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Matching PV Array Output With Residential Load by Optimisation of Array Orientation

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***Abstract*—Currently PV modules are positioned to receive the highest amount of incident radiation in a year. Therefore, the generation pattern is independent of the consumption and a large storage is required to compensate for the same. This paper studies the possibility of orienting the modules differently in order to match the consumption more efficiently.**

***Index Terms*—PV System, Smart Grid, Battery Storage**

I. Introduction

The usual guiding principle in the determination of optimal orientation for photovoltaic arrays in PV installations is maximisation of energy yield. That is, given a certain set of conditions, the modules are placed in such a way as to receive the greatest amount of incident irradiation in a year or season. It therefore follows that the systems generate power in a pattern which is independent of the pattern of power consumption and a large energy storage capacity is required for such systems [2]. In this project, the possibility of matching the daily power generation pattern more closely with the load trend by optimising the array orientation for power-load matching is investigated. Using high-resolution meteorological data, the case for a location in The Netherlands (Cabauw, 51.97°N 4.926°E) is evaluated in a computer model run in MATLAB. The power curve of a PV array is calculated and its trend compared to the load curve of a typical European power consumer, for a variety of array orientations. The aim is to find such an orientation as to minimize the storage capacity requirements for the PV system through closer power-load matching. To this end, the array is split into two groups, one facing East and the other facing West, such that their peak production occurs not in the middle of the day, but closer to the morning and evening respectively. The viability of this strategy is assessed, and an attempt is made to find an optimal array configuration to better match the load curve.

II. Methodology

It is observed that the residential load curve and the PV generation curve do not peak at the same time. The PV curve has its peak around midday and the residential load peaks in the early evening [1], leading to a mismatch between generation and demand. This issue is currently solved by the use of batteries, or by other energy sources in hybrid systems [3]. Unfortunately, the cost of storing electricity is much higher than the cost of generation. This study examines the possibility of reducing the use of storage by varying the azimuth and tilt of the PV panels. This is done to obtain two separate PV generation curves; one for the morning(east-facing panels), and one for the evening(west-facing panels). The east-facing panels start generating power earlier than south-facing panels. Similarly, the west-facing panels stop generating power later than south-facing panels. As a result, in total power is generated for a longer period of the day but with a lower peak than that of a yield-maximizing orientation. The advantage here is that power is being generated when there is a demand, therefore the need for storage could be minimized. Figure 1 shows the angles that describe the orientation of the module, with θ_M showing the module tilt and A_M the module azimuth.

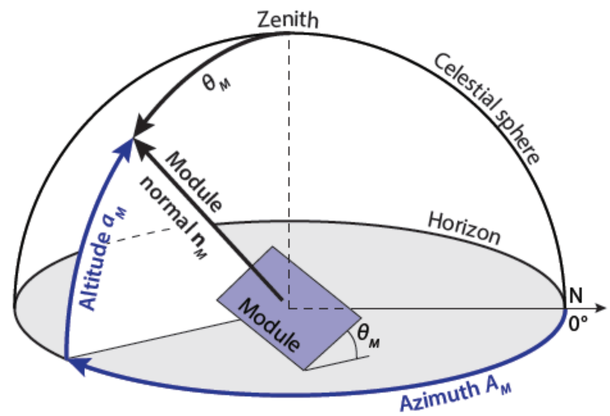

Fig. 1. Angles used in Defining Module Orientation

A. Irradiance

Global horizontal irradiance is the irradiance incident on a surface which is horizontal relative to the Earth. This global horizontal irradiance (GHI) is the sum of the diffuse horizontal irradiance (DHI) and the direct normal irradiance (DNI). The direct component is the portion of the irradiance incident on a surface which comes directly from the Sun; the diffuse component refers to the irradiance which falls on the surface after scattering by clouds and reflection from the sky. For a tilted surface a third component of irradiance may also be included: ground-reflected irradiance. The ground reflectivity is generally low, so this component is often quite small [4]. The incident irradiance on a surface is given by the relation:

$$G_t = B_t + D_t + R_t \tag{1}$$

in which G_t represents the total irradiance, while B_t, D_t, and R_t represent direct, diffuse, and ground-reflected irradiance respectively. The ground-reflected irradiance will be neglected due to its small magnitude. The direct component depends on the angle of incidence (AOI). The angle of incidence in turn depends on the solar position and the solar path and is only relevant to the direct component of the irradiance. In the general case of a tilted surface at angle θ, the angle of incidence γ is given by the following relation:

$$\gamma = \cos^{-1}[\sin\theta_M \cos a_S \cos(A_M - A_S) + \cos\theta_M \sin a_S] \tag{2}$$

The direct irradiance incident on the module is given by:

$$B_t = DNI \cos\gamma \tag{3}$$

The diffuse irradiance is described by a number of different models which attempt to calculate the diffuse irradiance on the basis of the portion of the sky dome which is seen by the module. It follows that a perfectly horizontal module receives the greatest amount of diffuse irradiance, from the entire sky, and tilted modules receive progressively less as the tilt angle increases. The MATLAB simulation in this project is based on the Simple Sandia Sky Diffuse model developed by Sandia National Laboratories. Circumsolar diffuse irradiance, which is caused by forward scattering of light rays in the area immediately surrounding the Sun, is not taken into account. Horizon brightening effects are also disregarded due to the complications involved in compensating for them. The total irradiance for the module at any instant is therefore:

$$\begin{aligned} G_t = DNI \cdot \cos[\sin\theta_M \cos a_S \cos(A_M - A_S) + \cos\theta_M \sin a_S] \\ + DHI \cdot \frac{1 + \cos\theta_M}{2} \end{aligned} \tag{4}$$

In the MATLAB model for evaluating irradiance, power, and yield, the irradiance incident on the panel at any instant is calculated according to equation (4).

B. Data and Model

High-resolution meteorological data is obtained from the Cabauw Experimental Site for Atmospheric Research (CESAR) database. A dataset containing global horizontal, direct normal, and diffuse horizontal irradiances as well as ambient temperature readings for every minute of the year 2013 is used as input for the MATLAB model. A solar position calculator is scripted in MATLAB which gives corresponding altitude and azimuth values for each data point in the CESAR dataset. The solar position calculator takes the coordinates, time zone, the date and time as inputs.

The solar position calculator then calculates and outputs altitude and azimuth for each minute, according to the method given by the Astronomical Applications Department of the US Naval Observatory. The main part of the model is a MATLAB function which uses the module (array) tilt, azimuth, area, efficiency and the time interval as inputs.

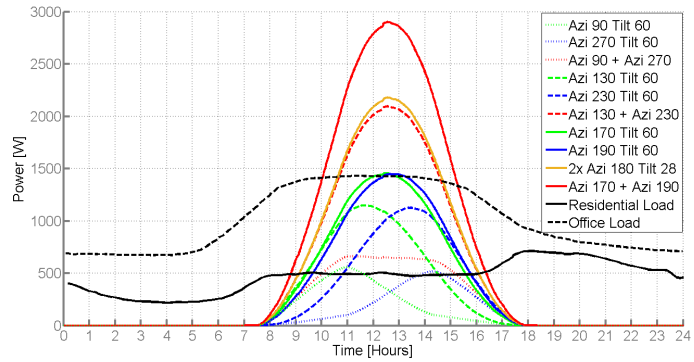

Fig. 2. Power for Varying Azimuth in Winter

The function then loads the input array with the irradiance and solar position data and calculates instantaneous incident irradiance and array power output for each minute of the input interval, before returning the following outputs graphically for the interval: solar altitude; angle of incidence; incident irradiance (optionally, direct and diffuse may be displayed separately); power. The array energy yield for the input time interval is computed via integration and a numerical value returned. In the study, electrical power generated by the array is computed as a constant fraction of the incoming solar radiation, i.e. a constant efficiency is assumed for the photovoltaic modules. The efficiency and module area values are taken from the datasheet of the Panasonic HIT 235S modules.

As a final step in the study, using MATLAB Optimization Toolbox algorithms, an optimal array configuration for load matching is computed by minimizing an objective function which is the total number of minutes in which PV generation is lower than the power demand, i.e. the residential load. An average rooftop setup area of 19m^2 is considered [5]. This area corresponds to an installed capacity of 3.54kWp. The optimal value of the objective function with the optimal array configuration variables is compared to the reference value which corresponds to a yield-maximizing orientation. The difference shows the improvement in load-matching - the increase in the number of minutes when the load is fully carried by the PV array. The input data for the optimisation routine is a dataset similar to the initial 2013 data, but with averaged values from 2011 to 2013 inclusive.

III. Results

A. Varying Azimuth and Tilt

Winter: The effects of varying the module azimuth while holding tilt constant and then vice versa are investigated. Winter, for this study, starts on 5th November and ends on 4th February. The model is run for a clear day in winter for module azimuth values from 90° to 270° in 10° steps, while the tilt is

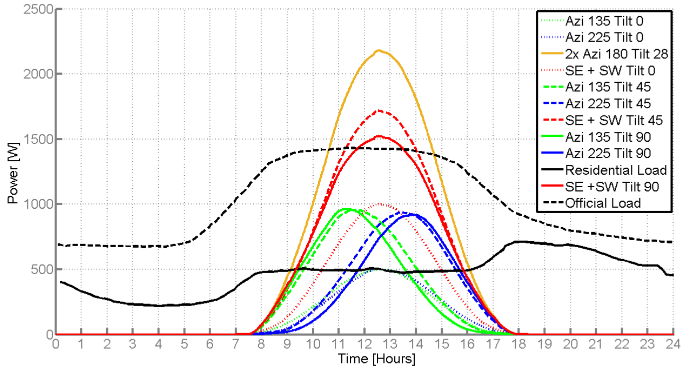

Fig. 3. Power for Varying Tilt in Winter

maintained at 60°. To simulate the configuration in which the array consists of East- and West-facing modules, the power curves of two sets of modules symmetrically arranged relative to South are summed. Symmetrical arrangement is when both sets of modules are moved by the same value with respect to direct south and have the same tilt. The module arrays will have the same tilt and the azimuth will be $(180° - x)$ for East-facing modules and $(180° + x)$ for West-facing modules, x being 10° in this case. This power curve is compared to the power curve of a year-round yield-maximizing orientation, which for the Netherlands is determined to be at 28° tilt and 180° azimuth. Figure 2 shows the simulation results for the three array orientations. The power curve of each module group is shown in green for East-facing module group and blue for West-facing module group. The total power curve for the array is red, the power curve of the yield-maximizing orientation is orange, and the residential and office load curves are black. These are all presented in a single graph for comparison. The main observation from the power curves is that the time of peak power output during the winter moves from about 12:30 for a South-facing module to 11:00 for an East-facing module, while the peak power output reduces to about 40% of the same for a South-facing module. The West-facing module group displays a similar result, peaking at 14:20 to about 40% of the South-facing orientation. However, it is clear from the graph that no advantage in load matching can be obtained by using this array configuration, as the power output peaks do not move far enough towards the load peaks. An important observation is that the South-facing array is outperformed by the East-facing plus West-facing array - the peak power for the latter at 170° and 190° azimuth is about 27% greater than the South-facing arrays peak. Another simulation is run with a constant module azimuth of 135° and 225°, and the results for 0°, 45°, and 90° tilt compared to a South-facing array at 28° tilt. The result is presented in Figure 3. Here the power curve for the East-facing module group is identical to that of the West-facing module group when the tilt is 0° - perfectly horizontal orientation renders azimuth irrelevant. At 45°, the peaks are at about 11:30 and 13:30, moving to 11:20 and 14:50 at a 90° tilt. As in the azimuth-variation simulation, all power curves lie within the yield-

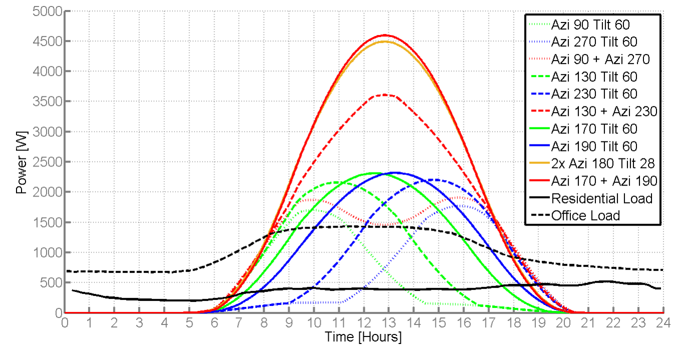

Fig. 4. Power for Varying Azimuth in Spring

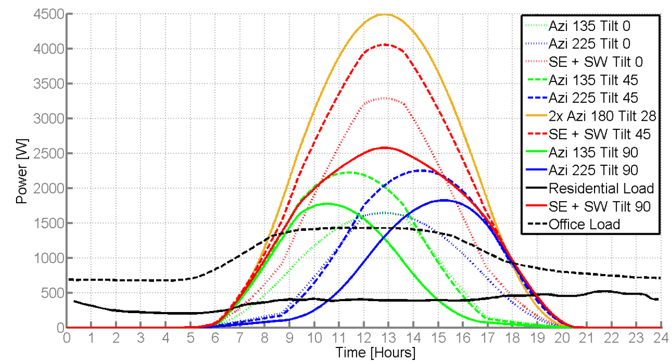

Fig. 5. Power for Varying Tilt in Spring

maximizing power curve, with a significant drop in total power output, peaking at 50% of the 45° South-facing configurations peak.

Spring: Spring is defined as the period between 4th February and 6th May. The spring simulation for varying azimuth, Figure 4, depicts a shift of peak time from midday to earlier hours for the East-facing module group, and to later hours for the West-facing module group. Crucially, the combined power curve for the whole array remains within the power curve for the yield-maximising configuration. Therefore, as with the winter simulation, load-matching improvement is not evident. The effect of tilt on the power curve of the PV array is illustrated in Figure 5 below. Clearly the change in tilt has little effect on the peak timing; it only affects the power level. It follows from the graph that the gains in load matching are to be derived by optimising the azimuth. However, Figure 4 indicates that the gains are negligible.

Summer: Summer begins on 6th May and goes on till 6th August. The variation of PV generation with changing azimuth, while maintaining a constant tilt of 60°, is shown in Figure 6. It is observed that a small portion of the East-facing and West-facing curves lie outside the yield-maximizing curve. The East-facing and West facing panels start and stop generating power at 03:45 and 21:00 respectively. The yield-maximizing configuration starts generating power at 05:30 and stops at 20:00. In the next simulation, the Azimuth is kept constant and the tilt is varied. As seen in Figure 7, for a higher tilt the panels catch more of the available direct irradiation

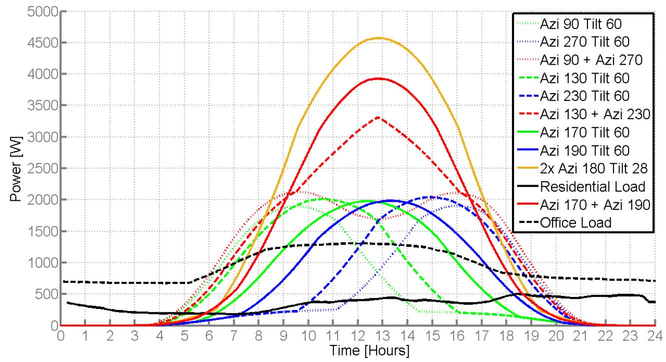

Fig. 6. Power for Varying Azimuth in Summer

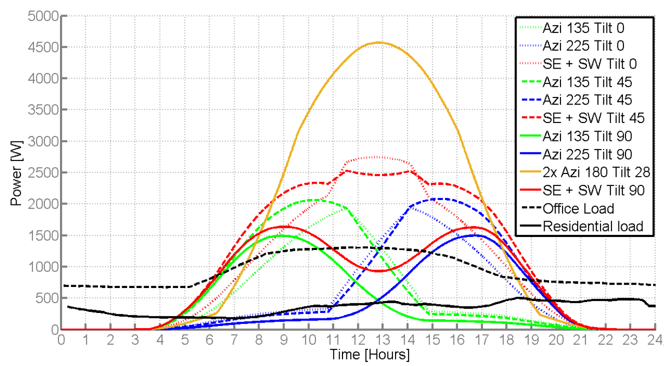

Fig. 7. Power for Varying Tilt in Summer

and the East-facing and West-facing array generation curves show a separation. This separation reduces as the tilt angle is decreased. In summer, it is seen that load-matching by varying azimuth and tilt can be achieved on clear days as there is more direct light available for a larger part of the day.

Autumn: The remaining part of the year, 6th August to 5th November, is considered to be Autumn. The Figure 8 illustrates the variation of PV generation in autumn for varying azimuth. The East-facing and West-facing curves almost completely lie within the yield-maximizing curve. The combined power curve is higher than the yield-maximizing curve for an azimuth configuration of 170° and 190°. Figure 9 illustrates

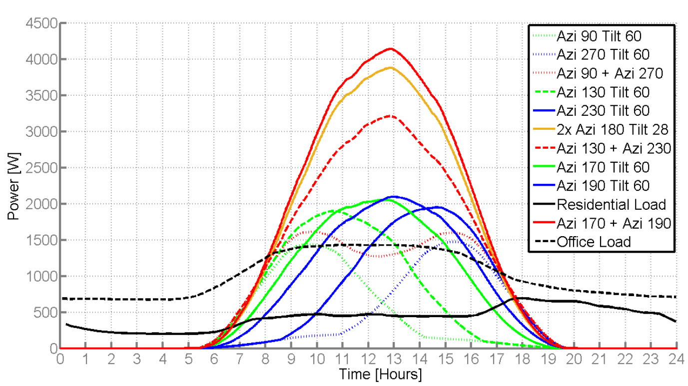

Fig. 8. Power for Varying Azimuth in Autumn

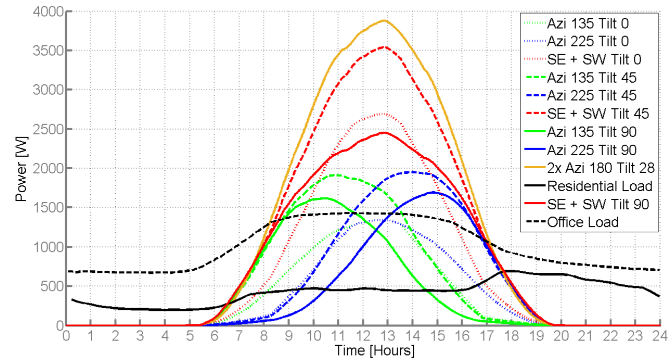

Fig. 9. Power for Varying Tilt in Autumn

the variation of PV generation with varying tilt. The East-facing and West-facing curves show a slight separation as tilt varies. The effect of tilt on the separation of the curves is not prominent.

B. Optimisation Results

As described in the Methodology section, an optimisation routine is run using the MATLAB optimization toolbox. The results are shown in Table I. The first column shows the duration of the optimisation period - month, season and the entire year. The second and third columns of the table show the number of minutes for which the load is greater than the PV generation. The second column, *Ref*, shows this value for the currently-used yield-maximising orientation, corresponding to 180° Azimuth and 28° Tilt for the location. The third column, *Opt*, shows this value for the optimised orientation. The difference between the two is the number of additional minutes where the generation is greater than the load, when compared to *Ref*. The last four columns show the optimised orientation of the East- and West-facing modules. Another development from the previous section is that the modules are not positioned symmetrically. In this part of the study the module orientations vary independently of each other.

From the table it is evident that there is a lot to be gained in the sunnier months and this gain strongly diminishes as the days grow shorter. For example, a gain of 1850 minutes is seen in the month of July i.e. the use of the battery is reduced by 1850 minutes with the new orientation. Similar gains are observed for the months of May, June and August as well. However, the month of October shows a meagre gain of 3 minutes, which is negligible over a month. Minuscule gain is also observed in the months of November, December, January and February. The next section of the table shows the results of the simulation run for the four seasons. spring shows a gain of 1704 minutes, which is comparable to autumn with a value of 1860 minutes. An interesting observation is that the gain in autumn is comparable to the gain in July. This shows the influence of direct sunlight on the gain. The gain observed in summer is considerably higher, 5108 minutes. The amount of gain in Winter is virtually negligible, at 23 minutes. The final section shows the result of the simulation run for an entire

TABLE I
OPTIMISATION RESULTS

	Ref	Opt	Gain	Tilt [deg]		Azimuth [deg]	
	[min]	[min]	[min]	East	West	East	West
Jan	34990	34968	22	29.98	31.05	179.73	182.69
Feb	27861	27852	9	26.16	24.68	172.43	182.38
Mar	26294	25969	325	32.50	42.07	100.91	260.09
Apr	22376	21196	1180	37.24	50.21	90.37	269.94
May	20344	18713	1631	42.49	56.19	90.47	269.91
Jun	18226	16523	1703	31.66	46.22	90.34	270.00
Jul	19645	17795	1850	39.35	56.89	90.28	270.00
Aug	22988	21164	1824	34.47	49.82	90.02	269.96
Sep	24707	24082	625	41.95	58.71	95.39	262.26
Oct	30313	30310	3	24.50	24.70	176.58	180.39
Nov	32547	32539	8	26.16	28.07	176.58	185.51
Dec	36786	36771	15	31.81	32.80	178.98	180.00
Spr	77653	75949	1704	31.91	34.33	102.29	265.00
Sum	58193	53085	5108	36.96	50.68	90.00	270.00
Aut	78916	77056	1860	34.97	46.38	104.89	261.52
Win	103292	103269	23	30.45	30.53	180.00	180.03
Year	317077	310960	6117	34.62	39.09	116.37	258.03

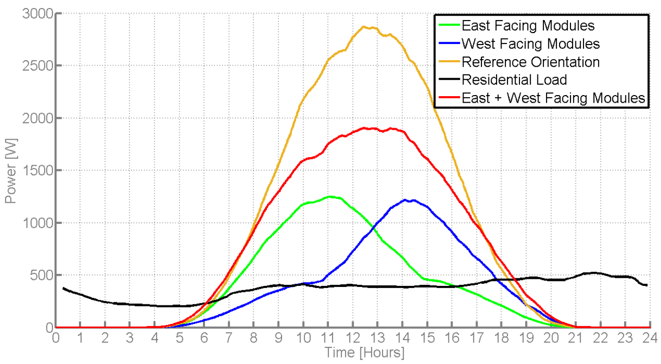

Fig. 10. Power for Optimised Orientation in Spring

year. As can be seen, the gain is highest for the year round optimum, which is expected. However, it is not much higher than the gain obtained for summer. Changing the optimised orientation every month would yield a total gain of 9195 minutes. A seasonal change to the optimised orientation yields a gain of 8695 minutes. Therefore, changing the orientation seasonally might be a fair trade-off for the reduction in gain. All situations yield better load matching using the optimised orientations and reduce the time during which power is drawn from the storage or grid.

Spring: Figure 10 shows the power generation with the optimised orientation for a clear day in spring. There is a small advantage gained by using the optimised orientation. The red curve crosses the load line earlier in the morning and later in the evening, when compared to the reference orientation curve. The advantage is quite small in this case. This is accompanied

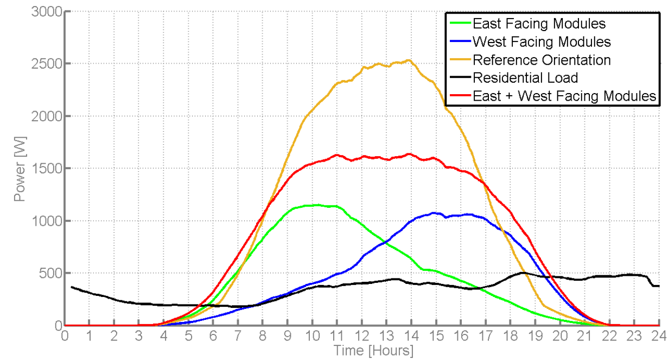

Fig. 11. Power for Optimised Orientation in Summer

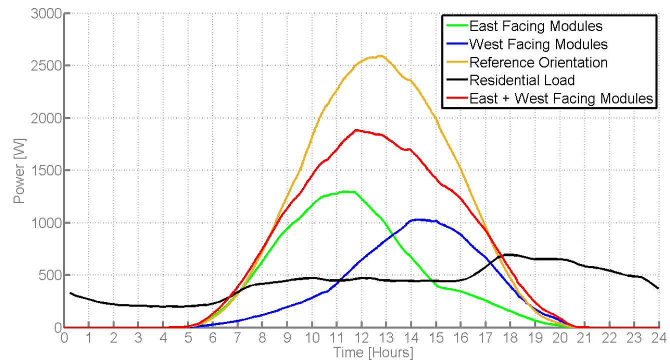

Fig. 12. Power for Optimised Orientation in Autumn

by a large reduction in peak power generation. This is reflected in a smaller gain value seen in the table shown earlier.

Summer: The gain is significantly higher in summer, when the days are longer, and the Sun's arc is higher and longer. Figure 11 shows the power generation with the optimised orientation for a clear day in summer. As seen in spring, there is a significant drop in the peak generation with the use of the optimised orientation. On the other hand, the load matching is far better as the East-facing modules start generating much earlier and stop generating much later in the day. This is seen as the red curve crosses the load curve much earlier in the morning and much later in the evening when compared to the reference curve, which is the desired result. As a result of this large gain on every day, the gain in summer is 5108 minutes. There is a large improvement in load matching performance seen in summer with the optimised orientation, when compared to spring or autumn.

Autumn: The performance in autumn is comparable to spring, were the gain is minimal. As seen in Figure 12, the gain during the morning and evening is very small. Also, the load peak in the evening is higher than in spring and summer. This means that generation in the evening must also be higher to match it. The days are shorter in autumn and there the possibility of matching the generation with this peak load grows more and more unlikely. Due to these factors a gain of 1860 minutes is obtained for autumn, which is comparable to the value for spring.

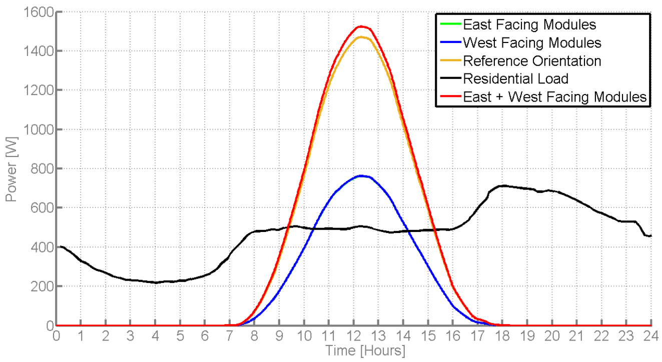

Fig. 13. Power for Optimised Orientation in Winter

Winter: Winter is the least favourable part of the year for any load matching goals; the load peaks are sharp and the days are short. This is reflected well in Figure 13. The days are not long enough to reach the evening peak and the effect of module orientation has little effect on the generation pattern. An interesting observation is that with the use of the optimised orientation, the peak generation increases slightly. Surprisingly, the optimum value obtained for winter is almost identical to the reference orientation. This is the reason behind the East- and West-facing modules having almost identical generation patterns. Due to this fact there is very little gain in winter, just 23 minutes.

IV. Conclusions

On the basis of the simulation results for each of the seasons, shifting the power curve by a sufficient extent to better match the residential load by way of changing the array orientation is feasible in the Netherlands. The large diffuse component in the incoming radiation causes the gains in the early and late hours of the day to be minimal, summer being an exception. Oversizing the array can partially cover the peak loads, but this still results in a surplus of power during the day-time, which must be stored or dumped. The fickle weather that is characteristic of the Netherlands also contributes to keeping gains marginal. That being said, a significant improvement in load-matching is observed in summer, when the amount of direct radiation is higher and the days are longer. Slight gains are observed on clear days in spring and autumn as well. Therefore, the possibility of load-matching by varying module azimuth and tilt is expected to be higher in regions with clear skies and abundant direct radiation.

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