

Tanțău, Adrian Dumitru; Regneală, Horațiu; Coraș, Eliza Laura

Article

Layout design as a risk driver for energy efficiency of photovoltaic power systems

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Table of Contents

1	THE RELATIONSHIP BETWEEN ORGANIZATIONAL STRUCTURE AND MARKET ORIENTATION. AN EMPIRICAL APROACH TOMÁS CABELLO CABELLO, University of Seville, Spain MARÍA ÁNGELES REVILLA CAMACHO, University of Seville, Spain MANUELA VEGA VÁZQUEZ, University of Seville, Spain
48	EFFECTS OF E-BANKING ON GROWTH OF CUSTOMER BASE IN KENYAN BANKS BICHANGA WALTER OKIBO , University of Agriculture and Technology, Kenya ALI YATTANI WARIO , University of Agriculture and Technology, Kenya
64	THE PENETRATION OF BUSINESS INFORMATION SYSTEMS IN SMALL AND MEDIUM-SIZED ENTERPRISES IN ITALY AND HUNGARY: A COMPARATIVE STUDY SELENA AURELI, University of Bologna , Italy MASSIMO CIAMBOTTI, University of Urbino , Italy PÉTER SASVÁRI, University of Miskolc, Hungary
96	DETERMINANTS OF LOYALTY TOWARD BOOKING.COM BRAND RAQUEL DA SILVA E CRUZ, Instituto Politécnico de Leiria, Portugal ALZIRA MARIA DA ASCENSÃO MARQUES, Instituto Politécnico de Leiria, Portugal
124	LAYOUT DESIGN AS A RISK DRIVER FOR ENERGY EFFICIENCY OF ADRIAN DUMITRU TANȚĂU, Bucharest University of Economic Studies, Romania HORAȚIU REGNEALĂ, Bucharest University of Economic Studies, Romania ELIZA LAURA CORAȘ, Bucharest University of Economic Studies, Romania

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Layout design as a risk driver for energy efficiency of photovoltaic power systems

Adrian Dumitru Tanțău,

Horațiu Regneală,

Eliza Laura Coraș

Bucharest University of Economic Studies, Romania

atantau@fabiz.ase.ro

regnealahoratiu@gmail.com

eliza.paicu@yahoo.com

Abstract

This paper explores the existence of a correlation between the energy efficiency generated by photovoltaic power systems and the layout design of the photovoltaic panels, as well as the level in which the layout design acts as a risk driver for energy efficiency, in the context of solar energy.

Improved energy efficiency is the decisive response to the weight of the climate change, limited conventional energy sources and technological innovation challenges with the purpose of carbon emissions reduction. However, the dangers hampering energy efficiency form a field of study less explored in the specific literature. As a result, in this paper, we seek to address the energy efficiency issue on the background of photovoltaic power systems, by focusing our attention on the technological parameters that influence it: the layout design of photovoltaic (PV) panels.

Our methodology is based on a practical study performed over a period of one year on a photovoltaic field in Romania. The analysis was made with PV-syst software version 5.11., which helped us measure the photovoltaic system performance under three different variants, defined by the parameters that impact on the energy efficiency of the PV system. We have found that the generator inclination, the angle made by the panels shading horizontal distance and the distance between two consecutive rows of panels influence the power generated by the whole system, with direct effect on energy efficiency.

The results of our study can guide a photovoltaic power system to boost its energy efficiency, while reducing the technological risks residing in practical manipulation of technical specification. This paper will contribute also to the literature of energy efficiency in the context of highly sought renewable energies by aligning technical parameters with performance ratios in a risk management and efficiency framework.

Keywords: photovoltaic energy, energy efficiency, layout design, photovoltaic power system, PV panels

1. Introduction

At an international level governments are moving towards developing and implementing policies aimed at reducing carbon emissions across sectors of commerce and industry (Hurst, 2012) thus showing an increased awareness of the dreary future of the conventional sources of energy and the need to change the focus on the renewable energies. The stakeholders in the energy field agree that improved energy efficiency is a critical response to the pressing climate change, economic development and energy

security challenges that many countries face. Therefore, an amplified concern regarding energy efficiency is on the focus.

The increase of primary energy consumption and the emissions of green-house-gases coming from the use of fossil fuels have drawn the attention of public policy makers of most developed countries on industrial energy efficiency. In particular, within the European Union, the implementation of the so-called Directive “20-20-20” (i.e., 20% reduction in GHG-emissions, a share of 20% of energy produced by renewable energies and 20% improvement in energy efficiency) (European Council, 2009), will make the implementation of cost-effective energy efficiency measures within industry really of fundamental importance for firms’ competitiveness.

The literature provides a wide range of studies regarding the role of market forces in delivering energy efficiency, and how market-based instruments play a central role in most national energy efficiency policies (Energy Efficiency Governance: Handbook, 2010), but a lesser attention was given to technical parameters that expand energy efficiency. Consequently, this study wishes to cover this gap in the literature by addressing the technical characteristics of photovoltaic power systems that drive efficiency and their power to overcome the risks they might generate. We seek to prove that an optimal design of PV panels positively influences the energy efficiency of the whole PV system.

The majority of the studies regarding PV efficiency target the capital cost reduction as major source for competitiveness. However, in this study we address the energy efficiency issue by approaching a technological variable: the layout design of PV panels in a large PV plant (>1MWp) where due to large numbers of rows the technological variable has a great impact in the production of energy.

Through this research, we endeavour to investigate how the most consistent way to improve the energy efficiency of a photovoltaic power system is to mathematically determine the optimal influences of geometric conditions of the sun and designing factors (the generator inclination, the angle made by the panels shading horizontal distance and the distance between two consecutive rows of panels) to the performance of a PV system. In order to do that, we first perceive these parameters as risk drivers for energy efficiency in order to finally determine how their optimal approach leads to an increase of performance of the whole system. We also examine how a better design approach helps improving energy efficiency and reduce the cost of ground source-based energy system.

This article describes a methodology to compare the energy benefit that may result from optimizing the layout design of the photovoltaic panels, in scope of creating maximum possible energy for the given conditions. The methodology used is based on a practical study performed over a period of one year on a photovoltaic field in Romania. The analysis was made with PV-syst software version 5.11., which helped us measure the photovoltaic system performance under different variants, defined by the parameters that impact on the energy efficiency of the PV system. This research was facilitated by one author of this study who is the CEO of a company active in the development, design and construction of photovoltaic electric stations, which is the biggest producer of Romanian PV and supply of electricity.

Consequently, there are two objectives of this paper. The first objective is to describe a methodology to compare the energy benefit that may result from optimizing the layout design of the photovoltaic panels, in scope of creating more energy efficiency. The second objective is to explain how the layout design of PV panels acts as a risk driver for the energy efficiency of the whole PV system.

The structure of the paper is as follows: we first provide a theoretical overview on solar energy risks, the energy efficiency of photovoltaic power systems, PV power systems, in order to explore the background of our research, and then we set our analysis on the Romanian photovoltaic market. After presenting

our methodology of research we next focus on our practical results which prove that the layout design of the PV panels acts a risk driver for energy efficiency, validating the data using other existing models.

2. Theoretical background

2.1. PV power systems

Photovoltaic technology is characterized by high capital costs and zero fuel costs. This is unlike conventional technologies that typically require high fuel costs and a low initial investment (Abulfotuh, 2007). A photovoltaic power generation system consists of multiple components like cells, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output. These systems are rated in peak kilowatts (kWp) which is an amount of electrical power that a system is expected to deliver when the sun is directly overhead on a clear day (Parida et al., 2011).

Photovoltaic systems are growing in popularity as source for electrical energy. The demand for PV systems has grown by an average of 30% per year over the period 1990–2010 (Solar Energy Market Growth-Global Market Size, 2011), on the background of cost reduction and prices. This decline in cost has been driven by economies of manufacturing scale, manufacturing technology improvements, and the increasing efficiency of solar cells (Solar Energy Market Growth-Global Market Size, 2011).

There are two main types of photovoltaic system installations: (1) on-grid systems and (2) off-grid systems (Module Pricing, 2012). On-grid systems are connected to the utility power distribution system, i.e., the power grid, and are used either to supplement utility power or to supply power to the power grid. Off-grid systems are not connected to the power grid and are typically used as a stand-alone source of electrical energy in remote areas. On-grid systems accounted for 96% of the worldwide PV installations in 2009 (Solar Energy Market Growth-Global Market Size, 2011) (Yuventi, 2012) and are the focus of our study.

The PV modules in a centralized system are usually first connected in series to achieve a sufficiently high voltage; the individual strings are then connected in parallel to allow the system to generate more power. The centralized system only has a central MPP tracker for the whole PV array. The practical output power of a centralized system can be obtained by solving the power–voltage (P–V) characteristic of the PV array (Liu and Duan, 2012).

A PV system generates electrical power from solar radiation incident on solar cells. PV modules consist of many solar cells connected using conductive metal strips. The quantity of cells and the way that they are electrically connected determines the electrical characteristics of the corresponding module (Yuventi, 2012).

Photovoltaic conversion is the direct conversion of sunlight into electricity without any heat engine to interfere. Photovoltaic devices are rugged and simple in design requiring very little maintenance and their biggest advantage being their construction as stand-alone systems to give outputs from microwatts to megawatts (Survey of Energy Resources 2007, World Energy Council).

The term photovoltaic literally means light producing electricity. Turning photo (light) into voltaic (electrical current), is the basis of how photovoltaic panels work. So, photovoltaic efficiency refers to how efficiently a solar cell or solar module produces electricity. Photovoltaic efficiency describes the efficiency or conductivity of solar panels – the percentage of radiation (sun) energy that can be converted into electrical energy (Whitburn, 2012).

In PV power systems, efficiency is strictly related to sustaining a prolonged lifetime of the PV system, through maintenance, innovation and technological improvement (Abulfotuh, 2007). Since efficiency is measured in terms of available resources generating higher profits or constant revenues with lower amounts of resources, the financial dimension is crucial for measuring the cost-effect duo in the solar energy industry. Access to finance is currently a big concern, since PV systems have high initial costs even their efficiency is proven in the course of their lifetime. In developing countries, markets have benefited from the steady decline in solar PV prices, but they have also been stimulated by continued multi-lateral and bi-lateral development aid. This has meant that solar has been an enabling technology for developmental programs for education, clean water, and healthcare (Solar Energy Market Growth-Global Market Size, 2011).

Depending on regional sunlight condition, solar power is usually not competitive enough compared to fossil fuels. To achieve this requires further reductions in manufacturing and installation cost of solar panels or improvements in PV design systems (Abulfotuh, 2007). One approach for achieving greater efficiency in solar energy production is to analyze a specific improvement in PV design systems, respectively the layout design of PV panels.

Two kinds of influencing factors would have effects to the performance of PV system. The first kind is geographic conditions, such as local weather condition, altitude and latitude. The geometric conditions cannot be changed and determine the optimum performances can be gained by PV systems. Pre-designing should be carefully taken to ensure that the geometric conditions are suitable for PV system. The second kind focused on in this paper is designing factors, such as system selection, building's orientation, installation location, area of PV panel and tilt angle. These influencing factors can be analyzed carefully to obtain an optimum performance of PV system (Shi and Chew, 2011).

The power output of PV module was characterized depending on incidence angle and the orientation. Song et al. (2008) analyzed the performances of PV modules by using a full-scale mock-up model in South Korea. It was obtained that: (1) the PV module with a slope of 30°, facing south, provided the best power performance according to an annual power output, producing about 2.5 times higher power output than that with the vertical module; and (2) the increased inclined slope of the PV module resulted in reduced solar energy transmission, which producing a significant reduction of power output for the PV module with a slope over 70°. Yoon et al. (2011) experimentally gained that energy saving can be improved up to 47% by changing orientation and its shading effect originated from the building mass. Sun et al. (2011) presented that optimum performance of buildings in Hong Kong gained by a tilt angle from 30° to 50° and orientation of south or southwest. The efficiency of PV module is also dependent on its surface temperature. Experiments taken by Park et al. (2010) showed that power decreased about 0.48%–0.52% per the 1°C increase of PV module temperature. Also they suggested that property of the glass used for the module affects the PV module temperature followed by its electrical performance. Fossa et al. (2008) obtained that proper selection of separating distance and heating configuration can noticeably decrease surface temperatures (Shi and Chew, 2011).

For PV, electricity generation is maximized when the modules are normal (i.e., perpendicular) to the incident sunlight. Variations in the sun's angle that are due to the season and time of day reduce the capacity factor of fixed-orientation PV systems. This can be mitigated, in part, by tilting stationary PV modules to maximize annual sunlight exposure or by incorporating one- or two-axis solar tracking systems, which rotate the modules to capture more normal sunlight exposure than is possible with stationary modules (2010 Solar technologies market report).

Panels typically produce the most energy if tilted at an angle equal to the latitude of the location but system design economics may dictate a more cost optimal orientation. In addition, avoid any shade on

photovoltaic modules since shade on any single module can negatively affect the output of the entire array (U.S. Department of Energy Federal Energy Management Program, 2012).

In their paper, Liu and Duan (2012) presented an energy efficiency analysis method to evaluate the energy efficiencies of integrated photovoltaic systems with different power configurations. They have discussed the principles and performance of seven types of power configurations for photovoltaic systems and they presented the simulation results of each configuration under different partial shade and electrical parameter mismatch conditions to quantitatively evaluate their energy efficiencies. The authors built their simulation model of a PV module using the SABER software (Synopsys Saber Sketch, 2007). PV cells in a PV module are reverse-biased when they are shaded. If the reverse voltage is high enough, the shaded PV cells become a load and dissipate power due to the flowing avalanche current. Hence, some bypass diodes are included in the PV module to solve this problem. Normally one bypass diode is used to bypass 20–40 PV cells, therefore there are usually 1–3 bypass diodes in a commercial PV module. In order to simplify the analysis, the PV module includes only one bypass diode in the SABER model (Liu and Duan, 2012).

The quantitative evaluation of Liu and Duan (2012) shows that AC module and photovoltaic DC building module based system are two more potential solutions for integrated PV systems applications for its excellent anti-shading and anti-mismatch performances: ignoring the loss of the balance of system, the energy efficiency of AC module and DC building module based system is near 100%. A common shortcoming of them is that the converter efficiency is currently lower than the centralized inverter, and consequently the efficiency optimization of their converters is an important issue in the future research.

Woyte, Nijs, and Belmansa, (2003) evaluated the impact of partial shadowing on the array performance based on the monitoring result from a 5 kWp photovoltaic system, which consists of three independent subsystems (a central inverter, a string inverter, and a number of AC modules). Hussein, Ahmad, and El-Ghetany (2004) evaluated the impact of tilt angles and orientations on the annual performance of PV modules (mono-crystalline silicon type) based on a single diode model of PV modules. A statistical analysis method was proposed by Nagae, et al. (2006) to evaluate the output performance of the photovoltaic modules.

Another study was conducted by Houssamo et al. (2013), presenting an experimental comparison, under real solar irradiation, of four most used maximum power point tracking (MPPT) methods for PV power systems: Perturb and Observe (P&O) and Incremental Conductance, as tracking step constant, and improved P&O and Fuzzy Logic based MPPT, as variable tracking step. Using four identical PV, under strictly the same set of technical and meteorological conditions, an experimental comparison of these four algorithms was done. Following two criteria, energy efficiency and cost effectiveness, the comparison shows the advantage of use of a MPPT with a variable tracking step. In this work, energy efficiency is emphasized by tests performed in situ and based on operation during 9 h while other studies use as main criterion the maximum power during few tens of seconds. The principle criteria, which are taken into account for choosing the most suitable MPPT algorithm for PV power system, are maximum energy efficiency, calculation time, and simple implementation (Houssamo et al., 2013).

The MPPT algorithm enables to extract the maximum of power whatever the operating meteorological conditions, solar irradiance (g) and PV cell temperature (h). Since the earliest MPPT method published in 1960s, the authors counted over than fifteen MPPT methods, which be classified following to MPP process seeking into indirect and direct method (Salas et al., 2006). The indirect methods, such short-circuit and open-circuit methods, need a prior evaluation of the PV panel, or are based on mathematical relationships or database not valid for all operating meteorological conditions. So, they cannot obtain exactly the maximum power of PV panel at any irradiance and cell temperature. On the other side, the

direct methods operate at any meteorological condition. The most used methods among them are: Perturb and Observe (P&O), Incremental Conductance (INC), and Fuzzy Logic (FL) based MPPT (Houssamo et al., 2013).

However, quantitative evaluations exploring existence of a correlation between the energy efficiency generated by photovoltaic power systems and the layout design of the photovoltaic panels are scarce and thus we seek to mathematically investigate the optimal influences of geometric conditions and designing factors (the generator inclination, the angle made by the panels shading horizontal distance and the distance between two consecutive rows of panels) to the performance of a PV system.

2.2. Energy efficiency of photovoltaic power systems

A simple definition of energy efficiency considers the relationship between how much energy is introduced into a process and the useful output that the process can generate (Patterson, 1996). Energy efficiency is the undepletable and fast-deployment resource we have in hand that will realize our energy security and stability objectives at a fraction of the cost needed to expand our resources (Abulfotuh, 2007). Renewable energy and energy efficiency reduce the risks associated with fuel price volatility and can facilitate an industrial boom, create millions of jobs, foster new technology, and revitalize the manufacturing sector (Bezdek, 2007).

Energy efficiency and renewable energy are said to be the twin pillars of sustainable energy policy. Both strategies must be developed concurrently in order to stabilize and reduce carbon dioxide emissions. Efficient energy use is essential to slowing the energy demand growth so that rising clean energy supplies can make deep cuts in fossil fuel use. A sustainable energy economy requires major commitments to both efficiency and renewables (Prindle and Eldridge, 2007). Energy efficiency is one of the most potent and cost effective ways of meeting the demands of sustainable development and lower fossil fuel dependency. Improvements in energy efficiency can be achieved either by decreasing total energy use or by increasing the production rate per unit of energy consumed (Salta et al, 2009).

Energy efficiency improvements refer to a reduction in the energy used for a given service or level of activity. The reduction in the energy consumption is usually associated with technological changes, but not always since it can also result from better organisation and management or improved economic conditions in the sector ("non-technical factors") (Energy Efficiency Governance: Handbook, 2010). In our study we focus on technological parameters that drive energy efficiency.

Improving energy efficiency will have two major benefits: supply more consumers with the same electricity production capacity and slow down the electricity demand growth, and reduce the investment needed for the expansion of the electricity sector (World Energy Council, 2008). Reducing energy use reduces energy costs and may result in a financial cost saving to consumers if the energy savings offset any additional costs of implementing an energy efficient technology. Reducing energy use is also seen as a solution to the problem of reducing emissions. According to the International Energy Agency, improved energy efficiency could reduce the world's energy needs in 2050 by one third, and help control global emissions of greenhouse gases (Hebden, 2006).

The Energy Efficiency Governance: Handbook (2010) highlights that the main drivers for pursuing energy efficiency are to reduce imported energy, to reduce domestic demand to maximize exports, to improve industrial competitiveness, to reduce production costs, to contribute to global challenges raised by the climate change, to recue indoor and local pollution. On the other side, the same source draws attention to the barriers to energy efficiency, structured in five large categories: market, financial, information and

awareness, regulatory and institutional, technical. Market barriers mainly refer to the fact that Market organization and price distortions prevent customers from appraising the true value of energy efficiency. Up-front costs and dispersed benefits, as well as the perception of complexity and riskiness of the investment, discourage the investors on the financial side. Lack of sufficient information on the part of consumers, to make rational consumption and investment decisions acts also as a significant obstacle. On the regulatory and institutional side, incentive structures encourage energy providers to sell energy rather than invest in cost-effective energy efficiency. The technical barriers to energy efficiency refer to the lack of affordable energy efficiency technologies suitable to local conditions and insufficient capacity to identify, develop, implement and maintain investments.

Energy efficiency improvement is often hampered by market, financial, informational, institutional and technical barriers (Energy Efficiency Governance: Handbook, 2010). In our research, we have narrowed down the focus on technical barriers to energy efficiency and we seek to prove that a technological specification of a photovoltaic power system has the strength to influence the energy efficiency level of the whole system.

In their study, Trianni and Cagno (2012) identified the most relevant barriers to energy efficiency and found that two major problems were the lack of capital and the knowledge mismanagement (lack of data or inappropriate information to support the energy efficiency decisions). However, the next ranked barrier, the lack of technical internal skills, points out to the focus of our analysis, the key technological factors that drive energy efficiency. Since knowledge is the most critical resource of a company, the ability to efficiently manipulate the existing technology and its parameters is a prerequisite of competence. In this study we focus on one specific attribute that creates the premises for efficiency or, as wee, might act as a risk factor in solar energy output: the layout design of the PV panels.

2.3. Photovoltaic energy risks

The continuous increase in the energy demand is driving to an increased attention to the efficiency and the environmental compatibility of power plants, which is now also devoted to renewable systems and not only to conventional fossil fired power plants.

We have found a large spectrum of risks affecting photovoltaic energy projects, which appear throughout the entire project lifetime: Construction risk (risk of property damage or liability stemming from errors during the building of new projects); Company risk (risk affecting the viability of the project developer, for example, risks related to key personnel, financial solidity and technical ability to execute on plans); Environmental risk (risk of environmental damage caused by the photovoltaic park including any liability following such damage); Financial risk (risk of insufficient access to investment and operating capital); Market risk (risk of a cost increases for key input factors such as labour or modules, or rate decreases for electricity generated); Operational risk (risk of unscheduled plant closure due to the lack of resources, equipment damages or component failures); Technology risk (risk of components generating less electricity over time than expected); Political and regulatory risk (risk of a change in policy that may affect the profitability of the project, for example changes in levels of tax credit or RPS targets. Also, this includes changes in policy as related to permitting and interconnection); Climate and weather risk (risk of changes in electricity generation due to lack of sunshine or snow covering solar panels for long periods of time); Sabotage, terrorism and theft risk (risk that all or parts of the solar park will be subject to sabotage, terrorism or theft and thus generate less electricity than planned) (Worren, 2012); the risks of handling of the equipment and the materials that are used for producing it (Thadani, 2011); the risk of release of toxic materials (silicon that is used on the panels is generated by mining

silicon dioxide and then subjecting it to intense heat) into atmosphere and affecting people's respiratory systems (Thadani, 2011).

Even if a thorough classification of risks involved in the PV power systems is critical for identifying what may affect the overall performance of a system producing energy from sunlight, the literature provides little analysis on what factors act as a driver for efficiency of a PV system. We have chosen to focus our analysis on technological factors that behave as risk driver for energy efficiency on PV power systems. Through this study we analyze how a technological component of a PV system acts as a mitigation factor or as a risk enhancer.

3. Research methodology

Our methodology is based on a practical study performed over a period of one year on a photovoltaic field in Romania. The study was made in the context of the opened market, due to renewable energy support law which made Romania a prime target for applications in PV-solar generation. Most projects are concentrated in Dolj/Olt/Mehedinti counties where irradiation conditions are most favourable. The background of the study consists mainly in plants designed and erected by Romanian EPC Renovatio Solar and also in comparing other plant topologies others EPC have chosen.

The Romanian photovoltaic panel market shows a great potential for development. Romania is situated in the European B sunlight, which gives the country a major solar potential waiting to be tapped. With 210 sunny days a year, Romania is eligible for annual energy flow between 1000 and 1300 located kWh / sqm / year (Romania Power report Q3, 2013).

In the Renewable energy country attractiveness indices report (2013), The Ernst & Young ranks Romania 13th among the 40 countries analyzed. The Ernst & Young Country attractiveness indices (CAI) score 40 countries on the attractiveness of their renewable energy markets, energy infrastructure and the suitability for individual technologies. The indices provide scores out of 100 and are updated on a quarterly basis. The All renewable index (ARI) for Romania was 48,6 at February 2013, while the first place is being held by China with an ARI of 70.1, as shown in Table 1. However, in the solar indices ranking, Romania is found lower, the 24th out of the 40 countries analyzed, with a solar index of 41. Romania's solar market has continued to show high levels of market activity, reinforcing the attractiveness of the sector and supporting projections that indicate it will experience strong growth through 2013. The national energy regulator estimates 500MW–1,000MW will be installed by the end of the year (Renewable energy country attractiveness indices report, 2013).

Rank	Country	All renewables Rank (ARI)	Rank	Country	Solar index	PV	CSP
1	China	70.1	1	US	70	69	73
2	Germany	65.6	2	India	65	67	52
3	US	64.9	2	China	65	67	47
4	India	61.8	4	Germany	61	70	0
5	France	57.3	4	Japan	61	65	29
...
13	Romania	48.6	24	Romania	41	46	0
...
40	Bulgaria	35.2	40	Finland	25	28	0

Table 1. ARI indices and Solar indices at February 2013

(Source: Ernst and Young - Renewable energy country attractiveness indices report 2013)

The energy intensity of the Romanian economy is substantially lower than it was in the beginning of the 1990s, but is nevertheless the second highest in the EU after Bulgaria. The significant level of consumption in the energy-intensive sectors of iron/steel and chemicals is a major factor in the overall intensity. Households account for 41% of estimated cost-effective savings, according to the National Energy Efficiency Action Plan. Romania has long had a strong institutional commitment to energy efficiency, dating back to the creation of the Romanian Agency for Energy Conservation (ARCE) in 1990 (Eurostat, 2009).

However high the potential of the photovoltaic market in Romania, there is little practical research conducted in this field that correlates the energy efficiency in Romania with the risk dimension in this business. This led to explore, on the background on Romania PV systems, a technical variable (the layout design of the PV panels) which influences the energy efficiency of the whole system.

The technological risk is one of the highest threats in designing a PV project, and is easily enhanced by innovation driven challenges. Since competitive advantage in the field of renewable energies is achieved merely through efficiency criteria, an optimal design of the PV power system is based on innovative thinking and technological improvements or disruptive changes. In this study, we focus our attention on how a specific design layout of PV panels can induce higher energy efficiency and what risks reside in this technological aspect of the project. In this direction, we take into consideration the significant influence that the distance between two rows of photovoltaic panels has.

Photovoltaic power systems (> 500kWp - Class II) are built on flat land (agricultural, roof terraces straight or land set aside). The optimal energy efficiency refers to the following concept: install as many solar panels on a specific area so that the gain in energy production (energy yield) is maximum. A photovoltaic power system is composed exclusively of photovoltaic modules mounted on a metallic structure, tilted at an angle. The land is occupied by several rows of these modules and the layout design risk appears when they are too close to each other, causing overshadow, thus reducing the energy production.

4. Modeling description (Source: PV-syst Help)

The analysis was made with PV-syst software version 5.11. PV-syst is a tool that allows to analyze accurately different configurations and to evaluate its results in order to identify the best solution. It deals with grid-connected, stand-alone, pumping and DC-grid (public transport) PV systems, and includes extensive meteo and PV systems components databases, as well as general solar energy tools. For a given project, the user can construct several variations of the system ("calculation versions"): after specifying the desired power, choosing the PV module and the inverter from the internal database, PVsyst proposes an array/system configuration, which allows the user perform an early simulation. The simulation calculates the distribution of energies throughout the year. The main results are: the total energy production [MWh/y], essential for the evaluation of the PV system profitability; the Performance Ratio (PR [%]), which describes the quality of the system itself; the specific energy [kWh/kWp], an indicator of the production according to the available irradiation (location and orientation) (PV-syst, 2013). Figure 1 shows an outline of the project's organization and simulation process. The entire study is made by simulation, based on mathematical models used by PV-syst to determine behaviour of parameters in the following areas: irradiation computation, PV modules and solar inverters, grid systems presizing and simulation process. All components have in turn influence from other parameters. The

simulation involves about [fifty variables](#), which are all accumulated in monthly values. When starting, the early parameter definition parts in the program have already verified the consistency of all input parameters.

In a first step, the diffuse attenuation factor should be calculated, by integrating simultaneously shading and IAM attenuation factors over the viewed part of the vault of heaven. The same thing holds for the albedo attenuation factor. Then the hourly simulation performs the following steps, for each hour:

Incident "effective" energy calculation

- Reading one hour data on the Meteo file (Horizontal global irradiation, temperature, eventually diffuse irradiation and wind velocity). If not available, computes diffuse irradiation with the Liu-Jordan correlation model. If necessary, applies the horizon correction on the beam component,=> defined variables at this stage: GlobHor, DiffHor, BeamHor, T Amb, WindVel.
- performs the transposition (global, diffuse, albedo irradiances) in the collector plane, using either Hay or Perez model according to user's preference. This is done using solar angles at the middle of the time interval, calculated from project's site (not the site of the meteo file).

With explicitly given meteo files (TMY or own measurements), this could give not very reliable results at early morning or evening, if the time properties of the meteo file are not properly defined (legal or sun time), or if latitudes of the two sites is very different.

Defined variables at this stage: GlobInc, BeamInc, DiffInc, DiffSInc, AlbInc,

- applies the shading factor (if near shadings defined) on the beam component,
- applies the IAM factor on the beam component.

Defined variables at this stage: GlobIAM, GlobShd, GlobEff, DiffEff,

This leads to the so-called "Effective incident energy", i.e. the irradiation effectively reaching the PV cell surface.

4.1. Irradiation on the PV-field

It is called "effective incident irradiation" H_{eff} the luminous energy actually falling on the PV cells. It is obtained according to the following steps:

- If only monthly meteorological data available: Generation of **hourly synthetic meteo data** (horizontal global irradiance and temperature),
- If diffuse irradiance measured data not available: **diffuse irradiance model**,
- If **horizon** (far shadings): calculation of the beam effective component (in this version of the program, the diffuse is considered as not affected by horizon). At this stage, we have the Horizontal **global, diffuse and beam components** at disposal, with the relation: $G_h = D_h + B_h$.

Computation of the so-called "**incident energy**" by a **Transposition model**, i.e. calculation of the irradiance on the PV tilted plane. At this stage, the plane irradiance is composed of **global, diffuse, beam and albedo components**, with the relation: $G_p = D_p + B_p + A_p$.

Applying the **near shading** calculations (shading factor on beam, diffuse and albedo components), either linear or according to electrical array connexions.

Applying the **IAM** (Incidence Angle Modifier factor), this finally results in the G_{eff} irradiance, the flux effectively useable for PV conversion. H_{eff} will be the corresponding irradiation over a given time period. Note: G it is usually used for designing irradiances (flux expressed in $[W/m^2]$) and H for irradiances (energies in $[kWh/m^2]$).

4.2. Hourly synthetic meteo data

Synthetic data generation provides a mean of constructing meteorological hourly data from only monthly known values. This is required since numerous simulation processes have to be computed as

instantaneous values (or pseudo-instantaneous as hourly averages). This is the case, for example, with the transposition model which closely depends on the solar geometry.

4.3. Irradiance generation

For global irradiance, we dispose of well-established random algorithms – Aguiar et al (R.J.. Aguiar, M. Collares-Pereira, 1992), which produce hourly distributions presenting statistical properties very close to real data.

The algorithm first constructs a random sequence of daily values, using a Library of Markov Transition Matrices (probability matrices) constructed from real meteo hourly data of several dozen of stations all over the world. Then it applies a time-dependent, Autoregressive, Gaussian Model for Generating the hourly sequences for each day.

4.4. Temperature generation

For temperature, such a general model doesn't exist. We used procedures adjusted only on Swiss meteo data – Scartezzini et al (1990), for which generalisation to any world climate is not proved. In fact the ambient temperature daily sequence shows only weak correlations to global irradiation. Of course the temperature should be continuous, therefore this sequence is constructed using essentially randomly daily slopes, with constraints on the monthly average.

But daily profile can be much more related to the global irradiance. During the day, temperature behaves rather like a sinusoid, with amplitude related to the global daily irradiance, and a phase shift of two to three hours. The corresponding correlation parameters (for amplitude and phase shift) have been quantified from several Swiss region typologies. One can accept that these can be generalised to analogous typologies for other places in the world.

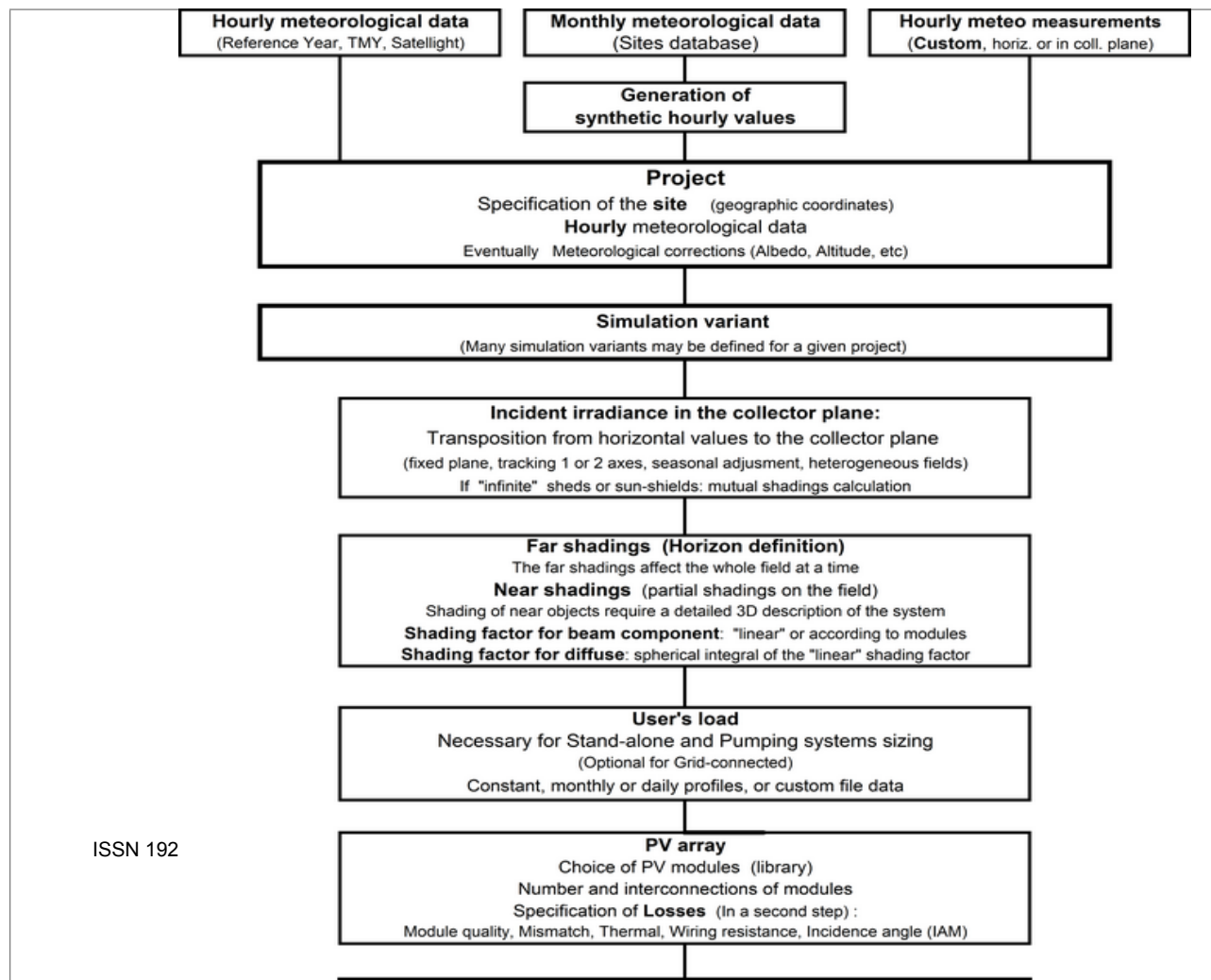


Figure 1. PVsyst simulation process

The software helped us measure the photovoltaic system performance under three different variants, defined by the parameters that impact on the energy efficiency of the PV system (Figure 4. Plantings A-B-C). All three variants target the effects in irradiation energy loss and electrical conversion in the PV panels due to shading and do not treat losses derived from this point (cable losses, inverter efficiency and so on). The software PV-syst is a tool that allows us to analyze accurately different configurations and to evaluate its results in order to identify its best solution.

Our analysis follows the behaviour over one year of a photovoltaic system that varies is the distance between rows (pitch 6m, 8m and 10m) keeping constant the angle of inclination of the panels (at 35°). The tilt angle is kept at 35° as this is optimum for Romania.

The equipment used in the analysis of structural variants consists in: a PV generator (4200 c-Si panels (mono-crystalline) 240Wp power and 14.5% efficiency with an area of 1.65 m² and a fill factor of 0.76) and a DC/AC converter (three phase solar inverter 17000W without transformer).

The simulation was divided as follows: Location A - pitch = 10m, location B - pitch = 8m and location C - pitch = 6m. All comparisons were made between these three variants and the scope was to identify the optimum performance and differences in energy efficiency.

5. Research results

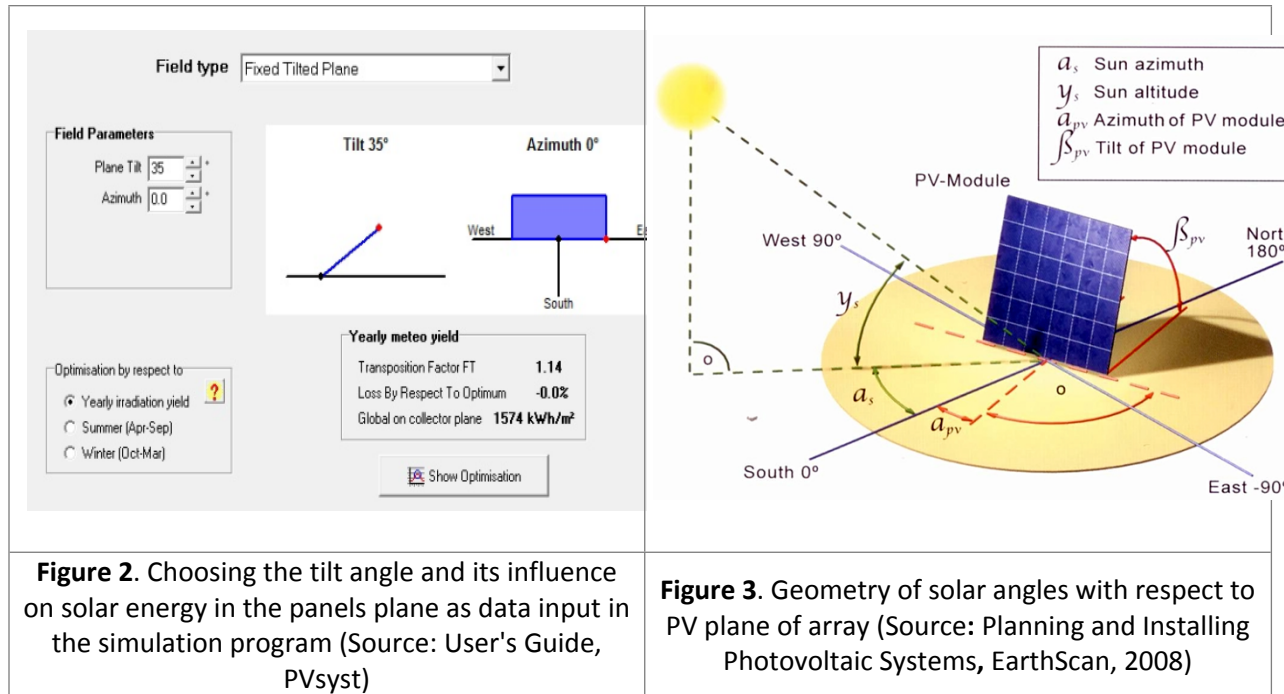
5.1. Layout design as a risk driver for efficiency

The analysis in this paper takes into account three crucial parameters in placing rows and rows conception photovoltaic generator:

- generator inclination (tilt)
- the angle made by the plane panels shading horizontal distance (shading angle)
- the distance between two consecutive rows.

The parameters resulting from the use of two other variables are: total installed power (Pk) and area occupied by it (Sk). The Report Sk / Pk (ha / MWp) provides a common basis for comparison of employment land at various photovoltaic systems.

Our analysis follows the behaviour over one year of a photovoltaic system that varies is the distance between rows (pitch 6m, 8m and 10m) keeping constant the angle of inclination of the panels (at 35°). Tilt angle is kept at 35° as this is optimum for Romania. A variation of 5° will produce loss of 0.5% of the global solar panel plan.



The system has an installed capacity of 1008kWp. The three variants use the same terms of losses (loss in panels, wiring losses, inverter efficiency) and the same climatic zone we studied. Details of these losses can be seen in the diagram specific to each variant presented in **Figure 7**.

To estimate the reduction in solar radiation due to shading lines (mutual shading), we can use the formula:

$$\Delta I(\%) = \frac{\gamma(\text{pitch}) \times f_{\text{diff}}}{180 - \beta}, \text{ where:}$$

ΔI =solar radiation lost (<10%);

γ = shading angle limit resulting from location at different distances (pitch);

f_{diff} = fraction of diffuse radiation for certain areas (for the Corabia, open area, agricultural 0.25);

β = tilt angle of photovoltaic panels.

For example, to limit the loss of solar radiation at 4% (the maximum acceptable value for high power photovoltaic) panels need to be tilted to 35°, lines to form an angle of 23°, considering diffuse radiation of 0.25. Hence spacing of 5.6m using the formula below:

$$d(m) = \frac{h_{\text{panouri}}}{\tan(\gamma)}, \text{ where:}$$

d = spacing;

h_{panouri} = height of the generator (m);

γ = shading angle limit.

If the angle of inclination β decreases, shading will be reduced and land area can be used better, but annual energy production decreases. Spacing width is dependent of modules wide of their inclination angle and shading limit. Basically shading angle limit must be lower than the solar elevation angle at the most unfavourable value. Energy loss according to tilt and shading angle limit can be seen in the Figure 4:

The object will present differences in energy production for the three spacing options. The simulation is made with PV-syst software version 5.11, the most advanced software simulation of a photovoltaic system performance due to complex mathematical models used. Thus the geometrical configuration and shadow fall on the plan and the determining factor for photovoltaic shading is done in a purely geometrical and analytical manner. For each position of the sun, the program first performs a transformation of the entire system coordinates to indicate the axis Oz 'in the direction of the sun. Next, for each element sensitivity of PV field (rectangles, polygons), each surface is projected on the elementary system of plane taking into account the considered land. Intersection property with positive projections of each element is then calculated. Meeting these basic shades creates a polygon representing the global shading. Loss factor is the ratio of surface shading of polygons as a shadow and the sensitive element.

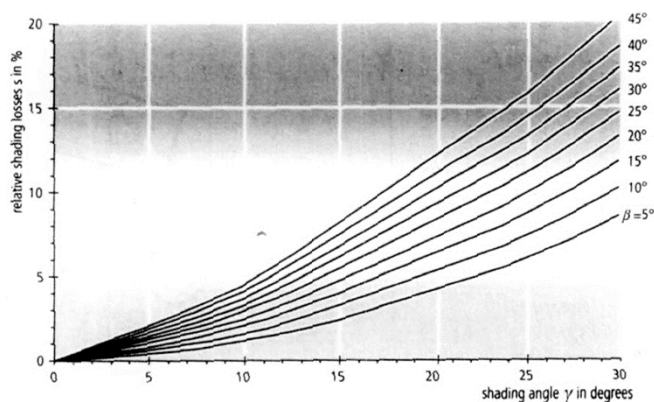
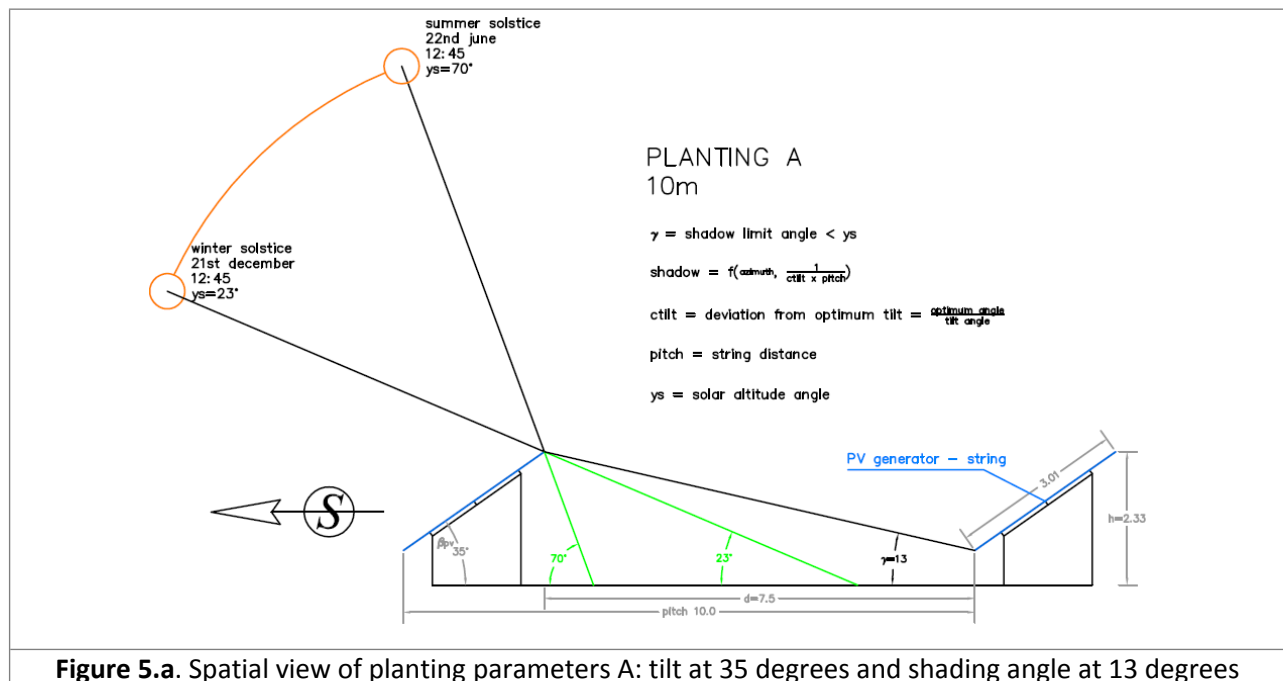


Figure 4. Energy loss due to mutual shading and angle of inclination relative to shading limit (Source: User's Guide, PVsyst)

The simulation was divided as follows: Location A - pitch = 10m, location B - pitch = 8m and location C - pitch = 6m. All comparisons will be made between these three variants and the scope is to identify the optimum performance and differences. The three variants can be visualized spatially in the Figure 5.a-c. The drawings show two profiled structures with 3 horizontal panels on each one, having only one variability: the pitch – the distance between one point of the first structure to the equivalent point of the second). Additional the sun position in the most favourable moment and least favourable moment of the year are influencing the shading from each structure to the next.



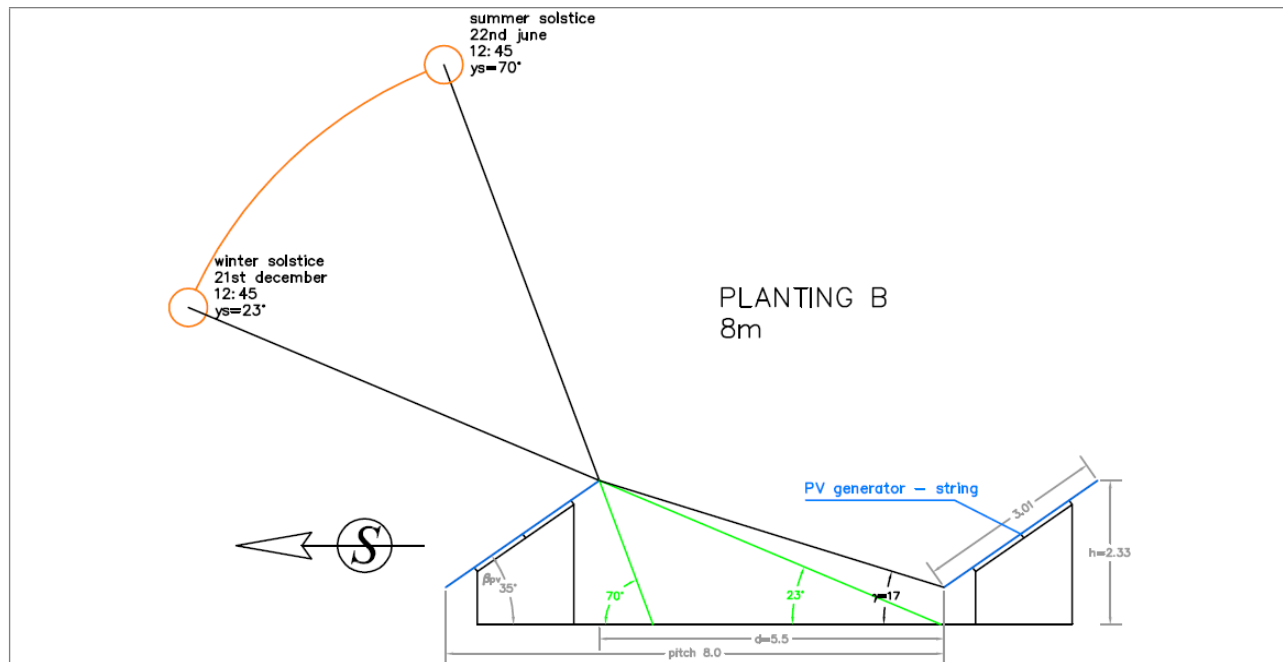


Figure 5.b. Spatial view of planting parameters B: tilt at 35 degrees and shading angle at 17 degrees

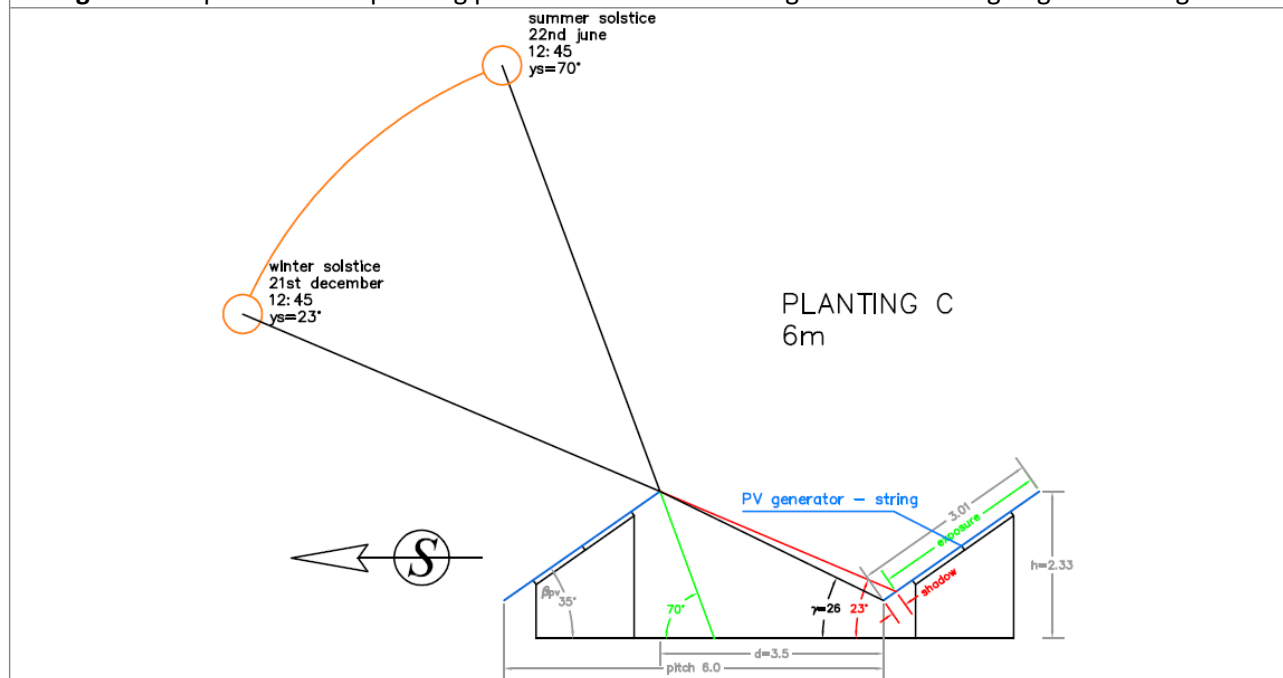
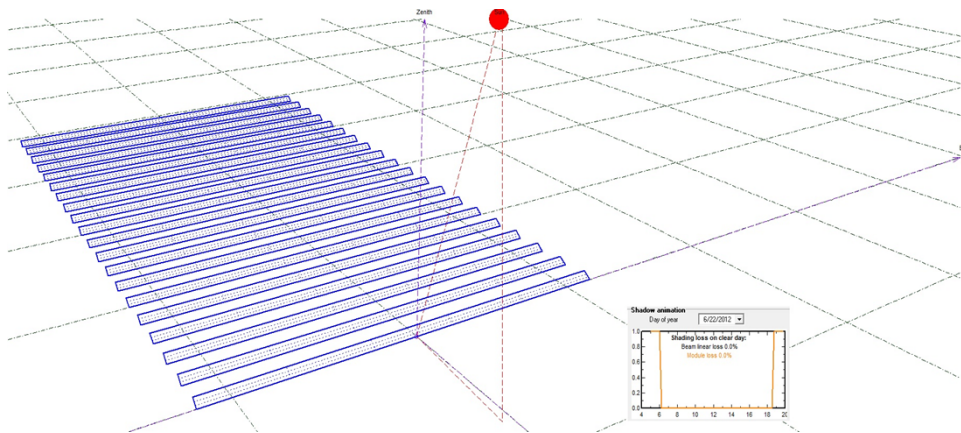
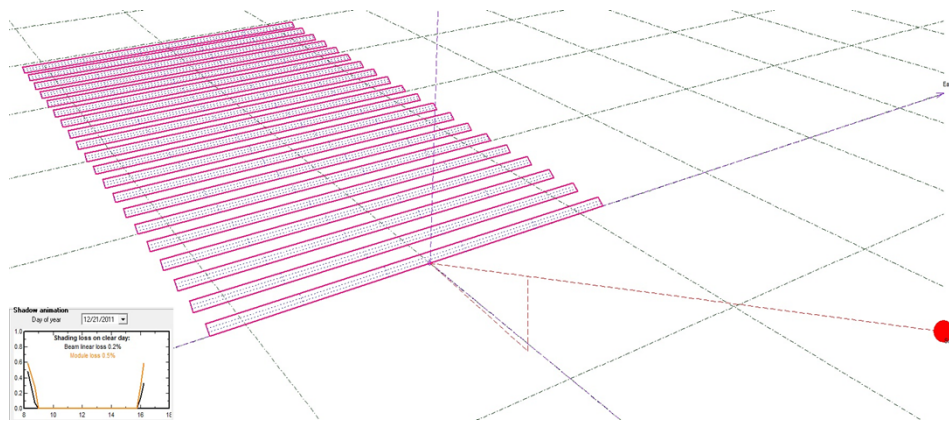


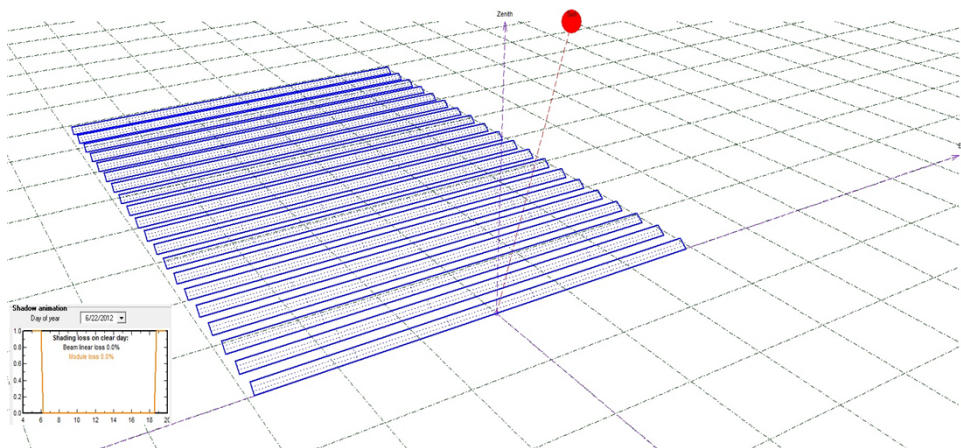
Figure 5.c. Spatial view of planting parameters C: tilt at 35 degrees and shading angle at 13 degrees



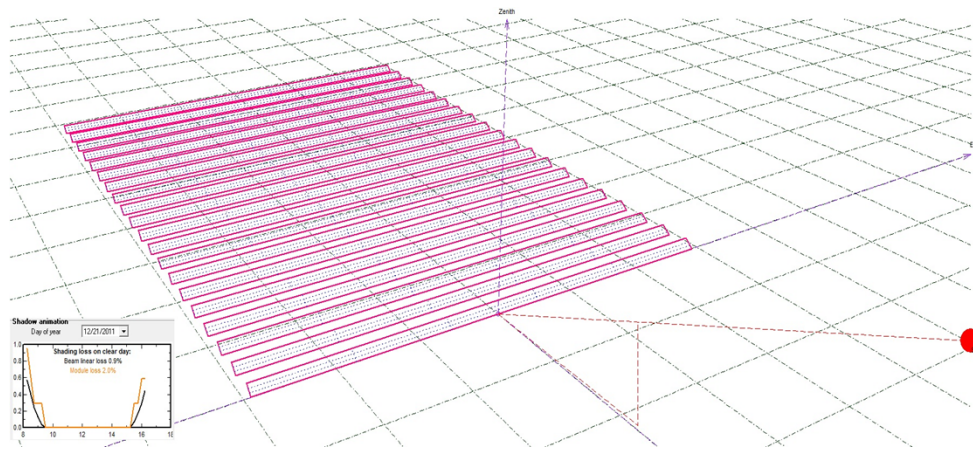
Photovoltaic plant 3D view, the summer solstice, the sun at zenith, location A (10m)



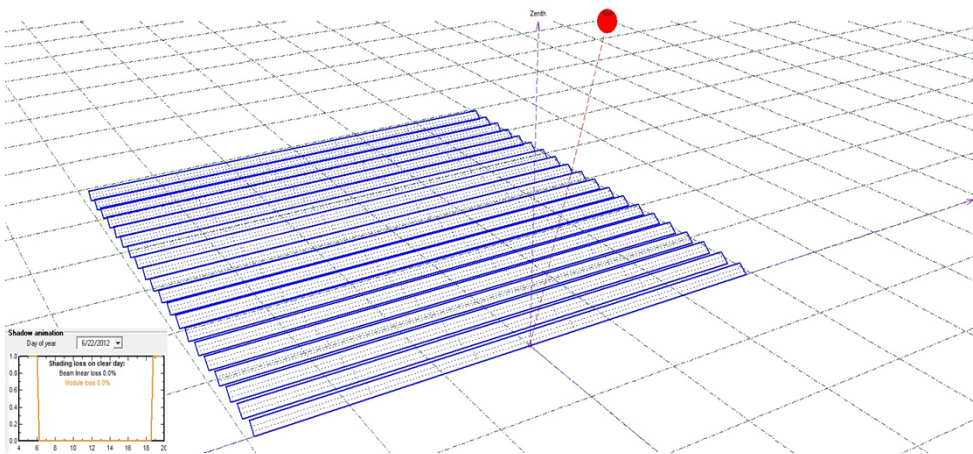
Photovoltaic plant 3D view, winter solstice, $\sim 0^\circ$ azimuth, location A (10m)



Photovoltaic plant 3D view, the summer solstice, the sun at zenith, location B (8m)

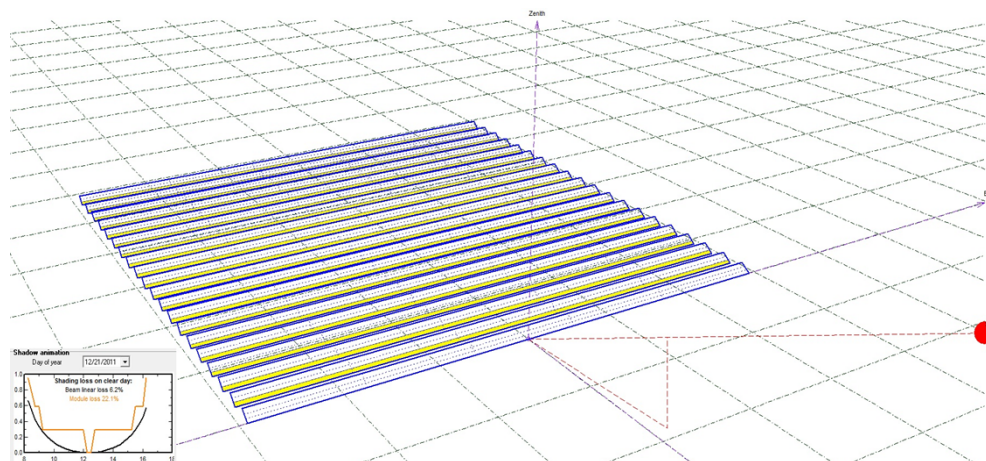


Photovoltaic plant 3D view, winter solstice, $\sim 0^\circ$ azimuth, location B (8m)



Photovoltaic plant 3D view, the summer solstice, the sun at zenith, location C (6m)

Following the idea for the Figure 5, the spatial view shows 20 PV structures with 3 horizontal panels. It is self implied that as you have more structures one behind another, the shading losses are increasing. If we would place a very long structure, instead of more, the system designed will have no shading. For the current analysis we used the same topology of rows for all three variants.



Photovoltaic plant 3D view, winter solstice, ~ 0° azimuth, location C (6m) (Source: PV-syst)

Figure 6. Plant layout in 3D, solar positions in different year seasons and shadings view

In Figure 6 we can immediately observe the major difference between location A and location C, the trajectories of shading and module losses are more pronounced in the latter, highlighting in yellow the shaded area in the lower position of the sun (even at noon). The shaded area increases with the increase of the azimuth angle. The losses quantified through this placement can be quite substantial (even higher as the plant is higher). In the following performance data can tracked on employment land for the three variants.

5.1.1. Simulation Results

Location	Pitch (m)	Shading factor	Specific energy Yf (kWh/kWp)	PR	Energy produced E (MWh/an)	Area occupied Sk (mp)	Unitary area (ha/MWp)	Land use report (%)
A	10	0,974	1382	0,832	1393	22222	2,204	27%
B	8	0,961	1368	0,823	1379	17833	1,769	33%
C	6	0,943	1333	0,802	1344	13444	1,333	45%

Table 2. Production and area simulation data for the three variants

As a direct observation of the results Table 2, it is clear that variant C offers almost double usage in the land, compared to variant A and as expected all three production parameters are lower compared to variant A. Regarding the ups and downs of these variants, the increasing of pitch above A will yield a lower and lower supplement in production, as opposed to decreasing below C, will yield a very high loss in shading. In conclusion, the optimum pitch is 8-9m and it is at final customer latitude whether he chooses land usage and accepts the losses. The C variant and below is recommended only in planting with imposed Pk and limited area. The simulation data for all three variants from PV-syst reports are listed in Tables 3-5. There are clearly indicated: global horizontal irradiation, ambient temperature, global incident irradiation in collector plane, effective global correction for IAM and shadings, effective

energy at the output of the array, energy injected into grid, efficiency Eout array / rough area, efficiency Eout system / rough area.

5.1.2. Performance Ratio

As the photovoltaic industry has grown in recent years, a need to clarify and educate entrepreneurs on the performance parameters of photovoltaic systems has emerged. They allow the detection of operational problems and the validation of the performance estimation models in the design phase. Industrial-scale use of standard performance parameters assists the investors in assessing various proposals for equipment, technology and methods of implementation. It offers confidence in the ability to obtain and maintain reliable systems of the highest quality. Three of the parameters listed in IEC 61724 can be used to define the overall performance of a reporting system for energy production, solar resource and the overall loss. They are: specific production (Yf), solar output reference (Yr) and PR (Performance Ratio).

Yf specific energy is the net energy produced (E) compared with the generator installed PV power (Pk). It is usually measured during a month or a whole year. This value represents the number of hours that the photovoltaic generator would operate at rated power to provide the same energy. Measurement units are hours or kWh / kWp. Yf parameter normalizes energy produced reported to the kW installed unit, as a consequence, is a convenient way to compare the energy produced by photovoltaic systems of different powers.

$$Yf = \frac{E}{Pk} = \frac{(kWh)}{(kW)} = (h),$$

Yr reference solar energy production H that is entering the panels plane reported to the reference radiation G0. This is the equivalent operating hours at the reference radiation. If G0 is equal to 1000W/mp then Yr is the number of peak sun hours, measured in hours. Yr defines the available solar resource photovoltaic system. It depends on the location, orientation panels and weather variability.

$$Yr = \frac{H}{G0} = \frac{(kWh/mp)}{(kW/mp)} = (h),$$

The coefficient of performance (PR, Performance Ratio) is obtained from reporting Yf to Yr. Normalizing it in relation to radiation, this indicator quantifies the overall effect of losses due to nominal values due to: inverter inefficiency, losses in cables, electrical parameters mismatch losses for photovoltaic panels, high temperature losses panels (silicon is sensitive to variations temperature), loss by shading, reflection losses in solar panel plan, dust or snow losses, losses due to network interruptions or component failure.

$$PR = \frac{Yf}{Yr} = (adimensional),$$

The values of this coefficient are reported usually for month or for year (like E). Values calculated for smaller intervals (daily or weekly) may be useful in detecting defects in components. Although PR may be confused with system efficiency it is rather an indicator of its operation. In other words, PR is how well the photovoltaic plant captures solar energy available and transforms it into usable energy to the terminals. There may be cases when a system with abundant solar resource is poorly designed (layout and design) or the opposite, a very well designed system is placed in an area with low solar radiation, and both systems can have an equal PR. Due to temperature losses in the photovoltaic panels the PR values may be higher in winter than in summer and normally can fall between 0.65 and 0.85. If dustiness of the panels is seasonal then difference between winter and summer may appear.

	GlobHor kWh/m ²	T Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray kWh	E_Grid kWh	EffArrR %	EffSysR %
January	51.6	-0.30	85.0	79.7	77310	75232	13.08	12.73
February	70.4	0.90	105.4	100.5	96858	94495	13.21	12.89
March	112.3	5.30	141.9	135.3	127860	124791	12.96	12.65
April	142.4	11.20	153.5	145.7	133942	130600	12.54	12.23
May	181.4	16.70	179.1	169.9	152323	148566	12.23	11.93
June	196.9	20.60	183.1	173.4	151457	147563	11.89	11.59
July	205.7	23.20	195.6	185.0	160268	156171	11.78	11.48
August	186.3	23.10	193.7	184.4	159664	155788	11.85	11.56
September	132.2	18.60	158.3	150.8	134105	130948	12.18	11.90
October	88.4	12.80	119.4	113.9	104541	101945	12.59	12.28
November	51.2	6.10	78.8	74.6	69988	68040	12.76	12.41
December	41.7	0.90	68.2	63.9	61243	59457	12.91	12.53
Year	1460.5	11.65	1662.1	1577.1	1429559	1393596	12.37	12.06

Table 3. Simulation results. Location A - pitch = 10m

The values calculated by the program are: horizontal global irradiation, ambient temperature, global incident irradiation in the collector plane, effective global irradiance after IAM and shadings corrections are applied, effective energy at the output of the PV array, energy injected into the grid, efficiency energy of the array reported to PV area, efficiency of the system reported to PV area. The values are averaged on a monthly basis and totalised at the end. The following two tables present the same parameters for the last variants.

	GlobHor kWh/m ²	T Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray kWh	E_Grid kWh	EffArrR %	EffSysR %
January	51.6	-0.30	85.0	77.0	74647	72597	12.63	12.29
February	70.4	0.90	105.4	99.4	95756	93405	13.06	12.74
March	112.3	5.30	141.9	134.5	127071	124013	12.88	12.57
April	142.4	11.20	153.5	144.8	133080	129762	12.46	12.15
May	181.4	16.70	179.1	168.9	151366	147619	12.15	11.85
June	196.9	20.60	183.1	172.4	150633	146737	11.83	11.52
July	205.7	23.20	195.6	183.9	159363	155269	11.71	11.41
August	186.3	23.10	193.7	183.6	158912	155043	11.79	11.51
September	132.2	18.60	158.3	150.0	133384	130228	12.12	11.83
October	88.4	12.80	119.4	113.1	103783	101188	12.50	12.19
November	51.2	6.10	78.8	72.9	68326	66398	12.46	12.11
December	41.7	0.90	68.2	61.6	59025	57254	12.44	12.07
Year	1460.5	11.65	1662.1	1562.1	1415347	1379513	12.24	11.93

Table 4. Simulation results. Location B - pitch = 8m

	GlobHor kWh/m ²	T Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray kWh	E_Grid kWh	EffArrR %	EffSysR %
January	51.6	-0.30	85.0	68.7	66441	64533	11.24	10.92
February	70.4	0.90	105.4	95.8	92253	89957	12.58	12.27
March	112.3	5.30	141.9	133.1	125663	122624	12.73	12.43
April	142.4	11.20	153.5	143.5	131819	128544	12.34	12.04
May	181.4	16.70	179.1	167.3	149936	146248	12.04	11.74
June	196.9	20.60	183.1	171.1	149422	145551	11.73	11.43
July	205.7	23.20	195.6	182.4	158049	153971	11.62	11.32
August	186.3	23.10	193.7	182.3	157819	153974	11.71	11.43
September	132.2	18.60	158.3	148.7	132245	129105	12.01	11.73
October	88.4	12.80	119.4	111.3	102112	99553	12.30	11.99
November	51.2	6.10	78.8	67.1	62653	60831	11.43	11.09
December	41.7	0.90	68.2	52.8	50386	48755	10.62	10.27
Year	1460.5	11.65	1662.1	1524.2	1378798	1343647	11.93	11.62

Table 5. Simulation results. Location C - pitch = 6m

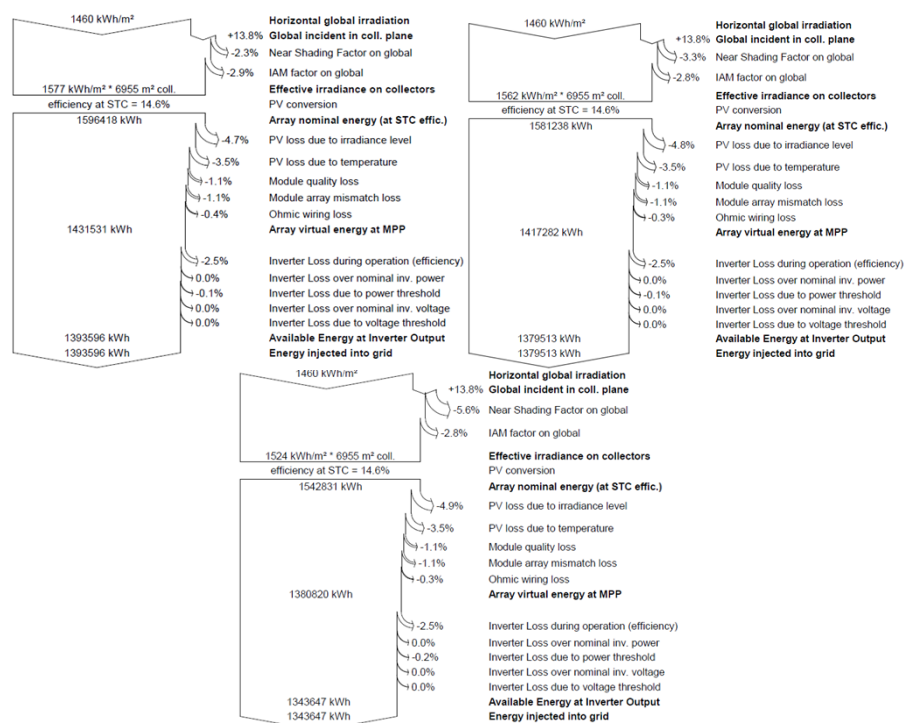


Figure 7. Loss Diagrams (Source: PV-syst report)

As shown in Table 6, the energy difference between option A and option C is 49MWh/year, representing 3.5% of production. Consequently, the placement option C, although it is most advantageous in terms of land area needed for construction, is the worst in terms of energy produced annually.

Variant B is considered a middle choice in the struggle between land usage and shading loss, also can be considered a solution that is not recommended to be crossed unless condition imposed. Also, following a simulation in financial terms of the two types of projects, we obtain the data presented in the Table 4. Therefore, C version will not be much cheaper (in terms of initial investment) than option A because the cost of land for construction, since planning the works and fencing bear the lowest project costs. However, looking at the whole project over a period of 25 years (the entire life of the project) major financial benefits can be observed.

	VAR C	VAR A
Project implementation costs	1.905.000 €	1.920.000 €
Operating costs per year	75.000 €	75.000 €
The discount rate	10%	10%
Present value of annuity for 25 years	3.652.338 €	3.814.500 €
The net present value	1.747.338 €	1.894.500 €
Cost-Benefit	192%	199%

Table 6. Comparing the extremes in financial terms

A is considered the best option that combines the area occupied and a low level of losses. Location variant C (pitch <7m) is not recommended unless it is expressly required, due to limits of surface and/or

installed power; another placement variant is not physically possible. If the ratio of land use (footprint of PV modules / total surface area with shade) falls below 27% then the increase in energy produced will be limited and further growth of the space will be less justified. A photovoltaic system is considered very good sized if the PR is determined at a value greater than 0.83 in the first 4 years of operation. The designer must balance losses accepted by the owner of the plant and the land area available for construction while achieving a performance as high as possible.

5.1.3. Validation of data

The first delicate stage is the treatment of the incident irradiation in the collector plane: it involves models for the estimation of the diffuse irradiation (from the global irradiation) and for transposition. These models proved to be the weakest link in the comparison process, with differences reaching more than ten percent for some of the data used. For the SIG installation at Geneva, the only site where measurements of the horizontal diffuse irradiation are available, the deviation does not exceed 2 to 3%.

Why the validation of the data may be proven difficult or at least challenging:

- The simulation results depend on many parameters, which may be set at any value in order to get the expected result... (for example: PV module quality loss, or mismatch, or soiling);
- The real meteo values when running are rarely known (or sometimes not recorded with sufficient care) and operating parameters measurements are also subject to errors;
- The real performances of the components used (especially the PV modules) is rarely checked in detail at the installation time.

For getting reliable conclusions, the measurement conditions and the validation process should be clearly defined. Namely comparisons between measurements and simulation should be performed in hourly values.

Below there are validations performed with old versions of PVsyst (1996) on 7 Swiss installations. The yearly power was predicted with an annual accuracy of the order of +/- 5%, except with an installation involving amorphous modules (which were not well modelled in this early version).

Installation	N 13	Marzili	LESO-Sheds	SIG	EIV	LESO-LRE	LESO-USSC
Site (Switzerland)	Domat-Ems	Berne	Lausanne	Genève	Sion	Lausanne	Lausanne
Field: type Tilt angle Azimuth	Anti-noise-wall 45° 25 ° East	Sheds 35° 37 ° East	Sheds 45° South	Sheds 35° 9 ° East	Sheds 45° South	Facade 90° South	Demosite 28° South
Installed power Field area	104 kWc 967 m2	25.6 kWc 170 m2	12 kWc 111.6 m2	7.6 kWc 61.5 m2	3.2 kWc 31.7 m2	3 kWc 28.6 m2	0.45 kWc 8.2 m2
Collectors: manuf. Type Nominal Power STC Measured Power STC Measurements Technology	Kyocera LA361 J48 48 Wc 48 Wc Ispra SI-poly	BP Solar BP495-Saturn 95 Wc 88 Wc Ispra SI-mono	Solarex MSX 60 60 Wc 55.1 Wc TISO SI-poly	Arco-Solar M55 53 Wc 50.8 Wc Ispra SI-mono	Photowatt BPX 47500 48 Wc 40.3 Wc TISO SI-poly	Flagsol Optisol/LESO 250 Wc Manufacturer SI-poly	USSC (USA) 17 Wc LESO a-Si:H tandem
Irrad. transposition: MBE (transpos.-meas.) RMSE (daily val.) RMSE (hourly val.)	2.8 % 5.5 % 11.7 %	-0.9 % 3.2 % 7.8 %	-6.0 % 9.6 % 15 %	-2.2 % 2.9 % 5.1 %	9.3 % 5.5 % 10.4 %		-11.3 % 7.7 % 11.4 %
Coll. Temperature model Wind velocity measurement K factor (input param.) MBE (simul-measure) RMSE (hourly val.)	No 29 W/m2K -0.3 °C 2.1 °C	No 29 W/m2K -0.5 °C 1.5 °C	No 29 W/m2K -0.03 °C 2.7 °C	Yes 20 + 6 vvent 0.8 °C 2.1 °C	No 29 W/m2K -0.7 °C 3.8 °C	No 13 W/m2K -0.2 °C 3.7 °C	No 23 W/m2K 0.0°C 2.8 °C
PV-Field DC energy Simul. Base: MBE (simul-meas.) RMSE (daily values) RMSE (hourly values)	Plane irrad. 5.6 % 8.7 % 11.0 %	Plane irrad. 1.0 % 10.0 % 15.5 %	(field #3) Plane irrad. -0.7 % 2.2 % 5.2 %	Horiz. irrad. 0.7 % 5.0 % 9.8 %	Plane irrad. 3.1 % 3.4 % 6.5 %	Horiz. Irrad. 1.4 % 10.8 % 17.7 %	Plane irrad. -13.6 % 8.9 % 13.4 %
System AC output MBE (simul-meas.) RMSE (monthly values) RMSE (daily values) RMSE (hourly values)	5.5 % 5.4 % 8.3 % 10.8 %	1.0 % 4.5 % 9.9 % 15.3 %	-0.7 % 1.1 % 2.4 % 5.5 %	1.9 % 1.7 % 5.3 % 9.7 %	2.8 % 1.2 % 3.3 % 6.5 %	2.7 % 8.2 % 12.7 % 19.0 %	-12.8 % 7.5 % 8.5 % 12.5 %

Table 7. Summary of 7 tested installations: comparisons between simulation and measurements

But other sites show differences going up to more than 10%. It should be emphasised that these results are highly dependent on the quality of the instruments used for the irradiance measurements

(especially the calibration and sometimes the positioning). We supposed that the standard deviation in hourly values is a good indication of the performances of the model itself, and in this respect, the installation of Marzili (MBE=1% and hourly RMSE < 7.8%) confirms their validity. The mediocre results of the LESO can be explained by the considerable distance (several hundred meters) between the horizontal solar meter and the measurement in the collector plane.

The second mode, array temperature model, is the estimation of the temperature of the PV field using values of ambient temperature and irradiation. This temperature only acts as an auxiliary parameter in the calculation of the electrical production of the field, and its specification is not critical. Our model, resulting from a simple thermal balance, gives remarkable results. By using the default value suggested by the programme ($k=29\text{W/m}^2\text{k}$) for all the collectors without back-covering, and by adapting this value for the integrated installations, we obtain, in all cases, errors lower than 1°C , with hourly dispersions of 2 to 4°C at the most.

The electrical output, measured at the collector array terminals (DC energy), is calculated by the simulation on the basis of the incident irradiation (given the shading and non normal incidence corrections), the temperature of the modules, and the collector model (operating at MPP), keeping in mind the ohmic losses of the wiring and the module's mismatch. The excellent results obtained especially in LESO-sheds, the SIG or at the EIV, show that these models work perfectly, at least for silicone crystalline modules (PV-Syst Contextual Help, 2010).

6. Conclusions, limitations and further research

The constant demand of energy determines a more growing attention to energy efficiency and the environmental capability of photovoltaic power plants to manage and mitigate the technological risks encountered.

In our study, we have explored the available literature written on the subject of energy efficiency and solar energy risks, focusing on the dangers hampering energy efficiency on the background on photovoltaic power systems. We have analyzed the extent of influence of technical parameters such as the generator inclination, angle made by the panels (the shading angle) and the distance between two consecutive rows of panels. We have conducted our analysis by using PV-syst software version 5.11., carrying out three simulations under three different variants defined by the parameters that impact on the energy efficiency of the PV system. This evaluation made in this way can assist investors in choosing the best topology for their current situation or production expectations, before the plant is erected or planned, making easier the direction to walk upon: more land for more power or less land for less performance.

In analyzing the efficiency and gain in the different designs, measurements were taken under three conditions, which yielded different results, but which showed how an optimization of the layout design of the PV panels positively influence the energy efficiency of the whole photovoltaic power system.

Moreover, using simulations in order to optimize the energy efficiency of a PV system can be regarded as a risk mitigation method, due to the various possibilities of identifying potential malfunctions of the system that might affect its performance ratios.

Future research should cover variable tilting, pitch choosing and PV panels layout on the structure and cabling methods as combined influence on the energy production. Due to high technologies equipments installed in a PV plant another research thematic will be the risk evaluation of plants components and mitigation of power loss in both design process and maintenance/operation in 25 years. Also as the

operation time is increasing for all equipments, it will become a firm necessity of upgrading or re-technologising the plant: inverters, some panels and transformers, cables.

Based on the obtained results we can affirm that the technological parameters monitored act as risk driver for energy efficiency of power plants and our approach presents interesting advantages from the point of view of practical applicability to larger power PV structures, in what concerns the technological risks involved.

The limitations of our study were given by the fact that our analysis was set in the perimeter of a single photovoltaic power system in Romania. We recommend further exploration to be undertaken using a more extensive area of research, respectively several more photovoltaic power systems.

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