Towards New Renewable Energy Policies in Urban Areas: The Re-definition of Optimum Inclination of Photovoltaic Panels

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Cite as: Weissenbacher, M., Towards New Renewable Energy Policies in Urban Areas: The Re-definition of Optimum Inclination of Photovoltaic Panels, J. sustain. dev. energy water environ. syst., 3(4), pp 372-388, 2015, DOI: http://dx.doi.org/10.13044/j.sdewes.2015.03.0028

ABSTRACT

The optimum inclination and orientation of fixed Photovoltaic (PV) panels has long been defined in terms of maximizing the annual electricity yield per capacity installed according to the hemisphere and latitude where the PV system is located. Such optimum setup would thus also maximize the output per system cost, but it would not maximize the output per unit of available area, and it would not necessarily optimize the contribution of photovoltaic electricity vis-à-vis overall electricity demand patterns. This study seeks to draw the attention of policy-makers to the fact that incentivizing lower-than-optimum PV panel tilt angles can be an inexpensive strategy to substantially increase the renewable electricity yield in a given area. It also discusses how such strategy can be incorporated into an overall supply/demand grid management and renewable energy integration plan.

KEYWORDS

Photovoltaic, Renewables, Energy policy, Inclination, Tilt, Cost of energy, Peak demand, Grid management, Energy planning, Residual load.

INTRODUCTION

This study has its roots in the search for solutions posed by space limitations in island and urban settings. The low energy intensities of renewables per unit area compared to high energy consumption per unit area in settings of high population densities will attract increasingly more attention, given that cities are growing and worldwide more people have been living in urban areas than on the countryside for the first time in 2008 [1]. The concepts described here originated in the analysis of the renewable energy potential of the island nation of Malta, at 1,300 people per km^2 one of the most densely populated countries in the world. Following its accession to the European Union, Malta was committed to achieve a 10% renewable energy consumption share by 2020, up from 0% in 2005 and 1% in 2011. With substantial resistance to onshore wind installations close to urban areas, and water depths prohibitive to conventional offshore wind technology almost everywhere around the islands, it was decided to base the largest fraction of the national renewable energy plan on a single reef-based offshore wind park of 95 MW [2, 3]. However, it has been shown that this offshore wind park is substantially more expensive in terms of cost per kWh of renewable electricity produced when compared to achieving the same output through photovoltaics [4]. With about 80% of food requirements being imported, ground-based solar PV farms would be a somewhat controversial option, while it has been demonstrated that available industrial roofs are sufficiently large to host enough PV panels to replace the entire planned offshore wind electricity production [4]. What is more, the potential of such flat rooftops, or principally any flat area, can be further increased by opting for relatively low panel tilt angles.

OPTIMAL INCLINATION AND SHADING

To maximize the renewable energy yield from a given area should be an obvious goal, but so is the aim to maximize the energy output per generation capacity installed. As will be illustrated here, these objectives might be conflicting as far as photovoltaic systems are concerned, because there is a relationship between panel inclination and the required spacing between rows of panels to avoid cross-shading.

Optimal inclination

The "optimal inclination" of fixed photovoltaic panels, referring to the tilt angle above the horizontal plane, has long been defined in terms of maximizing the annual electricity yield per panel area installed in relation to the angle of incoming solar radiation and thus the latitude at which the system is located. The optimal fixed tilt angle of panels that should always face south when installed in the northern hemisphere has been suggested to be 0.9 times the latitude to achieve the best yearly output in a 1958 study [5]. This was based on simplified assumptions to maximize the annual insolation per unit area. However, various authors have pointed out that the actual optimal inclination may somewhat differ from this recommendation according to site-specific conditions of diffuse and direct irradiation. Local weather conditions certainly influence optimal tilts [6]. In Malta (latitude 35.9°N), the rule-of-thumb would suggest an optimal inclination of 32°, while the actual recommendation put into practice is 30°. The search for the optimum tilt angle (and orientation) at different locations and in different climatic conditions has produced a vast array of journal papers [7-29], and a recent review emphasized that "for maximum energy gain, the optimum tilt angle for solar systems must be determined accurately for each location" [30]. In short, the academic literature usually associates optimum tilt with system output maximization, while the notion of optimum solar panel tilt needs to be redefined if more value is assigned to space and the importance of overall space requirements is emphasized. This has become even more relevant in light of decreasing PV system prices that allow for a deviation of previous strategies focusing exclusively on increasing electricity generation per system capacity investment.

Adjusting the tilt angle at least twice a year, for summer and winter settings, would require somewhat more complex fixtures but increases the annual output [31]. The typical generic recommendation found in the literature would suggest a tilt angle that is some 8° to 15° steeper than latitude in the winter and lower than latitude in the summer [6]. However, the optimal inclination in Cyprus (latitude 35°N), for instance, has been determined as 48° in the winter months (i.e., latitude plus 13°) and 14° (i.e., latitude minus 21°) in the summer [32]. To be sure, systems manually adjustable for two seasonal settings are not too common, in part, as will be discussed below, because the output gains are small. Similarly, single-axis tracked systems with a fixed inclination are often more economical than more complex double-axis systems because the additional gain through automated tilt adjustment typically does not justify the added cost. Generally, the gains achieved by tracked systems compared to fixed systems depend on the ratio of annual diffuse to global horizontal irradiation, with a low ratio providing for higher gains and thus benefitting tracked systems [33]. To be sure, fixed-angle mounting is the most common, with the least installation and maintenance costs, and the one most relevant for rooftops, while tracked systems have long been popular for ground-based solar PV parks in settings of high Direct Normal Irradiation (DNI) or generous feed-in tariffs.

Shading and spacing

The angle of "optimum inclination" as described above has a considerable impact on the space required to be left vacant between rows of solar panels to avoid cross-shading. Shading is especially critical when strings of PV modules connected in series are concerned, because the shading of a single module would influence the output of the whole string (though bypass diodes and per-panel microinverters compared to traditional per-string inverters would help the situation). The space to be left between rows to avoid cross-shading can be determined through sun path diagrams showing the apparent path of the sun at any chosen location for specific days. If fixed panels are to deliver electricity even on the shortest days of the year, around December 21 in the northern hemisphere, the respective minimum angle of the sun over the horizon can be read from such diagrams for that season. This angle will in turn determine how far the shadow of an object will extend on the ground away from the sun.

METHODOLOGY

Following the observation that lower panel inclination angles would substantially reduce ground-cover factors by reducing the need for panel row spacing [4], the effect was quantified as follows. A variety of tilt angles and the effect of deviation from perfect southern orientation (in the northern hemisphere) were modeled with respect to PV system output changes. The open-access Photovoltaic Geographic Information System (PVGIS) was used to create an output matrix (including seasonal output) relative to relevant tilt and orientation angles. In turn the spacing requirements to avoid cross-shading as per chosen tilt angle was calculated based on sun path diagrams for various panel setups (“portrait” and “landscape”) and PV system capacities, and the result was combined with the output matrix to show electricity yield per area utilized in relation to tilt angles. A method was devised to allow for a generic calculation of the relative yield per area utilized as a function of chosen tilt angle that is independent of the actual panel and array dimensions. Findings were evaluated in terms of low-tilt panel temperature, reflectivity, and maintenance issues as reported in journals and by installers and operators. The increased cost per kWh of electricity produced in various setups was evaluated as well. The output effect of lower tilt angles and orientations was compared to electricity demand profiles, and strategies to incentivize lower tilt angles and alternative panel orientations were investigated in the context of grid management and renewable energy goals from the policymaker’s point of view.

CALCULATIONS AND RESULTS

Electricity yield as a function of PV panel tilt angle

As mentioned above, a vast body of literature concerns itself with the impact of the chosen tilt angle on the output within the framework of determining the optimum inclination as traditionally defined. The tilt-output relationship has notably been of special interest with regard to buildings-integrated PV panels, which includes the extreme case of vertical panels and the use of PV panels as shading devices extending at a tilt from a vertical surface [34-36]. Nevertheless, there seems to be a wide bandwidth of scholars’ perception of the relationship. While Beringer *et al*. [37] in 2011 published a “Case study showing that the tilt angle of photovoltaic plants is nearly irrelevant”, a 2012 journal article maintains that “it is well known that the instantaneous and total energy generated for fixed tilt PV systems is heavily dependent on the tilt angle and PV orientation” [38]. To be sure, even standard textbooks indicate that the influence of the tilt angle on the annual output of flat plate non-concentrating photovoltaic systems of fixed orientation is low [39]. In a 2011 study Bayod-Rújula *et al*. used a commercial software package (PVSyst) to estimate the output of various types of PV panels at different tilt angles at the University of Zaragoza (latitude 41.6°N), showing that the annual difference between the optimal 30° and 10° is below 6% in terms of kWh per kW peak (kW_p) installed [40]. Huld *et al*. [41] reported that according to calculations based on PVGIS a PV system with two seasonal inclination angles, assuming biannual adjustment, would not gain more than 60-70 kWh per kW_p in the Mediterranean region when compared to the configuration of single fixed optimum angle. For comparison, a new PV system installed at fixed optimum angle would yield some 1,650 kWh/kW_p in Malta. The gain would thus be about 4%.

Modeled annual and seasonal PV system output for various tilt angles. To model the electricity output depending on panel orientation and tilt angle the Photovoltaic Geographic Information System (PVGIS) [42], a tool for the geographical assessment of solar resource and performance of photovoltaic technology, was employed. The model algorithm estimates beam, diffuse and reflected components of clear-sky and real-sky global irradiance/irradiation on horizontal or inclined surfaces at a selected location. For the Mediterranean, there is a choice of two solar radiation databases. One of these relies on ground measurements, which is most accurate if nearby ground station data actually exists for the chosen location to avoid less accurate interpolations based on stations located at a distance. The other is based on satellite data (CM SAF - The Satellite Application Facility on Climate Monitoring) to provide a fairly uniform coverage of large areas. As the potential problems associated with the satellite method (snow, mountain areas, very low winter sun at high latitudes) are not relevant in the selected area, and the output results matched measured PV output in the chosen location much closer, the CM SAF database was used for the calculations. As for the PV technology, crystalline silicon, CIS and CdTe can be selected. For the results presented here, crystalline silicon, the most common material, was chosen. The typical system performance ratio value of 0.75 for systems employing modules made of mono- or polycrystalline silicon was slightly adjusted (by less than 1%) to fit the optimal-inclination annual output of (initially) 1,650 kWh/kW_p as experienced in practice at the chosen location in Malta (latitude 35.9°N). Table 1 shows the modeled annual system output in percentage terms relative to the 100% value for 30° tilt for various lower tilt angles as well as orientations deviating from perfect south.

Table 1. Modeled annual PV system output in percentage terms relative to the 100% value of a 30° panel tilt in Malta (latitude 35.9°N) for various lower tilt angles and orientations deviating from perfect south

Tilt	Orientation									Tilt
	toward West				South	toward East				
	40°	30°	20°	10°	0°	10°	20°	30°	40°	
0°	88	88	88	88	88	88	88	88	88	0°
5°	91	92	92	92	92	92	92	92	91	5°
10°	93	93	94	95	95	95	94	94	93	10°
15°	95	95	96	96	97	96	96	96	95	15°
20°	95	96	98	98	98	98	98	97	96	20°
25°	96	98	98	99	99	99	99	98	96	25°
30°	96	98	99	99	100	99	99	98	96	30°

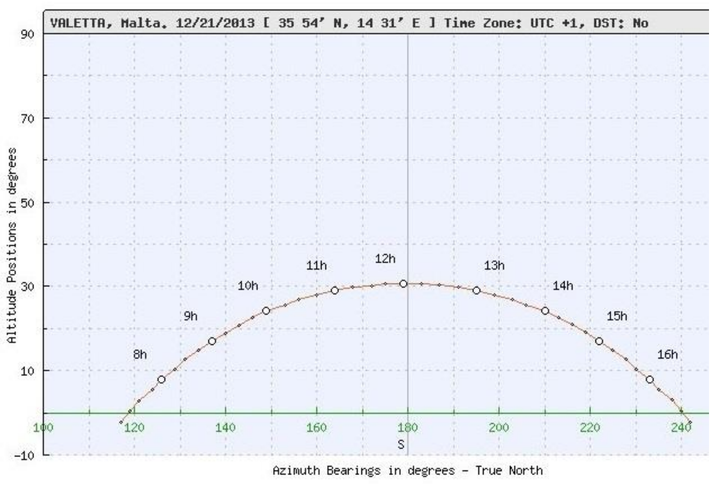
Table 2 shows the same, but for the output during the month of July. The results clearly demonstrate a low degree of dependence of annual output on panel inclination over the given range, with a loss of just 5% if the tilt is lowered from the recommended 30° to 10°. Furthermore, the results showed that losses due to non-optimal orientation are also low within the presented limits: a deviation from perfect south to either west or east by 40° leads to a loss of 4% at a tilt angle of 30°, and even less at lower tilt angles. As far as summer output is concerned, the model results show an 8% output gain for the month of July if the panel inclination is lowered to 10°, and that July output gains for all shown tilt angles are not sensitive to modeled orientation variations. Notably, no further gains can be achieved in July if the tilt angle is lowered below 10°.

Table 2. Modeled PV system output for the month of July in percentage terms relative to the 100% value of a 30° panel tilt in Malta (latitude 35.9°N) for various lower tilt angles and orientations deviating from perfect south

Tilt	Orientation									Tilt
	toward West				South	toward East				
	40°	30°	20°	10°	0°	10°	20°	30°	40°	
0°	108	108	108	108	108	108	108	108	108	0°
5°	108	108	108	108	108	108	108	108	108	5°
10°	108	108	108	108	108	108	108	108	108	10°
15°	106	106	106	106	106	106	106	106	106	15°
20°	105	105	105	105	105	105	105	105	105	20°
25°	103	103	103	103	103	103	103	103	103	25°
30°	101	101	101	100	100	100	101	101	101	30°

Spacing requirements according to chosen location and panel tilt angle

Sun path information. Before the PV system electricity output per area unit utilized can be calculated, the spacing requirements to avoid cross-shading need to be determined. The spacing requirements depend on the location, the chosen panel tilt angle, and the time span during which the PV system is expected to deliver electricity on a sunny winter day. All these factors are associated with the sun path observed at the location, which in turn determines the length of shadows. The sun path for any day at any latitude can be obtained through specialized PV planning software, but it can also be generated instantly at various Internet sites. (Professional photographers may rely on such information for their work, for instance.) Figure 1 has been generated through a website (SunPosition.info) that uses coordinates supplied by the National Geospatial-Intelligence Agency (NGA) and the Geographic Names Information System (GNIS). The factors delivered are the azimuth angle and the altitude angle. The azimuth angle is the horizontal direction expressed as the angular distance between the direction of a fixed point (as in true north, for instance) and the direction of an object. The altitude angle is the angular elevation of a celestial object above the horizon. As can be seen in Figure 1, the sun will be seen at an altitude of 17° about 42° towards the east and towards the west relative to true south in Malta on December 21 at 9 AM and 3 PM, respectively, while the altitude angle will be 24° and the azimuth angle ca. 30° relative to true south at 10 AM and 2 PM.



Time	Azim.	Alt.
09:00	137°	17°
09:15	140°	19°
09:30	143°	21°
09:45	146°	23°
10:00	149°	24°
11:00	164°	29°
12:00	179°	31°
13:00	195°	29°
14:00	210°	24°
14:15	213°	23°
14:30	216°	21°
14:45	219°	19°
15:00	222°	17°

Figure 1. Sun path diagram for a location in Malta (35.9°N 14.5°E) for 21 December 2013, with azimuth and altitude angles shown in tabular form on the right-hand side for 9 AM to 3 PM (created through the SunPosition.info website)

Spacing requirements according to azimuth and altitude angles. Figure 2 shows how the shadow of an inclined panel extends away from the sun according to azimuth and altitude angles.

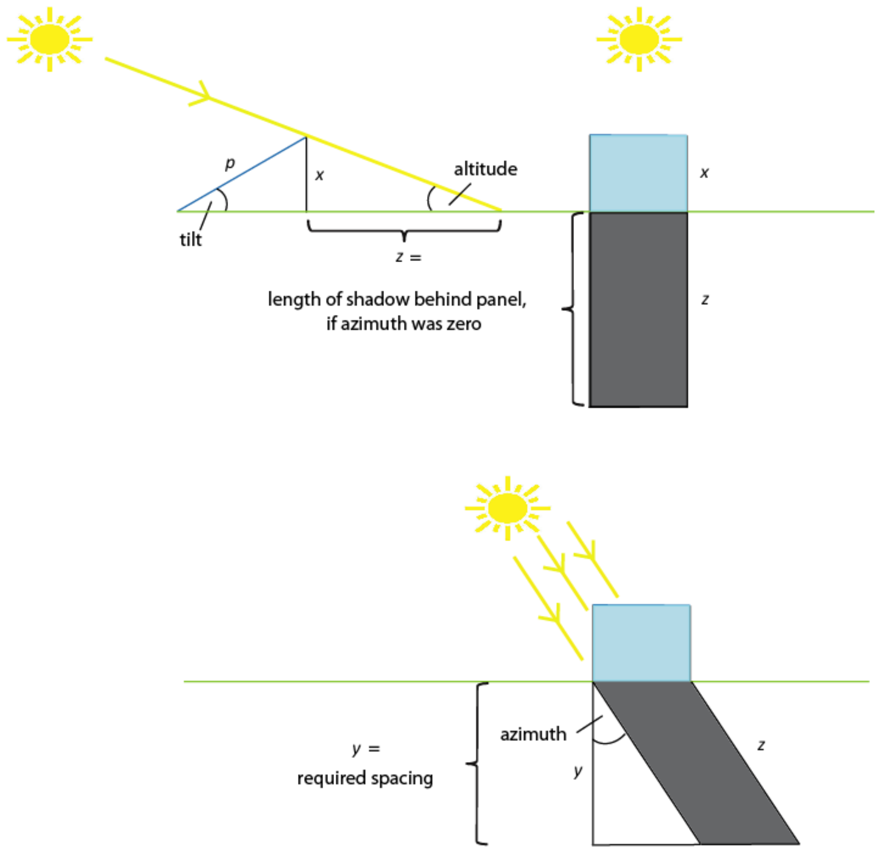


Figure 2. The length of an object's shadow extends away from the sun according to azimuth and altitude angles. The upper figure depicts the situation of an azimuth angle of zero, while the required distance between panel rows to avoid cross-shading is reduced for the same altitude angle if the azimuth angle does not equal zero (lower figure)

Referring to Figure 2, the trigonometric relations to calculate the required spacing distance y at given azimuth and altitude angles are as follows:

$$z = x \;/\; \tan[\text{alt}] = y \;/\; \cos[\text{azi}] \tag{1}$$

$$x = P\,\sin[\text{tilt}] \tag{2}$$

$$y = (P\,\sin[\text{tilt}]\,\cos[\text{azi}]) \;/\; \tan[\text{alt}] \tag{3}$$

If P is taken as 1,660 meters, which is a typical length for PV panels of 200 W_p (polycrystalline) to 245 W_p (monocrystalline) capacity, the required spacing distance y can be calculated for different tilt angles by using azimuth and altitude angles obtained as described above:

tilt: 30°	tilt: 15°
no shading 10:00 to 14:00:	no shading 10:00 to 14:00:
azi: 30°, alt: 24°	azi: 30°, alt: 24°
y = 1,614 meters = 1.9x	y = 0.836 meters = 1.9x
no shading 9:00 to 15:00:	no shading 9:00 to 15:00:
azi: 42°, alt: 17°	azi: 42°, alt: 17°
y = 2,017 meters = 2.4x	y = 1,044 meters = 2.4x

The results show that in Maltese settings the distance y in front of south-facing panels should be 2.4 times the vertical height x of any object in front of them if cross-shading is to be avoided between 9 AM and 3 PM on December 21, or 1.9 times the vertical height x if shading is to be avoided between 10 AM and 2 PM. A factor of 2 has in turn been used for the further calculations presented here. Figure 3 indicates how much space can be saved due to the decreased spacing requirements by lowering the tilt angle from the "optimal" 30° to 15° with a spacing factor of 2 (i.e. $y = 2x$).

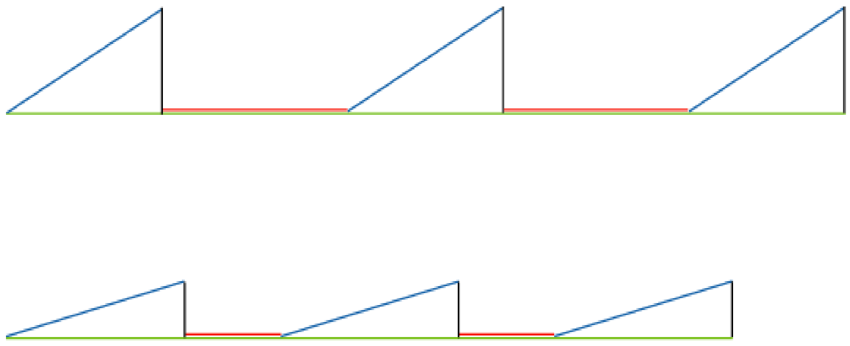


Figure 3. Lowering the panel tilt angle from 30° (upper part) to 15° (lower part) significantly reduces the distance to be left between strings of panels to avoid cross-shading, and thus the area occupied by the same number of panels. A spacing factor of 2 (i.e. $y = 2x$) has been used for the illustration

Area occupied by adequately spaced panel strings

With the spacing requirements established, the area occupied by adequately spaced strings of panels can be determined. The area requirements are represented by the spacing between the panels and the area underneath the panels, as shown in Figure 4.

Referring to both Figure 2 and Figure 4, the following relations can be noted:

$$\overbrace{P \sin[\text{tilt}] \cos[\text{azi}] / \tan[\text{alt}]}^{y} + P \cos[\text{tilt}] = T \tag{4}$$

With $y = 2x$, $y = 2 P \sin[\text{tilt}]$:

$$2 P \sin[\text{tilt}] + P \cos[\text{tilt}] = T \tag{5}$$

$$P \underbrace{\{2 \sin[\text{tilt}] + \cos[\text{tilt}]\}}_{A} = T \tag{6}$$

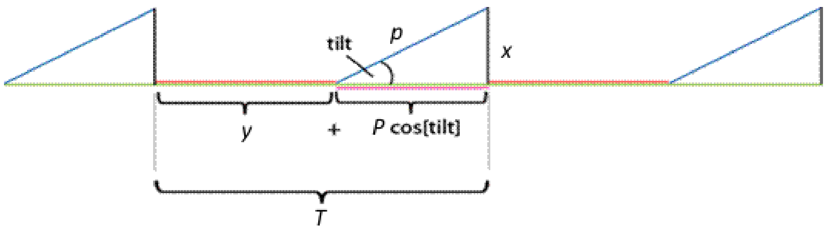


Figure 4. The area requirements of strings of PV panels are represented by the required spacing distance *y* and the distance underneath the panel (*P* cos[tilt]), with both distances changing according to the tilt angle employed

To be sure, factor *P* can take two different values for a given panel size, depending on whether the orientation "portrait" (smaller panel side touching the ground) or "landscape" is chosen for the panels. For a given orientation choice, *P* becomes constant, and the distance *T*, representative of the area requirement of multiple strings of panels spaced at adequate distance, will be a function of the tilt angle, the azimuth angle, and the altitude angle in the context of shading as described above. Notably, if *T* was to be minimized by choosing a tilt angle of zero, *T* would equal *P*. If adequate spacing is defined through $y = 2x$, as illustrated above, the distance *T* for a chosen panel orientation will be a function of the tilt angle only, and the factor *A*, equaling {2 sin[tilt] + cos[tilt]}, becomes representative of the area requirements of adequately spaced strings of panels at a given tilt.

Calculation of output per area utilized

The last step to calculate the output obtained from PV panels at different tilt angles per area utilized is to combine the area requirements with the output of PV systems that employ various panel tilt angles. Table 3 shows for south-facing panels the annual PV system electricity output for six lower tilt angles relative to the 100% value for the "optimum" 30° tilt in Malta (latitude 35.9°N), and relates this output to the space requirements to obtain the output per occupied space. Table 4 shows the same for the output in the month of July. Figure 5 shows the large gain in terms of output per area to be occupied by the PV system compared to the small decrease in output per capacity installed when the tilt angle is lowered from the "optimum."

In principle an assumption would have to be made on the spacing requirement in front of the first panel row. Sometimes flat roofs have boundary walls for safety reasons, and these could be somewhat higher or lower than the panel arrays, or the installer might decide to lift the entire setup, especially in case of smaller installations. However, for larger installations with several panel rows the one spacing requirement in front of the front row quickly becomes irrelevant compared to the total system area requirements (or can be assumed as being the same as for the other rows).

The method devised here allows for a quick calculation of the output that can be achieved with fixed-tilt PV installations on a given area of land or rooftop space, especially as compared to the tilt angle considered "optimal" (for which experimental data tends to be readily available). The factors T and A are representative of the area to be occupied by the installation according to area occupied by adequately spaced panel strings section and allow for a straightforward comparison of different setups, while the factor P can be obtained from panel specifications to calculate the occupied area in absolute terms. Typical panel dimensions, as taken from the specification sheet of a popular brand, are about 1.66 meters by 0.99 meters, with such modules consisting of 60 (156 mm × 156 mm) cells, and being rated up to ca. 245 W_p when monocrystalline, or ca. 200 W when polycrystalline. The choice of using panels in either "portrait" or "landscape" orientation will generally depend on the width of the available area, where width refers to the east-west stretch if the available plot allows for panels to face true south. (As shown in Table 2, deviation from perfect south would only result in minor losses and can thus be encouraged should this be required in order to allow for the placement of a significantly larger number of panels.) Any calculation with specific panel dimensions and panel orientations will confirm the results shown here in relative terms based on the equations provided above: The gains in output per unit of area available are large, while the output losses per capacity installed are very small, when the panel tilt angle is lowered below the angle that is generally considered "optimal." Naturally, the effect will get smaller in regions closer the equator, as "optimal" tilt angles will already be flatter. In Maltese settings, as demonstrated in this study, the electricity yield per square meter of space utilized with a 15° tilt angle setup compared to the 30° setup increases by 22% annually, and by 33% in July. Meanwhile the output increase for the setup with 10° tilt angles would be 33% per year, and 51% in July.

To be sure, the choice of "portrait" versus "landscape" orientation will not be influenced by the plot width alone. Maximizing the output from a given area would in principle call for the placing of as many panels as possible on a single plane (slope) to avoid spacing between panel rows altogether. Putting panels flat on the ground would be a variant of this strategy, but it would entail the largest losses per capacity installed. A long inclined plane, however, involves other issues. For reasons of safety (occurrence of strong wind) and visual impact, the height to which panels may extend over a flat roof is usually regulated. In Malta, this height was limited to 1.5 meters by authorities in 2007 (although the guidelines have not been strictly enforced). The height limitation is critical, as it determines how many panels may be placed onto a single plane in "portrait" or "landscape" orientation at different tilt angles before the limit is exceeded. Tilted at 30°, not even two panels of the given dimensions can be placed on one plane without exceeding a height of 1.5 meters in "portrait" orientation, while this is possible in "landscape" orientation. Observing the height limit of 1.5 meters, but assuming no limitations due to the exact plot shape, a 3 kW_p system consisting of fifteen 200 W panels as densely packed as possible in rows at various tilt angles would somewhat advantage the 30° tilt setup, because its "landscape" orientation with two panels per plane comes close to the 1.5 meter height limit. Nevertheless, the percentage increase for comparable setups employing lower tilt angles will result in percentage increases close to those given in Tables 4 and 5, thus indicating that the method devised here delivers results that are indicative for complex setups as well. Generally, a height regulation may be an additional incentive to employ low tilt angles, and the multiple-panel plane may be a good design especially for the last panel row. To be sure, the relations noted remain the same for planes that have multiple panels on one slope. The factor *P* just needs to be replaced by a factor $P_{effective}$ that would be a multiple of the single panel length *P* (Figure 6).

Table 3. Annual PV system output relative to the 100% value for 30° tilt in Malta (latitude 35.9°N) for south-facing panels at various lower tilt angles with output per area utilized. Factor *A* is representative of the area occupied by the PV installation according to the main text

Tilt	Relative annual output [%]	*A*	Rel. output/*A*	Rel. output per area utilized [%]
0°	88	1	88	164
5°	92	1.17	78.6	147
10°	95	1.33	71.3	133
15°	97	1.48	65.4	122
20°	98	1.62	60.4	113
25°	99	1.75	56.5	105
30°	100	1.87	53.6	100

Table 4. PV system output for the month of July relative to the 100% value for 30° tilt in Malta (latitude 35.9°N) for south-facing panels at various lower tilt angles with output per area utilized. Factor A is representative of the area occupied by the PV installation as described in main text

Tilt	Relative annual output [%]	*A*	Rel. output/*A*	Rel. output per area utilized [%]
0°	108	1	108	201
5°	108	1.17	92.3	172
10°	108	1.33	81.1	151
15°	106	1.48	71.4	133
20°	105	1.62	64.7	121
25°	103	1.75	58.8	110
30°	100	1.87	53.6	100

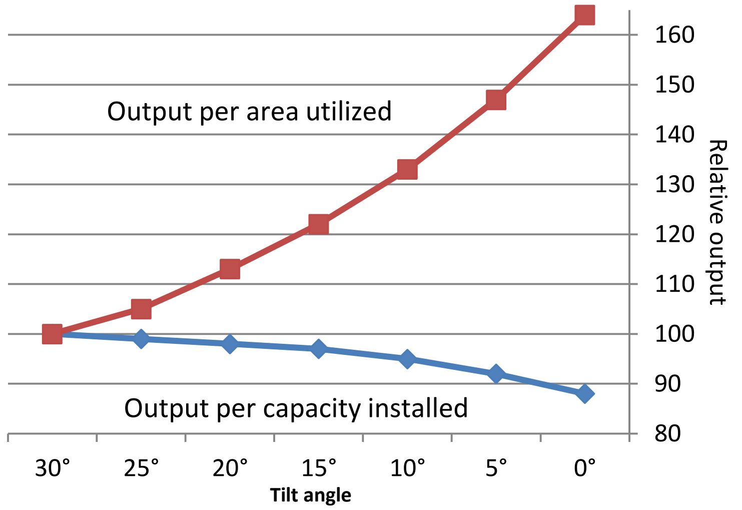


Figure 5. The gain in terms of output per area occupied by the PV system is large compared to the decrease in output per capacity installed when the panel tilt angle is lowered from the "optimum". The shown graphs are for Maltese settings in the context described in the main text

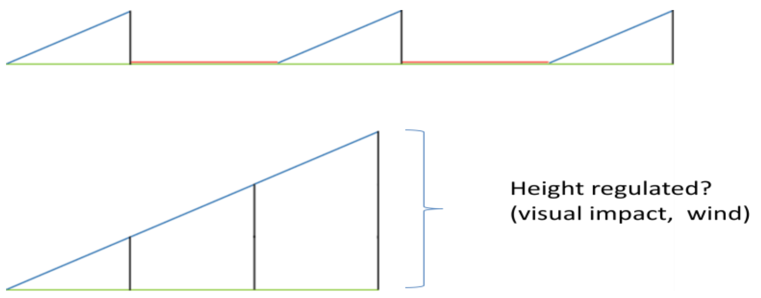


Figure 6. Placing multiple panels on one slope can in principle eliminate the spacing requirement. This figure shows a situation where $P_{effective} = 3\ P$

Grid integration issues

As evident from the annual and July output tables presented here, lower panel tilt angles shift more PV electricity generation towards summer months. In a separate study we have tested the effect of employing lower than usual PV panel tilt angles on overall electricity demand in Malta [43]. Figure 7 shows residual load curves for a situation where 169 MW_p worth of PV capacity in a 2020 scenario are employing either 30° or various lower tilt angles with south-facing panels. The chosen capacity is six times the PV capacity required according to Malta's National Renewable Energy Action plan when the output of 30° tilt panels is concerned. The residual load curves show that according to season (sun path, temperature) either steeper or lower tilt angles leave less residual electricity demand. Notably, there is no significant difference in the residual load during the summer when 30° tilt panels are compared to those of 20° and 10°. And when orientation variations are included in the model, it is not a flat-tilt setup but a 30° tilt with a southwestern orientation that would leave the lowest residual load at any hour during the year (on a Sunday afternoon in late April).

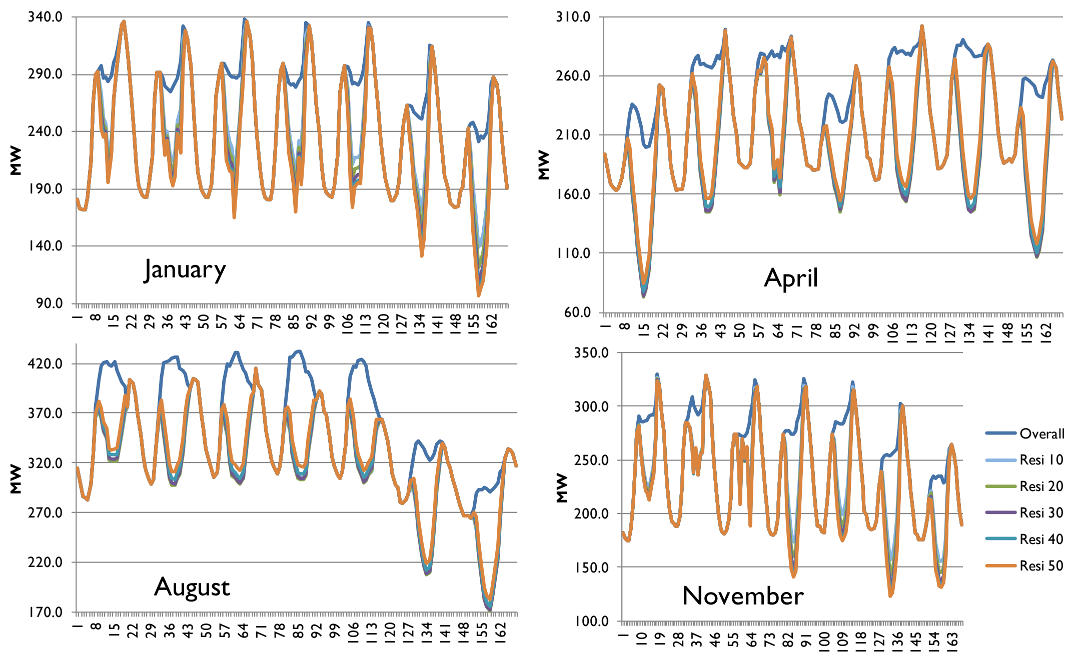


Figure 7. Seasonal residual load curves for projected 2020 Maltese electricity demand ("overall") and a PV penetration of six times the capacity as required by 2020 according to the National Renewable Energy Action Plan. Shown are hours of single weeks with all PV capacity south-facing for tilt angles varying from 10˚, 20˚, 30˚, 40˚to 50˚ [43]

In short, the grid integration aspect of lowered tilt angles has limited relevance when the comparison is based on the same installed PV capacity, but the differences will be enlarged according to Tables 4 and 5 when same-size utilized areas are compared.

CONCLUSION AND RECOMMENDATIONS

The method devised here allows for a straightforward evaluation of electricity output of PV systems in relation to tilt angle employed and total area occupied by the installation. The results clearly indicate that policymakers in any environment in which space is scarce should encourage the use of lower PV panel tilt angles within the described context. This includes cities, where the effective utilization of rooftop space would provide more renewable electricity generation close to the point of consumption and thus avoid transmission losses. Planers and installers should likewise be fully aware of the benefit of lower tilt angles whenever their goal is to maximize electricity output from a given rooftop or area of land. As the cost of photovoltaic systems has fallen radically in recent years [4], while the output decrease per capacity installed is within single-digit percentage points for tilt angles lower than "optimal," an accordingly small increase in levelized cost of electricity should most definitely be acceptable compared to the described increase in electricity production achieved per area unit of rooftop or other space utilized. In short, the falling costs of photovoltaic systems have in recent years significantly changed the relative value of panels compared to space wherever space is scarce [44]. The current paradigm of "optimally inclined" solar panels should change, and the focus should somewhat shift from electricity output per system capacity installed to include renewable energy harvested per unit of space available. Generally, any notion of "optimal" will depend on what should be optimized, but the notion of what is meant by "optimum tilt" has so far been very rigid in the literature, though with a noteworthy deviation concerning optimization for specific seasonal output and stand-alone systems seeking year-round energy autonomy rather than maximization of the annual energy yield [45, 46]. The definition of optimal azimuth angle (i.e. the orientation of panels) tends to be even less flexible. This may be viewed as problem in the context of a low awareness that, as shown in this study, deviation from the optimum results in very small output losses and should therefore be recommended if the given shape or orientation of a building roof or plot of land would suggest such deviation. Perhaps more significantly, the notion of what is optimal in terms of orientation can well differ from the single-system annual output maximization when the sum of all installations in a region is concerned or when a single system is being optimized according to self-consumption demand patterns [43].

Choice of specific low tilt angle

When it comes to recommendations of specific low tilt angles in the context described, local conditions of the sort that may not be reflected in models have to be taken into account. Due to practical experience PV installers and suppliers in Malta inform their clients that PV panels installed at less than 15° tilt need more cleaning to perform well because of increased dust accumulation, especially during the arid season. Based on the results presented here, and taking this information into account, it can thus be recommended to change the general tilt guidance from 30° to 15° in the context described. A recommendation of 10° inclination is less straightforward, because the additional cleaning requirement would increase the maintenance cost. This includes both labor costs and the cost of water that may be scarce during summer months. Nevertheless, a 10° tilt might be the right choice for particular industrial rooftop plants, e.g., if employed workers have idle time and sufficiently clean grey water is available for the cleaning of panels, say, twice a week. It may also be the right choice for buildings that self-consume a lot of electricity during summer days, such as food storage facilities that require a lot of cooling. Yet another issue is the fact that the performance of PV cells decreases with increasing panel temperatures, a situation promoted by lower tilt angles. However, Huld *et al*. [41] reported that shallow-angle reflectivity reduces more output for fixed panel systems than the effect of temperature does. In this respect the continued development of better anti-reflection solutions would benefit lower tilt angle configurations. Importantly, rooftop PV installations of lower-than-optimal tilt provide more shading for the roof, which keeps the building's roof cooler and reduces the cooling requirement for the building in the warm season. This would be an additional benefit generally supporting the recommendation provided here, though adequate roof insulation would reduce the gain, and the total year-around energy balance would play a role because buildings with more open roof space would absorb more energy during sunny winter days to reduce heating requirements.

Management of summer peak electricity demand and high PV shares

The feature that lower tilt angles provide for a significantly higher output during summer months in terms of output per area utilized (Table 5) may also be an advantage in a macro-planning context in areas of high daytime summer electricity demand that is typical for regions of warm climate where roofs tend to be flat and the summer cooling demand tends to be high. On a large enough scale the increased summer PV output may then translate into considerable cost savings for the electricity sector as a whole, because it is more expensive to meet peak demand than base demand with conventional means. In Malta, for instance, where the power sector is currently undergoing a profound change, the base load has traditionally been met through steam turbines running on heavy fuel oil, while gas turbines, fueled by gas oil that is over 50% more expensive than heavy fuel oil on a weight basis, were fired up to meet peak electricity demand. Notably, gas turbines, though valued for their flexibility, show reduced efficiency at part-load. This point needs to be taken into consideration when policymakers are planning for PV electricity to cover part of the daytime electricity demand. To be sure, it may turn into a concern in regions of high PV penetration if too large shares of the total electricity supply would be contributed by PV installations, for instance during sunny week-ends (when overall electricity demand tends to be relatively low). This issue received special attention due to the "50.2 Hertz effect" that could take large PV capacities from the grid all at once, causing an unmanageable sudden power variation that would be amplified by a consequent simultaneous re-connection. (The "50.2 Hertz effect" refers to a requirement for generators connected to the low voltage distribution network to immediately shut down when a frequency of 50.2 Hz is reached.) Another problem associated with high PV (or more generally intermittent renewables) shares may occur when part of the base load is covered by renewable electricity, because it can be difficult or expensive to alternately switch off and on the traditional base load generation systems (such as coal-fired steam turbines). In this respect lower tilt angles may be viewed a disadvantage, if PV output would be less evenly distributed throughout the year, and more concentrated in the summer. Here the advantages of a wide spread of both tilt and azimuth angles may instead come into play. If collective production from uniform orientation/tilt starts overshooting demand on some days of the year, there would be value in managing the distribution from the macro-standpoint, for instance by orientating a percentage of all fixed-tilt installations to the east and to the west to achieve a more balanced output distribution throughout the day. (This could also be achieved through energy storage options, but those tend to be costly [47].)

Table 5. PV system electricity output per square meter utilized, annually and for the month of July, in percentage terms relative to the 100% value for 30° tilt in Malta (latitude 35.9°N) and two selected lower tilt angle configurations, with panels orientated towards true south and adequately spaced as described in the main text ($y = 2x$). Summer output would be significantly higher from any given area if a 15° or 10° angle would be chosen

Tilt	Annual output [%]	July output [%]
10°	133	151
15°	122	133
30°	100	100

Incentivizing low tilt angles

No matter if a shift towards more summer and less winter output would be desirable or not, lower tilt angles as described here will provide for a substantially increased annual output and thus for larger renewable energy shares in a given region. In Malta this might be essential to meet renewable energy goals as imposed by the European Commission, especially in the context of potential goals that go beyond the 2020 targets. If lower PV panel tilt angles would become part of an overall renewables strategy, there would be various conceivable ways how to incentivize their implementation. Grant schemes such as those previously witnessed in Malta for industrial roof-based PV installations are capped and thus encourage a setup with highest per-panel output that leaves space vacant. Feed-in tariffs, on the other hand, could be differentiated to compensate low-tilt setups for slightly lower output per capacity installed in order to achieve optimal and full utilization of the available space. Generally, the steep decline in PV panel cost has increased the relative cost contribution of space to overall cost, which should promote the better utilization of space. Along similar lines, optimal utilization could perhaps be best achieved through high enough rents wherever rooftop (or other) space is indeed leased by the developer of the project. Besides, governments could even regulate tilt angles in the context of an overall national renewable energy policy in order to ensure best utilization of available space or to manage electricity supply patterns. In Malta this might be especially relevant, as much of the available rooftop space is in industrial estates that are state-owned. Importantly, the cost of the incentive, may it be a higher feed-in tariff or any other measure leading to the use of lower tilt angles, needs to be evaluated within the overall context of electricity supply/demand management and in comparison to the cost of meeting summer daytime electricity (peak) demand through other means. And it needs to be compared to the support required by other renewable energy options: The cost of electricity produced by an onshore PV system with less-than-optimally inclined panels is still lower in Maltese settings, for instance, than the cost of various proposed marine-based renewable energy options such as offshore wind, wave, and floating PV. It is thus more reasonable to promote the use of lower tilt angles on the limited rooftop space available to achieve overall renewable energy goals as cost-effectively as possible.

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Paper submitted: 16.01.2015
Paper revised: 02.03.2015
Paper accepted: 02.03.2015