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ASSESSING THE DESIGN OPTIONS FOR THE OPTIMISATION OF A 2MWp GROUND MOUNTED PV SYSTEM IN MALTA

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ABSTRACT: The objective of large scale PV installations in space constrained countries has gradually shifted from production maximisation to that of reaching an optimised economic performance. The main reason for this is the ever decreasing price of the modules. This has resulted in systems with lower tilt angles, increased mutual shading and overloading of inverters by design, in the continuous quest of balancing reduced yield with development costs over the entire lifespan of the project. This approach has shifted the traditional view of evaluating a PV installation from a Euro/watt approach to the use of optimisation metrics such the Levelised Cost Of Electricity (LCOE) or Internal Rate of Return (IRR). Optimisation can be simply described as a balancing act, evaluating tradeoffs to assess which combination gives the best economic performance. By its very nature, optimisation is an iterative process.
This paper evaluates a number of design parameters which, together with production modelling within the context of the Maltese solar climate, aims at identifying an optimum design for the building of a 2MWp ground mounted PV installation. Among the issues considered are; layout optimisation with issues of tilt, cross shading and cabling options, and inverter architecture whether string or central including dc-to-ac rating.

Keywords: Optimisation, Ground Mounted PV, Economic Performance

1 INTRODUCTION

Optimisation can be simply described as the task of finding a compromise between maximised energy production and development costs over the entire lifetime of the plant. It is a team effort by both engineering and financial staff. Optimisation is a measurable process. Where in the past, the Euro/watt would have been an acceptable optimisation metric, the present dominant approach is the use of the LCOE or IRR [1]. The superiority of these metrics is that they provide a means to evaluate the effectiveness of design alternatives over the entire lifetime of the project.

Optimisation starts with site selection. Sites with favourable terrain conditions, adequate physical access and grid connectivity are all essential to minimise initial costs. Having identified the site, optimisation is achieved by having designers tweek a variety of design parameters, termed "optimisation levers", until the desired goal is reached. It is an iterative process and includes, among other issues, aspects of module technology and mounting, tilt angle, row spacing and mutual shading, inverter sizing and architecture and other Balance of System (BOS) component selection. All of the above have an impact on the final energy exported to the grid, capital and operational costs which ultimately are all reflected on the economic performance of the plant.

Optimisation does not stop with the commissioning of the plant. Effective Operation and Maintenance (O&M), managed through monitoring systems, is essential to ensure that the plant stays within its economic targets.

Optimisation is very much site specific and time dependent. The constraints which a site presents, the solar resource available and the continuously changing prices of PV related equipment effectively result in the optimisation exercise having to be undertaken with every major project considered.

2 BASIC TERMINOLOGY AND DEFINITIONS

The physical layout of parallel rows typical of ground mounted PV installations may be described by the parameters shown in Fig. 1: the tilt angle (β), the limit angle (ρ), also referred to as shading angle and the pitch distance (P). The limit angle is a function of the sun's elevation (γ) and azimuth (Ψ), and the azimuth of the PV module itself (α). α has a zero value for south facing rows. The limit angle physically represents the limit before the preceding row casts a shadow on the next and is given by the following equation [2].

$$\tan \rho = \tan\gamma / \cos(\Psi - \alpha)$$

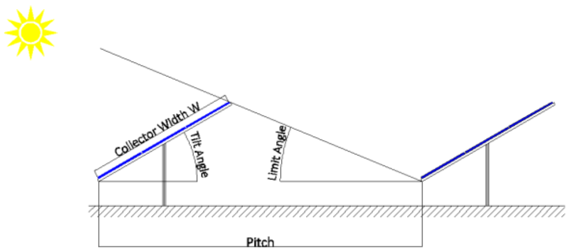

Figure 1: Parameters describing row arrangements

An indicator used in these studies is the "land utilisation factor" which is the ratio of the collector area to the ground area occupied by the PV installation. For equally spaced rows, this is equal to the ratio of the collector width (W) to the pitch distance.

Land utilisation factor = collector width W/pitch P

3 TILT ANGLE AND ROW SPACING OPTIMISATION

Traditionally, the concept of array layout with multiple rows would have followed a 3 steps process:

1. Adopt a tilt angle which gives optimum performance for the site geographical location. In the case of Malta, modelling software show that on a yearly basis, the optimum performance for a fixed tilt single plane (equivalent to having rows with infinite pitch and limit angle of 0˚), is reached at an angle of around 32˚.
2. Complete avoidance of mutual row shading between solar time 9.00hrs to 15.00hrs, on the 21st December. This solar window is particularly important for the Maltese scenario where the direct component of the solar radiation is more than 50% of the total global radiation with winter still classifying as a period of significant solar radiation [3]
3. A south orientation irrespective of the geometry of the site.

This philosophy targeted maximisation of energy, mainly driven by the high price of the modules in the past. Economic optimisation today requires a different mindset. The present approach goes for a much lower angle than the site optimum tilt so as to maximise land utilisation. Resulting mutual row shading is managed by having modules wired in strings of parallel lines along the length of the tables. This also leads to the fact that some optimisation goals may have conflicting requirements. For example, the lower the tilt angle, the higher the land utilisation but which comes at the expense of reduced yield. An LCOE calculation could identify the right balance, by taking into consideration both the cost of land and the revenue from the exported energy.

For the purpose of this paper, the spectrum of tilt angles considered for the production modelling iterations, range from 10˚ to 45˚ in increments of 5˚. Tilt angles lower than 10˚ are not considered practical in view of reduced self cleaning capabilities. As shown in Figure 2 the pitch distance (and hence the land utilisation) is more sensitive to changes in the tilt angle rather than to variations in the limit angle.

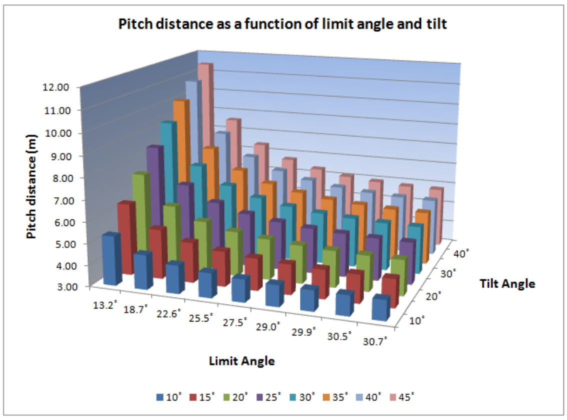

Figure 2: Variation of row distance with limit angles and Module tilt angles.

A subset of the limit angles shown in Fig. 2, at which there is significant variation in pitch distance, has been considered for the production modelling. Their corresponding solar windows are shown in the Table I

Table 1: Limit angles, for 21st December, Malta

Solar Window		Elevation	Azimuth	Limit Angle
08h30	15h30	12.7˚	±48.3˚	18.7˚
09h00	15h00	17.0˚	±42.7˚	22.6˚
09h30	14h30	20.9˚	±36.7˚	25.5˚
10h00	14h00	24.3˚	±30.2˚	27.5˚

4 PRODUCTION MODELLING

Essential tools for the evaluation of optimisation options are production modelling software packages. Site characteristics such as the local weather data and near shading obstacles are inputted into the software which would already include an extensive database of PV modules and inverters. Together with basic assumptions such as soiling, albedo etc., algorithms model the amount of solar radiation reaching the array. The final energy injected into the grid is the ultimate output of the simulation after having taken into account a variety of losses occurring within the system.

PVsyst, version V6.08, developed by the University of Genève was used for the purpose of this paper. Simulations were carried out spanning a whole year in hourly steps.

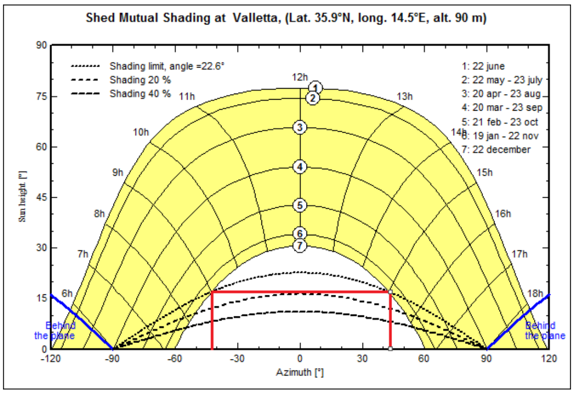

Figure 3: Solar path showing the solar window 09h00 to 15h00 corresponding to a limit angle of 22.6˚ (Source: PVsyst).

5 INVERTER SELECTION OPTIMISATION

The choice of inverters is crucial in many aspects of the design and finally on the economic performance of the project. Issues about string configuration, the original capital cost, O&M costs and operating efficiency of the chosen inverter architecture are all directly linked to the LCOE equation.

5.1 String vs. Central inverters

The available choice is between a large number of distributed string inverters or a few central inverters. The former has been considered as the best practice in Europe for quite some time while central architecture prevails in the US [4]. For this paper, production modelling has been done using Danfoss 12.5kW and 15kW string inverters and ABB 875kW and 1000kW central inverters.

Since it is common knowledge that the Euro/kWp price of solar inverters decreases with increased size, centralised inverters seem to be the obvious choice for large PV installations. However, when considering the total cost of ownership over the entire project lifetime, the initial capital investment may have a secondary role when compared to issues like uptime and maintenance costs so further analysis is needed to obtain the optimal result.

With hundreds of string inverters, a single failure would affect only a small percentage of the plant contrarily to the case of a major failure with a central inverter. Furthermore, replacement string inverters could be kept in stock and replaced in a matter of hours. Major failure on a central inverter can take days to sort out especially in the absence of specialised personnel in the country.

Installation of string inverters can be done in a matter of minutes and without the need of particular skills or specialised equipment or site preparation as is the case with central inverters. But perhaps the greatest advantage of string over central architecture is the availability of individual Maximum Power Point Tracking (MPPT) for each string input. This enables each string to continue operating at its maximum power point, independent of other strings, even in sitations of different irradiation conditions such as during partial shading. Such characterisic is a usefull optimisation tool as it allows operation with a reduced pitch without compromising the optimum yield from the unshaded strings.

Reputable central inverters, built on technology platforms which have been proven by years of experience in industrial applications are expected to operate for a long number of years by simply following a rigourous program of scheduled preventive maintenance. Altough with central inverter it is normal to have some sort of service contract, no allowance has to be made during the liftetime of the plant for its complete replacement as is the case with string inverters. Both the annual service contract cost relating to the central inverter and the one time string inverters replacement within the life time of the plant, are accounted for in the LCOE computation.

5.2 dc-to-ac ratio

The optimal matching of the PV array and the inverter is a complex but crucial factor in the overall performance of a PV installation. The general approach is to have the PV array bigger than the inverter power AC rating. The under laying justification is that the kWp rating of the array is given at Standard Test Condition (STC), conditions which are hardly met in reality. An oversized PV array would occasionally generate more power than what the inverter can handle. This results in a "fatter" power curve with a flat top, a condition of power limiting also referred to as *clipping* as shown in Fig. 4. This does not result in any loss or heat dissipation within the inverter, since, under these conditions, the inverter simply shifts the operating point on the I-V curve of the array by increasing the voltage which de-facto shifts away from the maximum power point.

Production modelling on PVsyst has shown that operation within the Maltese solar climate, up to a dc-to-ac ratio of 1.20, does not result in inverter overload losses . With a ratio of 1.44, modelling has shown clear clipping behaviour during cool spring days resulting in the inverter operating at full power for most of the time as shown in Fig. 4 and Fig.5. Operating the inverter for prolonged periods at full power may create issues of thermal stress on the inverter electronics with possible premature aging.

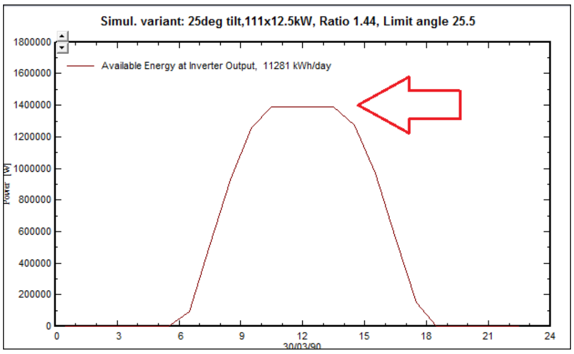

Figure 4: Plot of Power (W) over 24hrs showing clipping behaviour of string inverters with a dc-to-ac ratio of 1.44 as modelled on PVsyst.

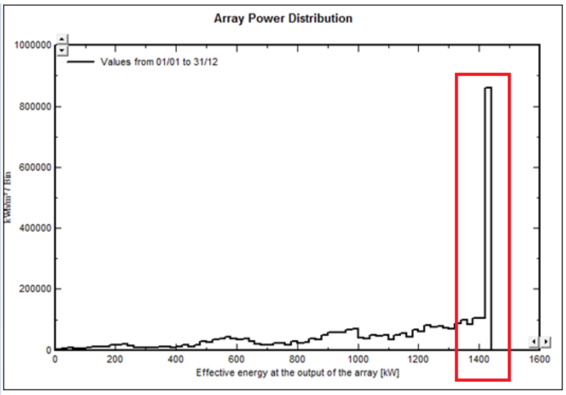

Figure 5: Binning plot(kWh/m²/Bin vs. Effective energy at the output of the arrary kW) from PVsyst showing the inverters operating for prolonged periods at maxium power as a result of a high dc-to-ac ratio.

One major driving force for high dc-to-ac ratios is the steady decrease in the price of modules. A fatter power curve translates into more kWh even if its peak value is capped as the area under the curve is larger than if no clipping occurs. The cost of lost energy must also to be evaluated in relation to the cost of inverters with higher power. This is the shift from a concept of having an ultimate aim of maximising energy production to that of optimising the plant economic performance.

6 MODULES AND PLANT LAYOUT

6.1 The mounting arrangement selected for this study is of a 3 tier panels in landscape orientation per mounting table. Each row on the table represents a string which is then connected to one of the 3MPP inputs of the inverter in string architecture. This arrangement greatly facilitates module wiring on site and allows yield optimisation of the 3 tiers independently. For central inverter architecture, all strings are connected in parallel to a single MPPT.

Partially shaded bottom strings experience drastic loss of power when installed in portrait rather than in a landscape orientation. The module used in this study is fitted with 3 by-pass diodes which effectively divide it into 3 segments along its length. By-pass diodes shunt away only the shaded segments of the module. This is clearly not possible in a portrait orientation where the entire module is lost during partial shading at the base.

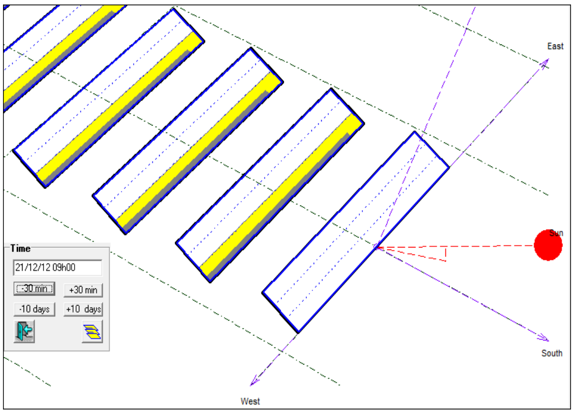

Figure 6: Module layout of 3 strings per table with horizontal orientation as presented in PVsyst. Partial shading at 09h00 (grey area) affecting the electrical performance of the bottom string (yellow area).

This version of PVsyst provides the option to define the electrical effect of shading as per “module layout”, where modules are assigned into strings both mechanically and electrically. This gives the most accurate evaluation of the electrical losses due to shading.

6.2 Another aspect of plant layout which has repercussions on Balance of System costs is the physical location of string inverters with respect to a centrally located transformer station. The options of centralised and de-centralised installed inverters are assessed in this study with respect to cable usage.

7 BALANCE OF SYSTEMS

The term Balance of Systems (BOS) covers all the components of a PV installation excluding the modules. As a result of the rapid decrease in the price of the modules, the minimisation of BOS costs has taken an important role in the optimisation of a PV plant.

Choices such as string length and inverter architecture have a considerable effect on the type and costs of BOS. For example, central inverters inevitably employ dc junction boxes which are not required with string inverters. The latter would employ instead ac junction box if a decentralised layout is implemented.

Under this heading, issues such as the cost effectiveness of employing low loss medium voltage transformers for the grid connection, or the balance between the level of granularity in the plant monitoring system and its costs are assessed.

7.1 Cable selection.

Traditionally, the determining factor in cable selection is the allowable voltage drop across the cable. For economic reasons, the maximum voltage drop allowed on the dc side is usually 1% of the string open circuit voltage at STC [5]. In line with other industrial application, 5% of the nominal grid voltage is commonly applied on the ac side as an upper limit [6]. It is the opinion of the authors, however, that evaluating voltage drops using STC parameters is simply a snapshot of the system at that full production condition. Since STC conditions are hardly met in practice, this approach may not result in the best choice of cable.

The approach adopted in this study in assessing cable selection is based on comparing the I^2R losses in the cables for different layouts and different cross sections. The I^2R is calculated on an hourly basis for the whole year. The required 8760 values of current are generated by the PVsyst simulation and exported as a CSV file for manipulation in EXCEL.

8 LCOE AND IRR AS THE OPTIMISATION METRICS

LCOE, expressed in cents per kWh, is traditionally employed to compare the cost of electricity from different technologies or different energy sources over the total lifetime of the project. A similar use of the LCOE is made in optimisation studies, where the LCOE takes the role of an internal metric in order to evaluate design options within the project in order to access whether such changes are economically beneficial over the project's entire lifetime. The LCOE approach encompasses on one hand all the project capital and operational costs and on the other hand the energy generation. The latter aspect takes into account a yearly degradation factor and an estimate of system availability.

A weakness in the LCOE calculation is its sensitivity the discount factor. An equally valid optimisation metric and which is not subject to the right evaluation of the discount factor, is the Internal Rate of Return (IRR). Expressed as a percentage, it represents the annual return of the investors from the project and traditionally is employed to gauge the worthiness of an investment. Optimisation aims to minimise the value of the LCOE and at same time to maximise the IRR figure.

In this paper, optimisation results are expressed in both LCOE and IRR. A discount factor of 5.68% has been adopted in the LCOE calculation. This figure has been established by evaluating the Weighted Average Cost of Capital (WACC) of a typical financial structure for a PV project of this magnitude.

9 MAIN RESULTS

As mentioned earlier, the design options which lead to plant optimisation are validated by the economic performance of the PV plant as measured by its LCOE and IRR. However, it is important to assess the results of some individual aspects of the plant design prior to evaluating their cumulative effect on the LCOE and IRR values.

9.1 Transposition gain and optical losses with tilt angle.

Transposition gain increases with tilt up to an optimum angle which is close to the latitude of the country, which in the case of Malta is about 35˚. The optical losses, a combination of irradiance loss due to mutual shading and reflexion losses, increase drastically with an increase in tilt as shown in Fig 7.

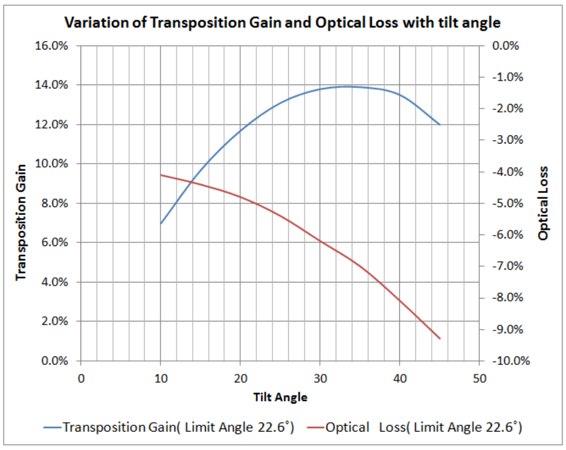

Figure 7: Varation of transposition gain and optical losses with tilt.

Combining these opposing effects results in the effective irradiance on the modules reaching a peak value at a tilt which is much lower than that at which maximum transposition gain occurs, as shown in Fig 8. This result shows that the common belief that energy production is maximised by having a tilt angle equal to the latitude of the place of installation does not apply to parallel row arrangements. Peak yield should occur at lower tilt angles.

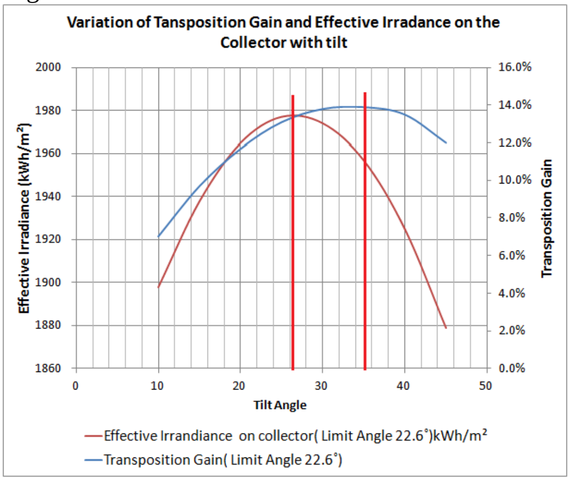

Figure 8: Variation of effective irradiance with tilt.

9.2 Yield with tilt and limit angle

Fig. 9 shows the plot of the specific yield with tilt for the range of limit angles considered in this paper for a central inverter configuration of 2x875kW. As was predictable, the best yields are obtained at the lowest limit angle (18.7˚) while the worst yield occurs at the highest limit angle (27.5˚). From an energy production perspective, the best performance is obviously obtained by spacing the rows furthest apart.

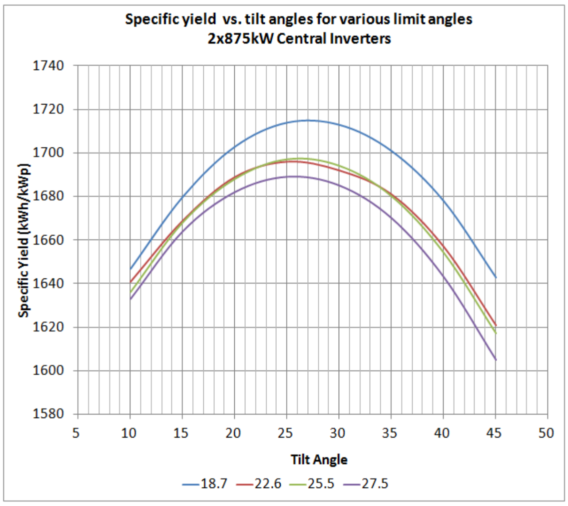

Figure 9: Variation of specific yield with tilt for the various limit angles considered.

The plots for limit angles 22.6˚ and 25.5˚ show negligible variation in the specific yield. The important repercussion of this result is that for the same specific yield, a plant layout with a limit angle of 25.5˚ would result in land savings of about 7% when compared to using a limit angle of 22.6˚, as shown in Fig 10. This pattern in the plots of the specific yield is common for all the inverter configurations considered.

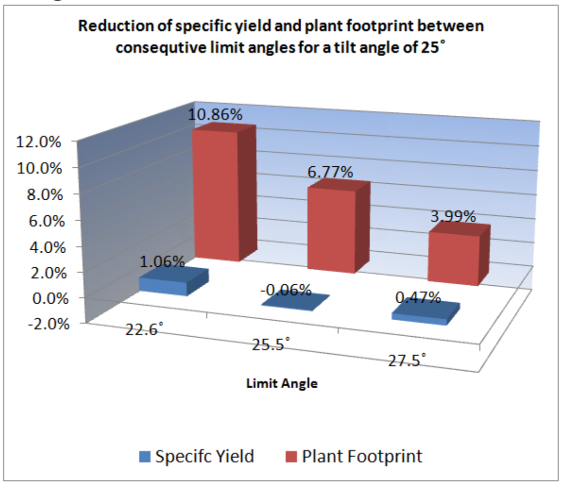

Figure 10: Reduction of specific yield and plant footprint for consequtive limit anlges.

9.3 Yield and inverter architecture

The expectation was that the effect of mutual shading resulting from the parallel rows layout on energy generation would be more pronounced with central inverters rather than with string inverter architecture. The latter, having dedicated MPPT for each string input, is able to adjust the operating voltage separately for the different shading conditions experienced on each string connected to individual inverters. This means that at any point in time, the PV plant would still be operating at maximum power point (MPP). On the contrary, in central inverter architecture, both shaded and unshaded strings are connected in parallel to the same MPPT resulting that during partial shading, the plant would not operate at MPP.

Shading of the beam component of the incoming solar radiation is presented in the loss diagram of PVsyst as electrical loss. Surprisingly, production modelling has shown that the difference between the two architectures in terms of electrical loss due to beam shading is negligible as shown in Fig 11. This figure compares the loss diagrams as generated by PVsyst of a plant configuration with 2x875kW central inverters to another layout with 116x12.5kW string inverters for the same tilt angle of 25˚ and limit angle of 25.5˚. The dc-to-ac ratios of the central and string configurations are 1.14 and 1.15 respectively. This diagram also shows that the "near shading losses" which represent the loss of diffused radiation, are much more severe than the electrical losses related to the shading of the beam component.

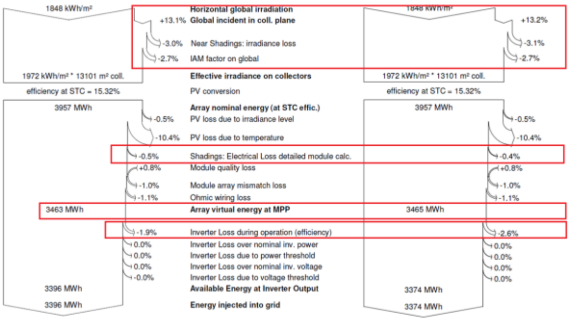

Figure 11: Comparing the loss diagram of one plant layout with central inverters (left) to another with string inverters (right).

9.4 Yield and dc-to-ac ratio

In view of the large kW rating of central inverters, manipulating the dc-to-ac ratio of a plant whose size is specified in MWp is quite restricted. For this study, the options of 2x875kW and 2x1000kW having a corresponding ratio of 1.14 and 1.01 respectively have been modelled. The 2x1000kW option has a marginally better yield. This is mainly due to a better Euro efficiency and due to operation close to the lower limit of the MPP voltage range of the 1000kW inverter model.

String inverter architecture offer much more flexibility from the aspect of the dc-to-ac ratio. Fig 12 shows the variation of the specific yield with tilt for various dc-to-ac ratios corresponding to a physical layout having a limit angle of 25.5˚. This plot reconfirms that a tilt angle of 25˚gives the best specific yield and that that a maximum value is reached at around a ratio of 1.20. Beyond this value, the specific yield starts to decline. This point corresponds to an operation which maximises energy production from the modules.

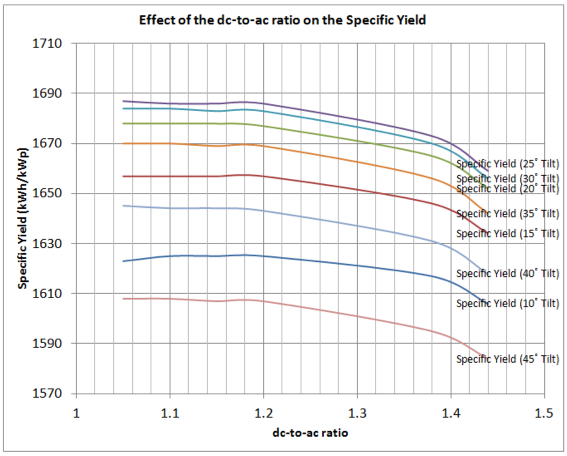

Figure 12: Specific yield for various dc-to-ac rations of string inverters

Worth remarking is that the rate of decrease of specific yield at or near optimum tilt is much higher than the rate of decrease for the non optimum tilts. Modules at very low or very high tilt would already be experiencing a low performance, hence, it is expected that the rate of decrease in specific yield resulting from an increased ratio to be less pronounced then if panels had a near optimum tilt.

9.5 Economic performance.

The economic performance is based on the production modelling results and the current costs for BOS and modules. Excluded are the profits for the plant developer as this is a very subjective element of cost.

9.5.1 String inverter architecture

For string inverter architecture, within the dataset considered, the highest IRR and lowest LCOE occur with the layout having a dc-to-ac ratio of 1.38 with values of 15.16% and 9.16c/kWh respectively. These occur at the lowest considered tilt of 10˚ and the highest limit angle of 27.5˚.

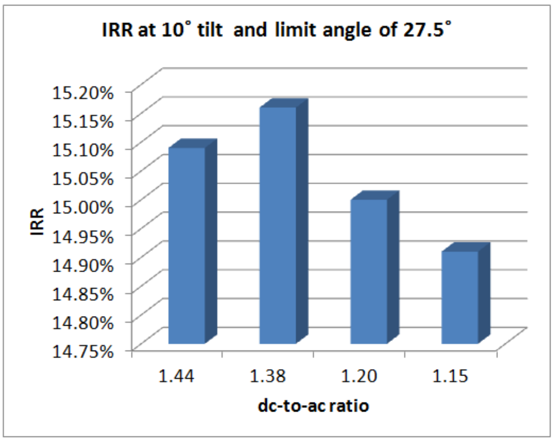

Figure 13: Variation of IRR with dc-to-ac ratio.

The theoretical value of tilt at which optimum IRR occurs can be found by working the derivative of the equivalent polynomial equation of the plot for this limit angle. This optimum tilt works out at 5˚.

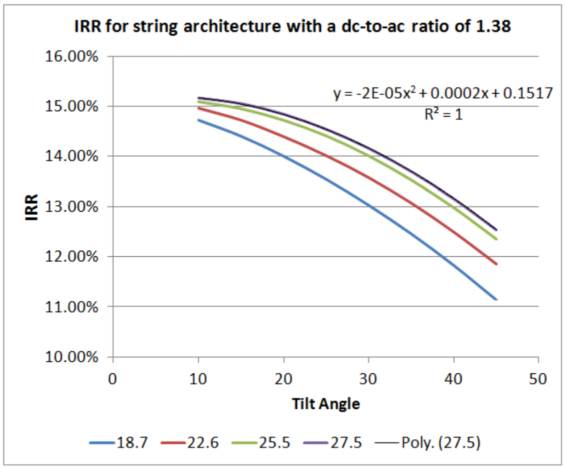

Figure 14: Variation of IRR with tilt angle

9.5.2 Central inverter architecture

The configuration with 2x875kW central inverters resulted in a slightly better IRR than the 2x1000kW layout with values of 15.38% and 15.36% respectively, not withstanding that the latter configuration has a slightly better specific yield. This better IRR could be attributed to the higher dc-to-ac ratio of 1.14 compared to 1.01.

10 CONCLUSIONS

The parameters leading to the best energy performance of the plant are the complete opposite to what is needed to reach optimum economic performance. While from an energy production perspective, a low limit angle of 18.7˚ proved to be the most favourable, from an economic perspective the highest limit angle considered of 27.5˚ gives the best performance. This clearly results from the high cost of land. At an average price of €33,500 per tumoli, the savings in land cost resulting from adopting a high limit angle outbalance the lost revenue from energy lost due to increased mutual shading.

On a similar note, a tilt angle of about 25˚ has been shown to give the highest specific yields. However, it has also been proved that it is more profitable to adopt low tilt angles in order to save on land usage. Although a very low tilt angle of 5˚ gives the highest economic performance, the associated IRR is neglecting the fact that a higher cleaning activity would be needed due to increased soiling. A compromise between self cleaning properties and a favourable IRR may result in a tilt of between 15˚ to 20˚. At a limit angle of 27.5˚ and a tilt angle of 15˚, the PV plant would cover an approximate area of 19 tumoli including service paths and clearance from perimeter fence.

It was also shown that from an energy optimisation perspective, the best yield is obtained with a dc-to-ac ratio of 1.20. However, from an economic perspective, the best return on investment is achieved with a ratio of 1.38 even though this will lead to occasional inverter overload.

Central inverter architecture resulted in better IRR and LCOE values than with string inverters. A major reason behind this result is the fact of having to account for string inverter replacement in year 11. The best economic performance is likely to be achieved using central inverters with the highest dc-to-ac ratio achievable within the limitations of central inverters ratings.

The effect of the hourly resolution of PVsyst on production modelling during partial shading may need to be investigated further. Production modelling of identical plant layouts, but which differed only in the limit angles of 22.6˚ and 27.5˚ showed negligible change in the electrical losses associated with beam shading. The difference between these two limit angles is exactly of an extra hour of shade during the 21st December. A shorter simulation interval of say 10 minutes instead of 1 hour may be more appropriate in order to reproduce more realistically what is taking place during this interval. This is especially relevant when modules are installed in a horizontal orientation and the action of the by-pass diodes.

Further studies could also investigate the sensitivity of the economic metrics to variations in cost of land and FIT.

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