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Optimal System Design for a Solar Powered EV Charging Station

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***Abstract*- Charging electric vehicles (EV) from photovoltaic (PV) panels provides a sustainable mode of transportation. In order to reduce the net costs of charging EV from PV and the grid, the PV generation and/or the EV charging can be controlled based on the energy prices in the grid. The traditional approach to designing the solar system for EV charging is to maximize the energy yield. In this paper, an alternate approach to PV system design is proposed by which the PV panels are orientated so as to maximize the PV revenue. This technique is compared with that of reducing the net costs by smart charging of the EV based on energy prices. Two case studies for Netherlands and Texas are done to compare the PV energy generated and the net cost of EV charging from PV based on the two techniques.**

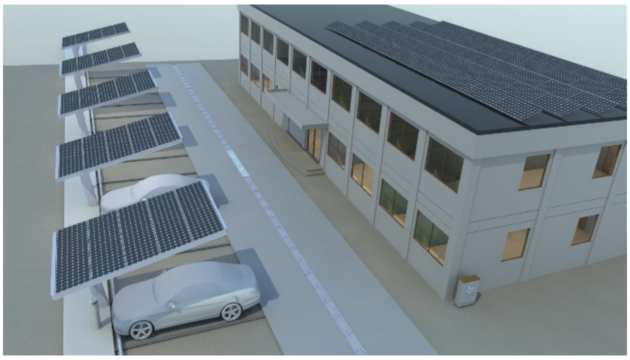

Fig. 1. Impression of a solar powered EV charging station

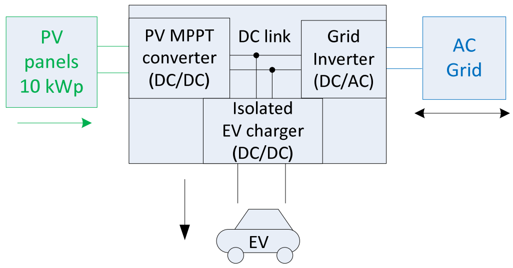

Fig. 2. Schematic of 10kW grid-connected solar EV charger

I. Introduction

Electric vehicles (EVs) are considered to be a clean mode of transportation as they have zero tail-pipe emissions. However, electric vehicles are only sustainable if the electricity used to charge them comes from sustainable sources. Unfortunately, the current electricity grid continues to be largely powered by fossil fuels, dominated by coal and natural gas [1]. So, when EVs are charged from such a grid, it results in indirect emissions at the power plants [2], [3].

A. Charging electric cars from photovoltaic panels

Charging of EVs from photovoltaic panels (PV) provides a distributed and sustainable method for powering electric vehicles [4]–[8]. There are several benefits to charging EV from PV such as,

- Reduced demand on the grid as the EV charging power is locally generated from PV [5]
- EV battery can be used as energy storage for the PV
- reduced cost of EV charging and reduced impact of changes in feed-in-tariffs [3]

Fig. 1 shows an electric vehicle charging station that is powered by solar panels installed on the top of the building and as a solar carport at a workplace. Since EV battery and PV are both fundamentally DC by nature, an integrated charger can be used for direct DC charging of EV from PV as shown in Fig. 2 [7]–[9]. The power balance equation for the charger including the energy conversion losses P_t^{loss} will be

$$P_t^{grid} = P_t^{PV} - P_t^{EV} + P_t^{loss} \tag{1}$$

where P_t^{grid} is the power drawn or fed to the grid, P_t^{PV} is the generated PV power, P_t^{EV} is the EV charging power. In the ideal case, P_t^{grid}=0 and the PV generation exactly matches with the EV charging demand. However, this is hardly the case in practice due to the diurnal and seasonal variation in solar generation. The solution to matching the PV generation and EV charging is to either design the PV system or control the EV charging so that P_t^{PV} closely matches with P_t^{EV}.

B. Literature review

Firstly, the EV charging can be controlled to match the PV generation; a method commonly referred to as smart charging [10]–[14]. In case smart charging, linear programming, non-linear programming and fuzzy logic can be used for optimizing the EV charging profile to closing match the PV generation and the periods of low energy prices [13], [10], [11]. Solar forecasting can help in improving the optimization, for example, the online short-term solar power forecasting [15], the autoregressive integrated moving average (ARIMA) models or any of the methods listed in [16] can be used.

The second approach is to optimize the PV system for meeting the EV charging demand. A simple but expensive way to do this is to use a dual-axis solar tracker, to get the

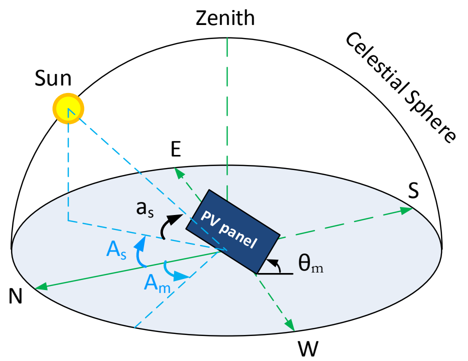

Fig. 3. Orientation of the PV panel is defined by azimuth angle A_m (measured from North) and module tilt angle θ_m (measured from horizontal surface)

TABLE I
PARAMETERS OF SUN POWER E20-327 MODULE

Quantity	Value
Area of module (A_{pv})	1.63 m^2
Nominal Power (P_r)	327 W
Avg. Panel Efficiency (η)	20.4%
Rated Voltage (V_{mpp})	54.7 V
Rated Current (I_{mpp})	5.98 A
Open-Circuit Voltage (V_{oc})	64.9 V
Short-Circuit Current (I_{sc})	6.46 A
Nominal Operating Cell Temperature (T_{NOCT})	45° C +/– 2 °C
Power Temp Coefficient (λ)	–0.38% / °C

maximum solar energy yield [17]. A cheaper approach is to install the PV system with a fixed orientation such that the orientation of the PV panels (tilt and azimuth of the modules) is so as to maximize the energy yield or match with the load or to increase the PV revenues [18]–[20]. While the first two methods are excellent from an energy point of view, it is not necessarily optimal from an economic perspective. This is because PV power is generally maximum in the afternoon, which is not always the time when the energy prices are high. So, if the net charging cost of EV from PV has to be reduced, it is important to orient the PV panels so as to increase the PV revenues.

C. Contribution

In case of charging EV from PV, the net cost is dependent on the cost of energy drawn from the grid given by

$$C_{net} = \sum c_t P_t^{grid} \Delta t = \sum c_t (P_t^{EV} - P_t^{PV}) \Delta t \qquad (2)$$

where c_t is the energy price for the time period Δt. If c_t is fixed, then maximising P_t^{PV} leads to lowering of the net cost. However, if c_t varies with time, then it is important to maximize the PV revenue, $(c_t P_t^{PV} \Delta t)$ or minimize the EV charging cost, $(c_t P_t^{EV} \Delta t)$, in order to reduce the net costs C_{net} of charging EV from PV.

Hence, the aim of this paper is to implement and compare two techniques to reduce the net costs of EV charging from PV. First is to optimally design the PV system (tilt and azimuth as shown in Fig. 3) in order to maximize the PV revenues $(c_t P_t^{PV} \Delta t)$, instead of the traditional approach of maximizing energy yield, $(P_t^{PV} \Delta t)$. The PV system is therefore designed to generate maximum energy at times of high energy prices and vice versa, thereby reducing the net cost. The second technique is to implement smart charging by controlling the EV charging power as to reduce the EV charging cost, $(c_t P_t^{EV} \Delta t)$ and the net cost, C_{net}. Two cases namely Netherlands and Texas are considered for comparing the two techniques. The choice is because Netherlands and Texas are different in terms of solar irradiance, temperature and energy prices and hence the comparison is expected to highlight the influence of these parameters.

II. SYSTEM PARAMETERS

For the analysis, a grid-connected solar charging station with a 10kW PV array is considered, as shown in Fig. 2. The 10kW$_p$ PV array is composed of 30 modules (5 strings of 6 series connected modules) of Sun power E20-327 modules rated at 327W, whose specifications are shown in TABLE I . For the case of the Netherlands, meteorological data for solar irradiance and temperature from the Dutch Meteorological Institute (KNMI) for Cabauw for 2015 is used, which has a resolution of 1 minute. In case of Texas, meteorological data with 1 min resolution is extracted from the *Meteonorm* software for the city of Austin, Texas.

The focus of this work is on workplace charging of EV from PV. This is because workplaces are ideal for solar EV charging as the employees' cars are parked for around 8 hours in the day when the sun is shining. With the long parking times, low charging powers are sufficient to provide adequate energy to the EV battery. For this study, it is assumed that employees are at the workplace from 9AM-5PM and the EVs are charged to with 29.6kWh of energy daily. This corresponds to an annual EV demand of 10804 kWh.

III. PV SYSTEM MODELLING

A. Estimating the PV module irradiance

In order to estimate the PV energy generation for different orientation, a model of the PV system is built in MATLAB. To estimate the solar irradiance on a module (S_m) with an azimuth (A_m) and tilt angle (θ_m), an estimation of the position of the sun is required as shown in Fig. 3. A solar position calculator is hence built by which the azimuth (A_s) and altitude (a_s) of the sun throughout the year at any location can be determined [21]. The azimuth angle A_m, A_s can range from 0° to 360° and the sign convention is 0° for North (N) and 180° for South(S). Similarly, θ_m, a_s can range from 0° to 90°.

With the sun's position, the irradiance on a panel, S_m with a specific orientation (A_m, θ_m) can be estimated using the geometric models in [18], [22] and the isotropic sky diffused model [22], [23]:

$$S_m^{DNI} = S^{DNI}(sin\theta_m cosa_s \, cos(A_m - A_s) + cos\theta_m sina_s) \qquad (3)$$

$$S_m^{DHI} = S^{DHI}(1 + cos\theta_m)/2 \qquad (4)$$

$$S_m = S_m^{DHI} + S_m^{DNI} \qquad (5)$$

where S^{DHI} is the Diffuse Horizontal Irradiance (DHI), S^{DNI} is the Direct Normal Irradiance (DNI) and $S^{DNI}{}_m$, $S^{DHI}{}_m$ are the components of DNI and DHI which is incident on the panel. From the above equation, we can see that the irradiance on the panel can be influenced by changing the module azimuth (A_m) and tilt angle (θ_m). Typically, the module tilt angle (θ_m) can be used to control the seasonal variation in the solar generation as the sun has a high altitude in summer and much lower altitude in summer. This means that a high module tilt increases the winter solar generation while a lower module tilt increases the summer generation. Similarly, the module azimuth angle (A_m) can be used to control the diurnal variation in the solar generation by facing the modules east to increase the generation in the morning and modules west to increase the generation in the evening.

B. PV power and energy output

In order to estimate the power of a PV array based on the panel irradiance S_m, it is important to consider the ambient temperature. The E20-327 PV module is rated for 327W at the STC ambient temperature of 25°. For other ambient temperatures (T_a), the PV array output power (P_t^{PV}) can be estimated using [19], [24], where T_{cell} is the temperature of the PV cells and N_p is the number of modules in the array:

$$T_{cell} = T_a + \frac{S_m(T_{NOCT} - 20)}{800} \tag{6}$$

$$P_t^{PV} = \frac{N_p P_r S_m [1 - \lambda(T_{cell} - 25)]}{1000} \tag{7}$$

IV. PV ORIENTATION FOR MAXIMUM ENERGY

Based on equations (3)-(7), the annual energy yield for different module tilt and azimuth is estimated for the case of Netherlands (NL) and Texas (TX) as shown in Fig. 4 and Fig. 5. The azimuth and tilt of the modules are varied in steps of 5° and 2°, respectively. The values for DHI, DNI, T_a are obtained for the year 2015 from the KNMI for Cabauw, Netherlands (51.971°N, 4.927°E) and from the *Meteonorm* software for Austin, Texas (30.155°N, 97.445°W) that have a data resolution of 1 min.

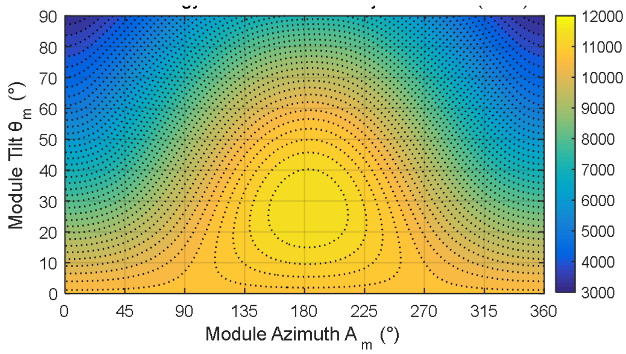

Fig. 4. Annual energy yield of a 10kW PV system in the Netherlands for different tilt and azimuth of modules

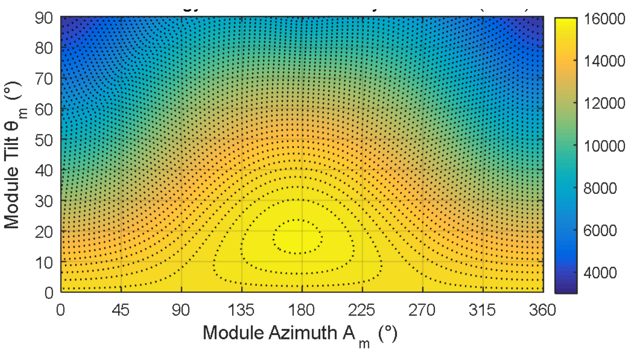

Fig. 5. Annual energy yield of a 10kW PV system in the Texas for different tilt and azimuth of modules

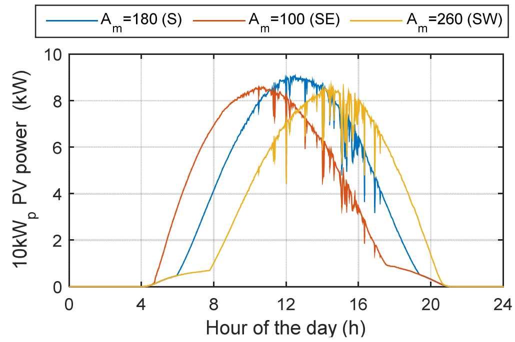

Fig. 6. Power generated by 10kW PV system for a summer day (Day 155 of year 2015) for south-east, south-west and south facing modules, all with a tilt angle of 28°

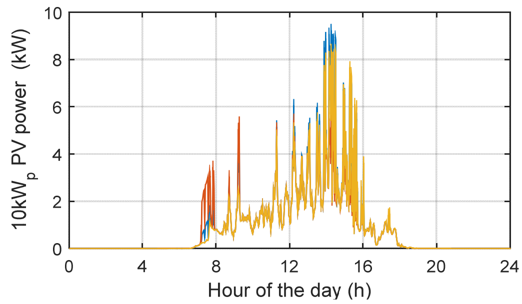

Fig. 7. Power generated by 10kW PV system for a spring day (Day 80 of year 2015) for south-east, south-west and south facing modules, all with a tilt angle of 28°. The legend is same as Fig. 6

TABLE II
PV ORIENTATION FOR MAXIMUM & MINIMUM ANNUAL ENERGY YIELD

	Annual yield	PV Yield (kWh)	A_m (°)	θ_m (°)
NL	Maximum yield	11,593	185	28
	Minimum yield	3,238	0	90
TX	Maximum yield	15,654	175	18
	Minimum yield	3,724	0	90

A. Cabauw, Netherlands scenario

It can be seen for NL in Fig. 4 that the maximum annual yield of 11,593 kWh is obtained for south-facing panels with A_m=185°, θ_m=28°. On the other, the lowest annual yield of 3,238.5 kWh is obtained for North facing panels A_m=0°, θ_m=90°. This shows that the annual yield can reduce by a factor 3.58 depending on the orientation of the panels as summarized in TABLE II. The annual yield gradually reduces as the tilt is increased or decreased from 28° and/or the azimuth of the panel is set away from the southern direction.

To further elaborate the effect of orientation, Fig. 6 shows the power output over one day of the 10kW PV system for day 155 of the year 2015 for the south, south-west, and south-east orientation, with the same tilt angle of 28°. It can be seen how the east and west facing panels facilities the increased generation of power in the morning and evening hours of the day, respectively. However, this only occurs on days with sufficiently high DNI. On a cloudy day with high DHI and little or no DNI, the effect of the module azimuth on the output is close to zero, for the same tilt angle of the panels. This is shown in Fig. 7 for day 80 of the year 2015 where panels with south, south-west and south-east orientation with the same tilt angle of 28° have nearly the same power output as well. Therefore, Fig. 6 and Fig. 7 together show both the potential and the limitation of controlling the output PV power by controlling the azimuth of the module. The module tilt, on the other hand, facilitates the control of the output power over the seasons of the year (not shown in the figure).

B. *Austin, Texas scenario*

In case of TX, Fig. 5 shows the annual yield of the PV system for different azimuth and tilt angles of the modules. The maximum yield of the PV system is 15,654 kWh which is 35% higher than the annual yield for the Netherlands case. The orientation for maximum yield is A_m=175° and θ_m=18°, and the lower tilt angle can be explained by the fact that Texas is at a lower latitude than the Netherlands. The minimum annual yield is 3,724 kWh, and it occurs when the orientation of the module is A_m=0°, θ_m=90°, i.e., a north facing module that is oriented perpendicular to the ground.

V. PV Orientation for Minimum Net Cost

In the previous section, the PV orientation for maximum energy yield was determined. In order to use the PV system for EV charging and to reduce the net cost of charging with variable energy prices, it is important to orient the modules so as to maximize the revenue.

A. *Energy prices*

For estimating the net cost C_{net}, day-ahead market (DAM) energy prices for 2015 from the Amsterdam Energy Exchange (APX) and Electric Reliability Council of Texas (ERCOT) are used for the Netherlands and Texas case, respectively as shown in Fig. 8. A wide variation in the costs can be seen between the months and between the Texas and Netherlands case. The annual average price for APX and ERCOT was found to be 2.64c€/kWh and 3.99c$/kWh, respectively.

Fig. 9 shows the average electricity price over a 24h period for ERCOT and APX. It is interesting to note that the prices peak in the morning and evening and dip in the middle of the day but the nature of this variation is very different for NL and TX. For NL, the morning and evening peaks are very close in price, and the dip in prices occurs in the afternoon around 4PM. On the other hand for TX, the evening peak prices occurs around 5PM and are much higher than the morning peak and those of the rest of the day.

B. *Optimal orientation for minimum cost: NL*

Based on the method in the previous section to estimate annual yield for different orientation, the net cost C_{net} for EV charging from PV are estimated based on (2). The EV is assumed to be charged at a fixed charging power of 3.7kW from 9AM to 5PM with no smart charging.

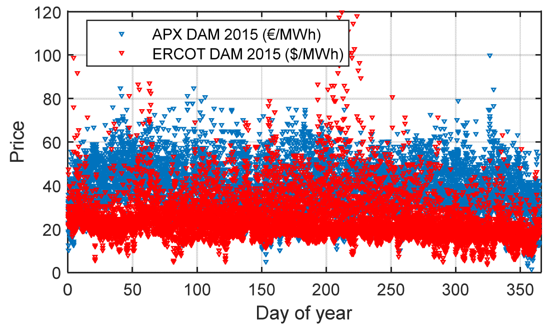

Fig. 8. Hourly day-ahead market prices from APX and ERCOT for 2015. For scale, values above 120$/MWh are not shown.

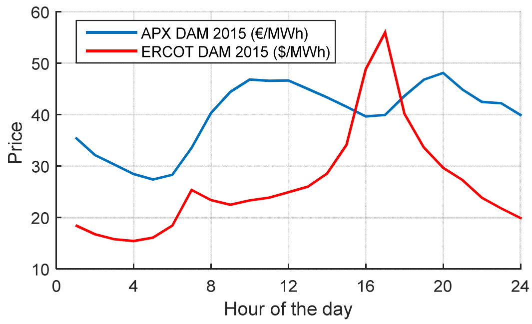

Fig. 9. Hourly day-ahead market prices from APX and ERCOT for 2015 averaged over a 24 hour period

Fig. 10 shows the net cost C_{net} for different combinations of module azimuth and tilt for the Netherlands and Texas scenario and several interesting observations can be made. Firstly, for the Netherlands case, the orientation resulting in maximum PV revenue, $(\sum c_t P_t^{PV} \Delta t)$ and the lowest net cost, C_{net}=25.21€ corresponds to A_m=180°, θ_m=28°, as shown in TABLE II. This orientation is not very different from the orientation for maximum yield (A_m=185°, θ_m=28°). Secondly, the shape of the contour plot in Fig. 10(a) closely matches the contour plot of Fig. 4. Thirdly, the net costs were found to be maximum for A_m=0°, θ_m=90° with C_{net}=391.65€, which is much higher than the minimum net cost value of C_{net}=25.21€. These observations point to the conclusion that the orientation for maximum yield results in maximum revenue as well for the Netherlands case considered. This is explained by the fact that APX 2015 energy prices has the first morning peak close to the afternoon in Fig. 9 when the PV generation is maximum. So orienting the panel to the south-east or south-west has the double disadvantage of lower energy yield as seen in Fig. 4 and lower revenue as seen in Fig. 9.

C. *Optimal orientation for minimum cost: TX*

On the other hand for the Texas case, the orientation resulting in the minimum net cost of C_{net}=(-130.45$) corresponds to A_m=225°, θ_m=20°. This orientation is facing westward by 50° with a marginally higher tilt of 2° when

TABLE III
PV ORIENTATION FOR MAXIMUM & MINIMUM NET COST

		Annual PV Yield (kWh)	Net cost (€ or $)	PV revenue (€ or $)	A_m (°)	θ_m (°)
NL	Max. yield	11,593.4	25.52	506.58	185	28
	Min. net cost	11,592.9	25.21	506.89	180	28
	Max. net cost	3,238.5	391.65	140.45	0	90
TX	Max. yield	15,654	-117.55	506.76	175	18
	Min. net cost	15,245	-130.45	519.65	225	20
	Max. net cost	3,761	270.94	118.26	5	90

compared to the orientation for maximum yield (A_m=175°, θ_m=18°) as shown in TABLE II. Secondly, the net costs for the TX case are negative, mainly driven by the fact that 10kW PV system generates more energy compared to the NL case. Thirdly, even though the orientation for "Minimum net cost" has 9.73% lower annual yield than the orientation for "Maximum yield", it still delivers 2.54% higher PV revenues and 10.97% lower net costs. Finally, the shape of the contour plot in Fig. 10(b) is very different from the contour plot of Fig. 5.

These observations show the influence of PV orientation on PV revenues when energy prices are considered. This is because the ERCOT 2015 energy prices, on an average, rise continuously from 9AM and peak at 5PM. This causes westward facing panels that generate more energy in the afternoon benefit from the higher energy prices.

VI. SMART CHARGING FOR MINIMUM NET COST

A. *Charging algorithm*

In this section, the aim is to implement smart charging of the EV so as to minimize the EV charging costs, $(\sum c_t P_t^{EV} \Delta t)$ and the EV-PV net costs over one day, $C_{net(d)}$. By doing so the optimized net costs over the entire year, C_{net} can be minimized for the smart charging scenario. The PV have panels have the same orientation as the orientation for maximum yield as seen in section IV. Smart charging is done based on the energy prices using the formulation:

$$\text{Minimize:} \quad C_{net(d)} = \sum c_t (P_t^{EV} - P_t^{PV}) \Delta t \tag{8}$$

$$0 < P_t^{EV} < 10\text{kW} \qquad \forall\, t \tag{9}$$

$$\sum P_t^{EV} \Delta t = 30\text{kWh} \qquad \forall\, t \tag{10}$$

$$P_t^{EV} = 0 \qquad \forall\ \text{t<9AM, t>5PM} \tag{11}$$

$$C_{net} = \sum C_{net(d)} \qquad \text{d=1 to 365} \tag{12}$$

Linear programming in MATLAB is used to implement the optimization over a 24 hour period from t=00:00h to 23:59h for each day of 2015 using APX and ERCOT energy prices for the NL and TX case, respectively. Since the resolution of the PV data is 1 min, Δt=1min as well. TABLE IV shows the annual EV charging costs and the annual net costs for the smart charging (SC) scenario for the NL and TX case. The net costs are compared in TABLE IV with the net costs for the scenario with economically optimal orientated PV (PVO) with fixed EV charging power of 3.7kW taken from TABLE II.

It can be clearly seen in TABLE IV that smart charging of EV based on energy prices results in much lower net costs than those obtained from optimally orientating the PV based on prices. For the NL and TX case, optimal PV orientation increases the PV revenues only by a factor of 0.06% and 2.5%, respectively. On the other hand, smart charging of EV is much better and reduces the annual EV charging costs by 20.1% and 36.34% for NL and TX case, respectively.

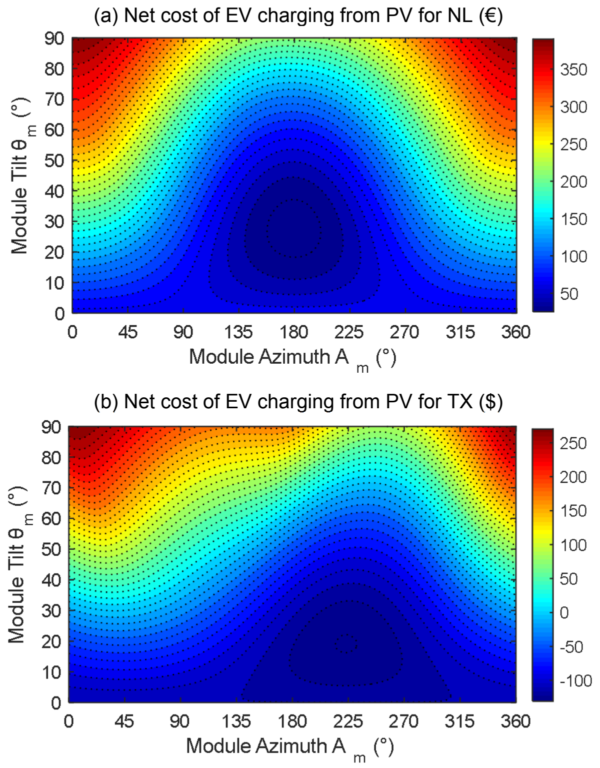

Fig. 10. Net cost of EV charging from PV for different tilt and azimuth of 10kW PV system for (a) Netherlands and (b) Texas scenario

TABLE IV
COMPARISON OF NET COSTS FOR SMART CHARGING (SC) AND OPTIMALLY ORIENTED PV (PVO) FOR NL AND TX

	PV Yield (kWh)	PV revenue (€ or $)	Charging EV Cost (€ or $)	Net cost (€ or $)	A_m (°)	θ_m (°)	
NL	11,593.4	506.58	424.95	-81.63	185	28	SC
	11,592.9	506.89	532.10	25.21	180	28	PVO
TX	15,654	506.76	247.73	-259.02	175	18	SC
	15,245	519.65	389.20	-130.45	225	20	PVO

B. *Implementation aspects*

Although two cases for Netherlands and Texas have been simulated here with day-ahead market prices, the method provided in this paper can be applied to different locations, and real-time market or intraday market prices can be used as well. The actual increase in PV revenues and reduction in net costs will vary on a case by case basis depending on the meteorological conditions, EV charging profile and the nature of the energy prices.

Secondly, besides the PV model used here, other PV models can be used as well, especially for the DHI and the thermal modeling of the PV. Thirdly, the losses in the power electronic converter for the PV and EV will marginally increase the net costs, and this aspect has been neglected in this work. Finally, full/partial shading of the PV panels due to nearby objects and buildings will reduce the PV output depending on their location and size. These factors are, however, beyond the scope of this work and can be considered in the future.

VII. CONCLUSIONS

This paper has shown that in a scenario with variable energy prices, there is a potential to orient the PV system and/or implement smart charging in such a way so as minimize the net cost of charging electric vehicles from solar. Installing the PV system based on the variation of electricity prices is contrary to the conventional approach of maximizing energy and has untapped potential for future EV-PV applications.

It was found that a PV system oriented with azimuth A_m=185°, tilt θ_m=28° and A_m=175°, θ_m=18° results maximum annual energy yield for the case of Cabauw, Netherlands, and Austin, Texas, respectively. If electricity prices for 2015 from APX and ERCOT were considered, then the optimal PV orientation for the minimum net cost for EV charging from PV was found to be A_m=180°, θ_m=28°, and A_m=225°, θ_m=20° for the Netherlands and Texas case, respectively. Thus, for the Netherlands case, the influence of 2015 APX prices was minimal, and the orientation for maximum yield and for minimum net costs was nearly the same. On the other hand for the Texas case, the ERCOT prices showed a trend to increase in the afternoon thus encouraging the solar panels to be oriented to the west so as to increase the PV revenue.

In the case of smart charging of EV based on energy prices, the annual EV charging costs were reduced by 20.1% and 36.34% for NL and TX case, respectively when compared to charging at a fixed power. Further, this reduction in EV charging costs was much higher than the marginal increase in PV revenues of 0.06% and 2.5% obtained by orienting the PV based on energy prices for NL and TX, respectively.

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