi = 31.5°$ yield as Width $= 41.6$ m and Length $= 213.2$ m. This is the maximum required length for this installation and is used for our initial analysis.

5. Determination of the most appropriate area for installation

Before selecting the final installation site, the most appropriate location within the community area, here Campus, should be defined based on GIS maps. Throughout the study, the Greek National Coordinate System is used. Any additional necessary information available in CAD files was converted accordingly to that system.

In order to do so, certain criteria or restrictions in this area should be met, aiming at the most efficient operation of the PV park (Hofierka and Suri 2002), the protection of the environment, the protection of archaeological areas, etc. (Charabi and Gastli 2011). In our case, two restrictions are considered (Routsis 2011):

5.1. *Shading Effect*

A total or partial shading, leads to inefficient operation of the PV panels. Partial shading can also cause overheating and damage the PV panel (hot spot effect). For this reason, the distance between any PV panel and any barrier (building, parking, etc.) should be at least twice the height of the barrier, which, in this case, may be one of the buildings inside the campus.

5.2. *Environmental restrictions*

The second criterion aims at the protection of the environment (Carrion et al. 2008). The area where the PV park will be installed has to comply with all environmental constraints. The legal framework concerning solar energy installations defines that the installation of PV power parks rated from 150 kW up to 2 MW capacity in areas characterised as NATURA 2000, National Parks, traditional villages and archaeological sites is generally restricted (Law 2742/99; Giannakourou 2005) and special provisions are applied according to the legislation in such case, e.g. Law 3851/2010, Gazette 583/2011. Even though inside the TUC Campus there is no such a restriction, reducing olive trees plantation in the Campus was not considered as a permissible option. In other communities this may be an issue, since, for instance, in Greece installation of RES in high productive farming land is not allowed (Law 3851/2010, Official Gazette 1528/7.9.2010). GIS tool can identify such user-defined, usually based on local legislation, restrictions as well.

Having calculated the unsuitable areas resulted by each restriction for siting the PV park (Figure 5 and 6), the Union operation of the ArcGIS® tool, is used to calculate the final restricted area for the PV park installation (Figure 7). Then, using the Erase operation of the ArcGIS® tool, the final suitable area for the installation of the PV park is computed (Figure 8).

The final position of the solar park is determined taking into account the criterion of minimum supporting structures required, which applies for south-oriented areas. In order to meet this criterion, contour lines for south-oriented areas are used. Due to the fact that the TUC Campus is not inclined to the south, additional erection constructions would be required increasing the installation cost. Therefore, having the final suitable area for the PV park installation, and considering the above criterion, the solar park is positioned in the location shown in Figure 9. The height difference (rise) is 17 m over a 197 m run, leading to a slope angle $\delta = 4.93°$. The final length of the park is 188.23 m.

6. Assessment of the distribution grid impact

Using the GIS application along with the Power World® simulator, the impact of the PVs operation on either medium voltage (MV) or low voltage (LV) distribution grid can be assessed. For small

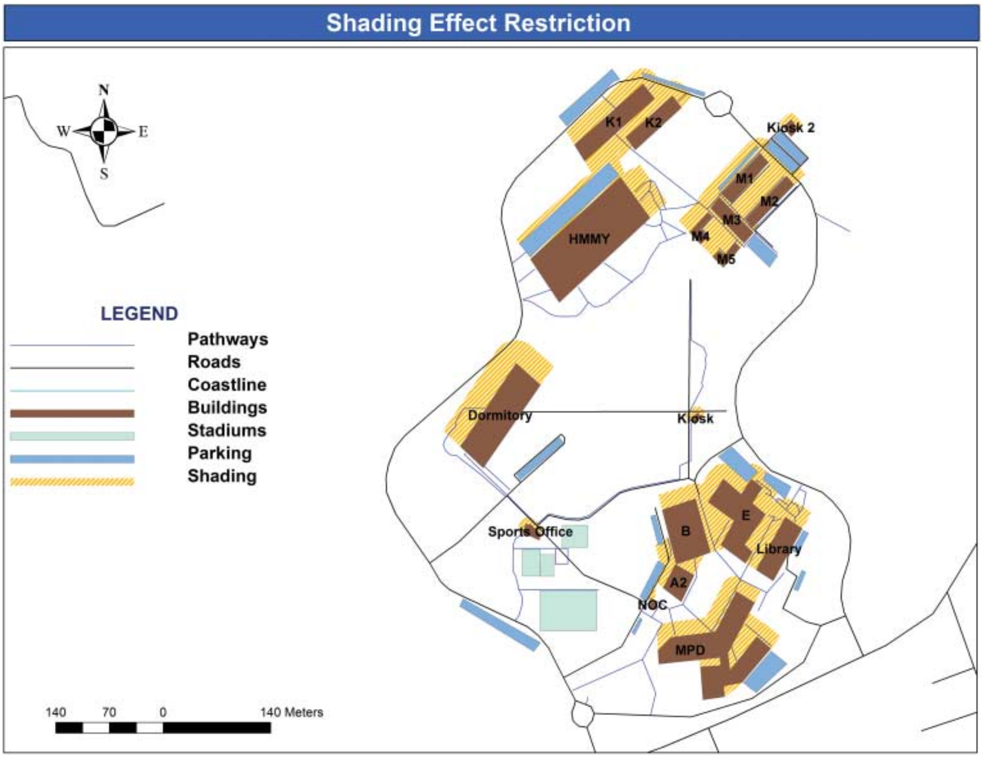

Figure 5. Map of restricted areas due to shading.

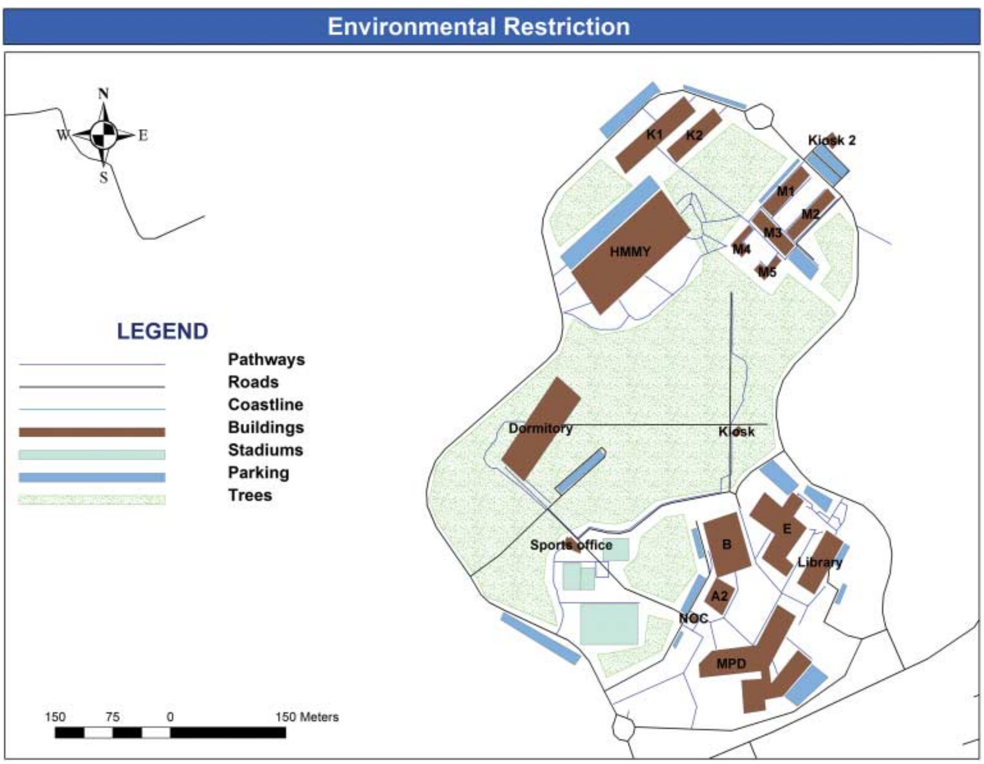

Figure 6. Map after applying the environmental restriction filter.

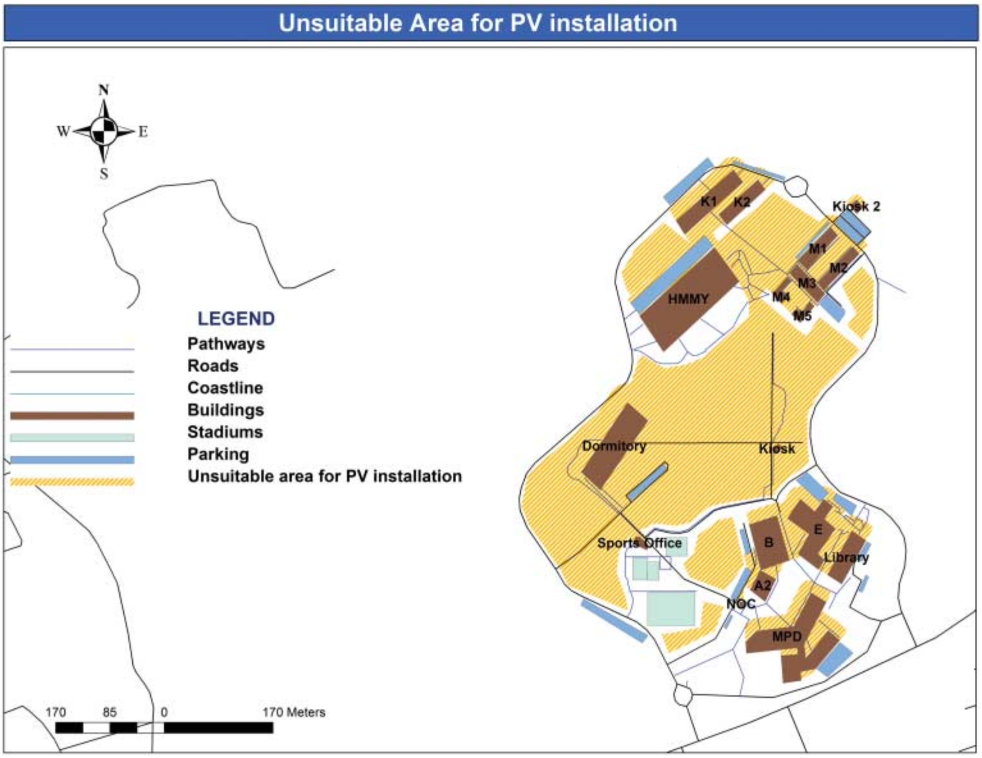

Figure 7. Map of unsuitable areas for PV installation.

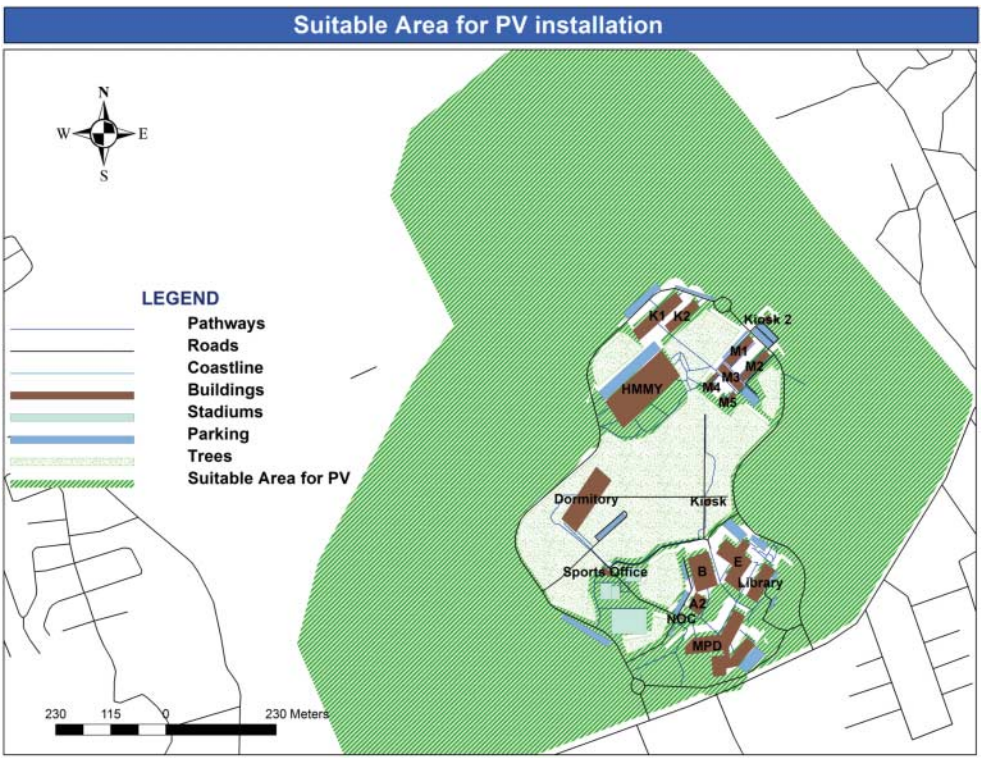

Figure 8. Map of suitable areas for PV installation.

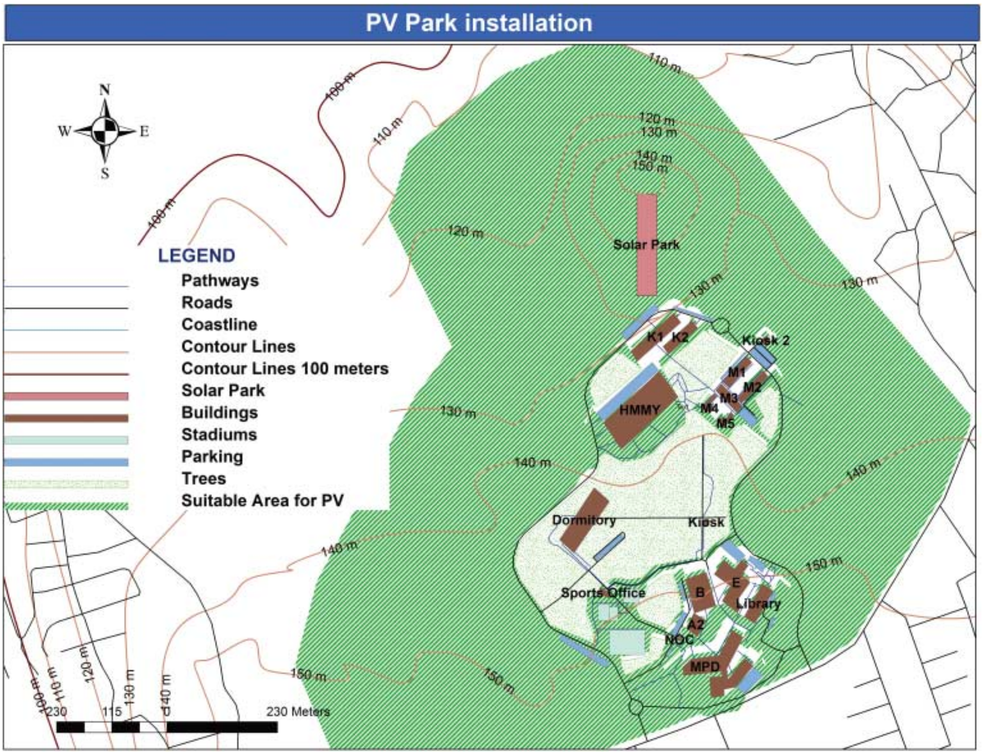

Figure 9. Map of the proposed PV park installation site including contour lines.

communities, there is usually one PCC where MV is transformed to LV. In larger areas with higher consumption, like inside the TUC Campus, MV is utilised. First, the steps for integrating the GIS maps into the Power Simulator environment are described. PowerWorld® (2012) Simulator is an interactive power systems simulation package designed to simulate power systems operation on a time frame, ranging from several minutes to several days. Two additional features of this software are: (a) it is shareware for networks up to 12 buses, as in our case, and (b) it is compatible with GIS softwares like the ArcGIS® 10.

6.1. *Integration of GIS maps with the power system analysis software*

The combination of GIS and power systems analysis software enables the examination of the PV operation impact on network losses, overload of the lines and the voltage profile of the buses considered. Some of the GIS-related features of the PowerWorld® Simulator include:

(1) Direct data exchange, in shape file format (.shp), from the GIS to the PowerWorld® Simulator and vice versa.
(2) Latitude/longitude coordinates for bus and substation objects can be specified; these objects can be automatically inserted into diagrams based on the coordinates.
(3) Background lines can be converted to transmission lines, substations or buses. This allows importing transmission elements as ESRI shape file data, and then converting the imported drawing objects to modelled system objects.
(4) Borders can be automatically inserted from the PowerWorld® border library or from user-defined border files.

Table 2. Buses description.

Bus	Map symbol	Description
1	DPEM bus	DPEM, RESTAU, DOR
2	ECE, ENVENG, MRED bus	ECE, ENVENG, MRED
3	Slack bus	PCC
4	PV	PV installation 20 kV
5	PV Low voltage	PV installation 0.4 kV

Taking into account the first feature mentioned above, all GIS data are input to the PowerWorld® Simulator and their display, according to the user preferences, is specified. The shapes of the descriptive data remain intact during this procedure. The buildings have been grouped in electrical buses as presented in Table 2.

6.2. *Modelling the distribution network*

Based on Figure 10, two load buses are considered: one for the DPEM, DOR and RESTAU and the other common for the rest of the TUC buildings, all of them at 20 kV. Bus No. 3 is the PCC with the Distribution Grid of the Chania district at 20 kV. The PV is connected to bus No. 5 and then via a 630 kVA transformer with transformer ratio 0.4/20 kV featuring 1% resistance and 4% reactance to bus No. 4. From there, via an MV distribution line whose cross-section is the result of the simulations is linked to the PCC. This complies with the Distributed Generation interconnection practices described by Papathanassiou (2005).

For connecting the substation with the two buses (1&2), copper wires are used with a cross-section of 16 mm^2. The ohmic and inductance impedances are 1.26 and 0.44 Ω/km, respectively. The maximum current that the line can withstand is 50 A, while the maximum load of the line is 1.732 MVA. Once the data from ArcGIS® have been transferred to the PowerWorld®, the *Insert Measure Line* command of the PowerWorld® is used for the calculation of the distances among the interconnected nodes.

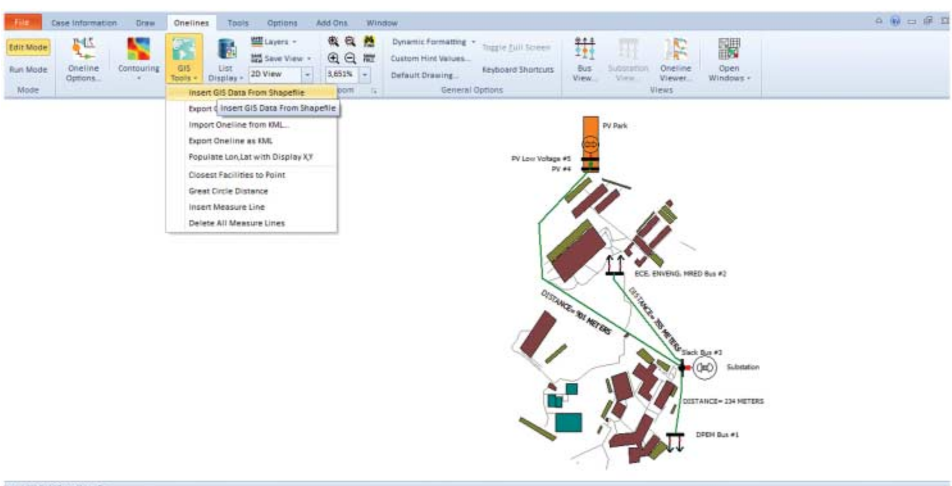

Figure 10. GIS data input to PowerWorld® simulator.

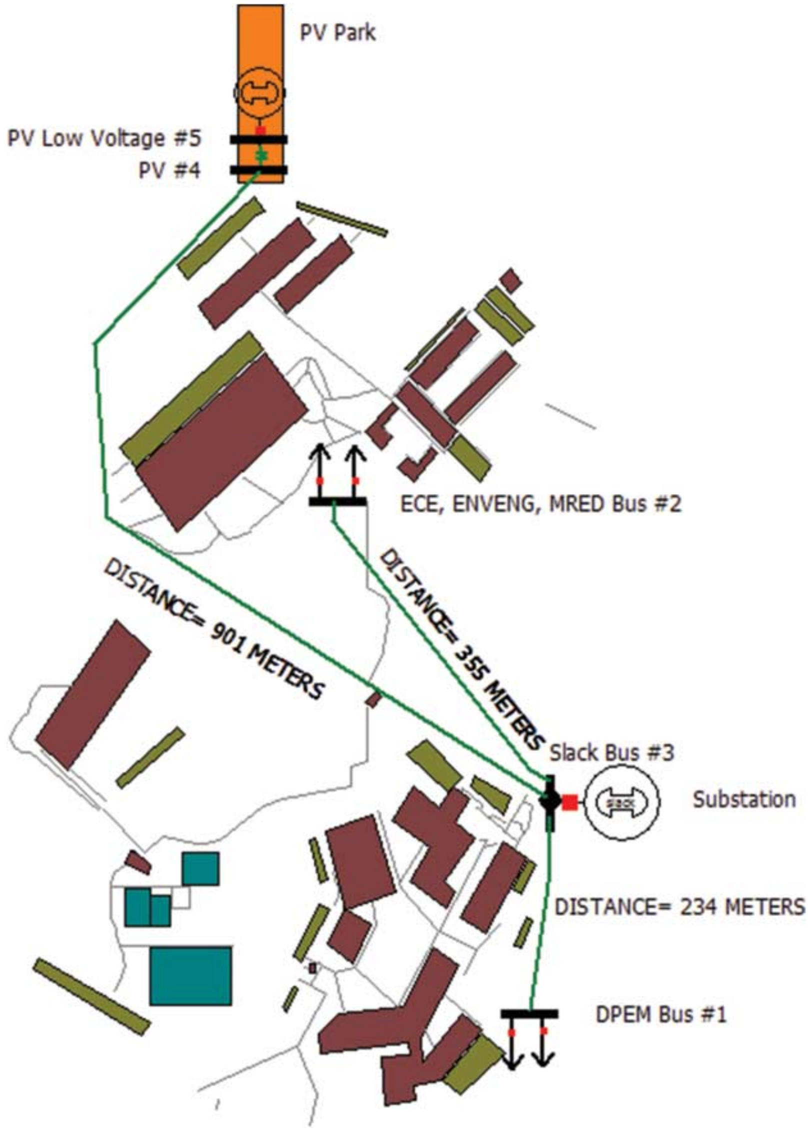

Figure 11. The distribution network of the TUC.

After the insertion of the data, the network under consideration has the form shown in Figure 11. The distance between the buses is also shown, e.g. the cable 1–3 length is 234 m, and the cable 2–3 is of 355 m.

The hourly demand of the Campus is estimated based on typical curves and monthly demand measurements. Since the heating/cooling demand of the building is rather high and follows typical patterns, two loads for buses 1 and 2 are considered: the load for electricity and the load for heating/cooling. The separation of the total TUC demand into these two portions is shown in Figure 12 for the summer day with the maximum power consumption on the left and for a winter day on the right.

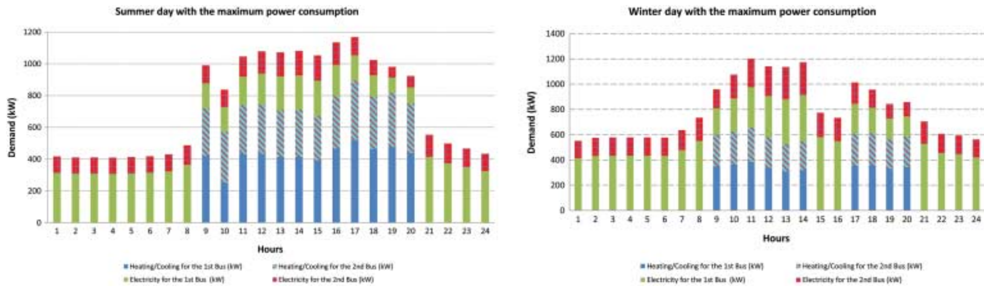

Figure 12. Distribution of demand for the summer and winter day with the maximum demand.

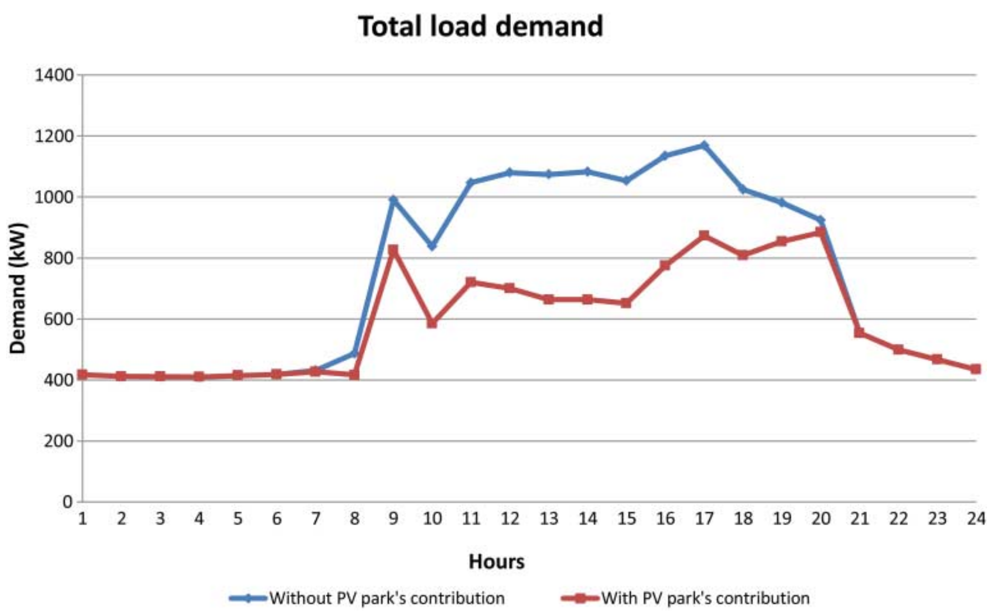

Figure 13. Total load demand with and without PV contribution.

6.3. *Simulation results*

Regarding the cross-section of the line 3–4, two values are examined in order to identify the best configuration, when the ArcGIS® data are integrated into the PowerWorld® simulator. Thus, the impact on network losses, when using either a 6 or a 16 mm^2 copper wire cross-sections, are examined, respectively.

The annual losses for the copper wire with a cross-section of 6 mm^2 are 499.6 kWh, or 0.07% of the production, while the annual losses for the copper wire with a cross-section of 16 mm^2 are 170.6 kWh and the respective percentage of production loss is 0.024%. Taking into consideration the installation cost (the cost of purchasing the cable, 7 €/m and 13 €/m, respectively) and the operation cost (the cost from the annual losses) for each cable, the copper wire with a cross-section of 6 mm^2 proves as the most appropriate solution. The ohmic and inductance impedances are 3.69 and 0.94 Ω/km, respectively. The maximum current that the line can withstand is 25 A, while the maximum load of the line is 0.866 MVA.

Additionally, the power drawn from the upstream distribution grid with and without the PVs is shown in Figure 13, taking also into account the losses before and after the PV installation.

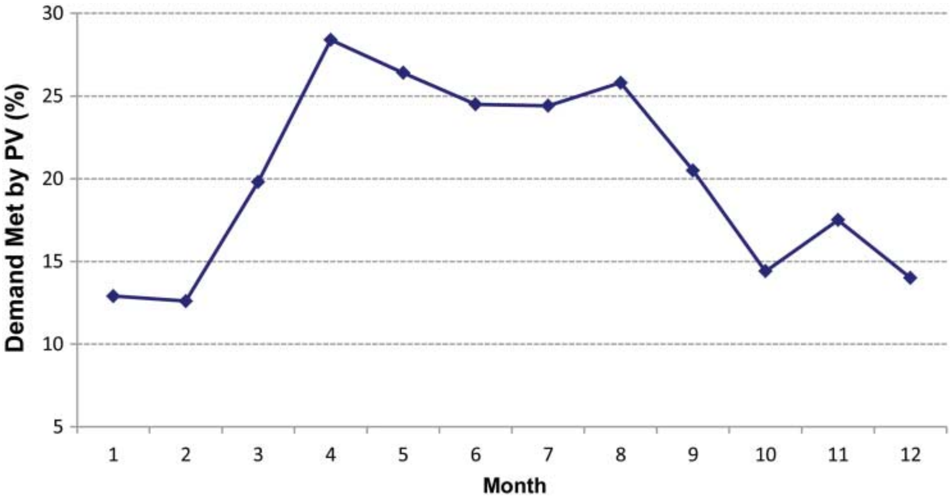

Figure 14. Monthly PV penetration.

During summer, the peak reduction can reach 27.66%, and the peak demand moves to evening production. The daily PV energy penetration is 19.5%. The impact on monthly energy balance is shown in Figure 14.

As observed in Figure 13 curves, the production of the PV is high around the mid-day hours. During the summer period, the cooling demand is also high around the same hours. Thus, the building management systems (BMS) could be scheduled accordingly, as to exploit the maximum available energy from the PV system.

Regarding the voltage profile, there are not any significant deviations noticed from the original operation, mainly due to the interconnection of the PV with a dedicated distribution line. A new high voltage/medium voltage transformer is about to operate shortly in the congested distribution grid of the Akrotiri area, thus the PV production is expected to greatly alleviate losses in the grid. This can be one of the benefits of organising distributed generation, like PVs, into Micrognids (Pecas Lopes et al. 2007; Vasiljevska, Lopes, and Matos 2012), as the one configured at TUC Campus with the suggested installation. Such a study can be easily incorporated in the proposed model, provided that the lines data are available.

7. Conclusion

This paper presents a simple but efficient methodology to site a PV park installation as part of a sustainable community, exploiting GIS tools. The importance of using such tools is significant due to competing end-uses for building, recreational activities and infrastructures. A variety of constraints are expected when planning a PV installation in inhabited areas, such as shading avoidance, slope of the ground, existing plantation and distances from the upstream distribution grid. Therefore, GIS software, capable of taking those constraints into account and utilising techniques described in this paper, can provide substantial aid to the siting of a PV, as derived by this case study at TUC Campus. An additional feature of GIS software is its compatibility with Power System analysis softwares, i.e. the ArcGIS® and the PowerWorld® Simulator. This advantage enables the PV planners to assess the potential impact of the installation under design on the distribution grid and select the most appropriate PV park connection line cross-section.

Moreover, in case of various potential siting positions, the one with the lowest losses can be selected.

Clearly, the compatibility of powerful tools, like GIS and power system analysis software is an essential aspect, not only for PV but also for RES planning in general, as referenced in the related bibliography as well.

Although a central Geodatabase of the campus was not used in this study, and only the information necessary for implementing our study was stored in the GIS map, the use of a Geodatabase is recommended, especially if additional sustainability actions are foreseen. If a Geodatabase of the area is available, the information can be stored in it. Otherwise, the data of the proposed study can be incorporated into a future Geodatabase. More information on Geodatabase structure can be found in (Ormsby, Napoleon, and Burke 2004).

The PV installation itself is highly desired, especially for the reduction of the summer peak demand in communities with high HVAC load and increased number of visitors. Combination of PV installation with energy efficiency measures can bring about significant benefits for the end-users. Energy efficient measures may vary from limited cost actions, such as awareness campaign, to costly but more efficient upgrade of building envelope or even to the implementation of more intelligent control schemes (Apostolou et al. 2013) for the community's equipment. Monitoring the demand, and not simply checking the electricity bill, is of great importance in maintaining the sustainability of the actions.

Additionally, such a combination could additionally provide support to weak or congested surrounding grids, postponing the need for grid upgrade investments.

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