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Economic and CO_2 Emission Benefits of a Solar Powered Electric Vehicle Charging Station for Workplaces in the Netherlands

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***Abstract*- The paper analyses the economic and environmental benefits of charging electric vehicles (EV) at workplaces in the Netherlands using photovoltaic panels (PV). A 10kW EV-PV charging system is used to charge the electric cars directly from photovoltaic panels. The cost of using a gasoline vehicle is compared with that of an electric vehicle that is charged from the grid or from solar panels. It is found that charging EV from PV results in huge savings in fuel cost, taxes and lower CO_2 emissions. A comparison is made for solar panels installed on rooftops and as a solar carport and the impact of feed-in tariffs on PV generation revenues is evaluated.**

I. INTRODUCTION

Electric vehicles (EV) are becoming increasingly popular as the future mode of transport. EVs provide a clean, energy efficient and noise-free means for commuting when compared with gasoline vehicles. The current forecast is that in the Netherlands there will be 200,000 EV on the roads in 2020 [1]. As per the Netherlands Bureau of Statistics, the number of (semi) electric cars in Dutch roads has reached 150,000 in the end of 2014. At the same time, there is a major move towards large-scale decentralized renewable energy production through photovoltaic (PV) system because of the falling cost of PV panels [2]. Industrial sites and office buildings in the Netherlands harbor a great potential for photovoltaic (PV) panels with their large surface on flat roofs. Examples include warehouses, industrial buildings, universities, factories, etc. This potential is largely unexploited today.

The combination of EV and PV provides a unique opportunity for sustainable charging of electric vehicles where the energy produced from PV panels installed in the work places can be directly used to charge EV during the day [3]–[6]. Fig. 1 shows an illustration of solar charging station for EV at workplace that has been developed at Delft University of Technology, Netherlands [7]. A modular 10kW EV-PV power converter is used to integrate the PV, EV and grid using a common DC link, as shown in Fig. 1 [3], [4]. The EV is charged using DC charging standards namely Chademo and the Combined Charging Standard (CCS) which facilitate both charging and Vehicle-to-Grid (V2G).

The motive is to maximize the use of PV energy for EV charging with minimal energy exchange with the grid. The advantages of such an EV-PV charger are:

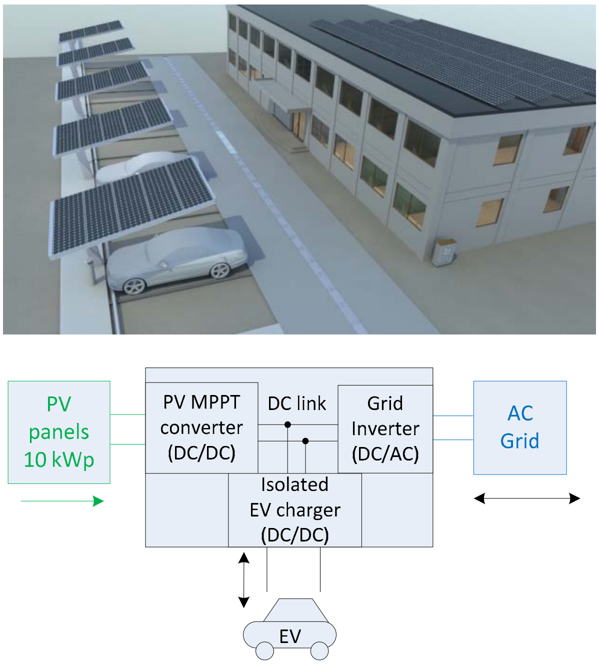

Fig. 1 – Illustration of a solar powered smart charging station for EV at workplace that has been developed by TU Delft (top) and architecture of the grid connected 10kW three–port EV-PV power converter (bottom)

1. Reduced energy demand on the grid as the EV charging power is produced locally from PV. The local use of PV energy partially/fully averts the negative impact of feeding PV energy into grid due to reverse power flow in the lines and overvoltage problems at feeder ends [8]–[10]
2. The use of locally produced PV energy for EV charging reduces the demand charges to be paid to the distribution system operator (DSO) due to increased EV charging load at the workplace
3. DC interconnection of EV and PV is more efficient than an AC interconnection [11]–[13]. Such an architecture as shown in Fig. 1 requires only a single DC/AC inverter to connect to the grid instead of separate inverters for the PV and EV [3].

4. EV battery doubles up as an energy storage for the PV, thereby removing the need for a separate storage device.
5. Long parking time of EV paves way for implementation of Vehicle-to-grid (V2G) technology where the EV acts as a controllable spinning reserve for the smart grid
6. Lower fuel cost and reduced/zero CO_2 emission due to charging of EV from a renewable source like PV.

The mutual advantage of charging electric vehicles from solar energy has been highlighted in [14], [15]. It has been shown that the potential to charge EV from solar energy results in a higher penetration of EV in the distribution network and reduces the amount of PV curtailment. Economic and environmental benefit of charging electric vehicles from solar panels at workplace has been analyzed in [16], [17]. It has been shown that with proper tariffs and charging control, there will be mutual benefits to the garage owner and the EV owner in charging from PV rather than from grid.

There are four main contributions of this work compared to earlier works. Firstly, a detailed model for the PV generation is built based on data from the Dutch Meteorological Institute (KNMI), which takes into account both the seasonal and diurnal variation in irradiation and temperature. Secondly, the paper compares workplaces with a 5day/week EV charging load like factories, office buildings and 7day/week EV charging load which corresponds to shopping malls, warehouses etc. Thirdly, the economic prospects of installing the panels as solar carport are compared to a rooftop PV installation. Finally, the impact of feed in tariffs on PV generation revenues is investigated and it is shown how charging EV from PV provides an economic incentive even when feed in tariffs are zero.

II. GASOLINE VS ELECTRIC VEHICLES

The average kilometers driven by a car in one year in the Netherlands is 20,000km (for cars>1500Kg weight which is typical for EV) [18]. This corresponds to a daily distance of 55km/day. With approximately 260 working days a year, 14,300km are driven on days going to the workplace. A major component of this is daily commuting to work which comprises 45km/day or ~80% of the daily distance driven [19].

The cost of using a gasoline car for daily commuting to workplace on workdays is summarized in TABLE 1. The yearly cost of fuel amounts to €2,013/year on average. The price of gasoline is taken as 1.69€/L and the vehicle is assumed to drive 100km with 8.33L of fuel. With respect to CO_2 emissions, the average emission of new cars sold in Netherlands is 119g/km, 109g/km and 107g/km for 2011, 2012 and 2013 respectively [20]. For 14,300 km of commuting distance a year, this results in CO_2 emissions of 1.8 tons/year as shown in TABLE 2. In the reality, the emission are much higher considering the two factors. Firstly there is a mix of new and old cars on the road, with the older cars having much higher levels of emissions. Secondly, the cars normally have higher emission during usage when compared to emission values obtained during testing [21].

The annual costs of using the gasoline car in TABLE 2 excludes the annual motor taxes and vehicle tax paid during vehicle purchase, that are fully based on CO_2 emissions of the car as per Dutch regulations [22]. For example, the owner of a 1500kg gasoline car in South Holland has to pay €912 annual motor taxes (Motorrijtuigenbelasting) as shown in TABLE 2. From 2016, this tax is zero if you own an EV and is reduced by 50% if the CO_2 emissions of the vehicle are less than 50g/km. In the same way, the vehicle tax paid during the purchase of a car (bpm) is directly proportional to the CO_2 emissions of the car as shown in Fig. 2. For example, the taxes to be paid when buying a car with 109g/km emission is €2884, while for a car with 180g/km emission, the taxes are €15,997. In case of an EV, the taxes are zero. For a diesel car, an additional fuel surcharge corresponding to an emission of 86€ per 1g/km of CO_2 emissions applies when the emission are over 67g/km. These aggressive emission based vehicle taxes has made Netherlands the leading country in Europe with respect to lowest average CO_2 emissions of newly sold cars [20].

On the other hand, an EV costs an average €10,000 more than a corresponding gasoline vehicle in the Dutch market with respect to size and comfort. But the costs of charging the EV are much lesser than using gasoline. For example, the NEDC driving range of the Tesla Model-S (85kWh) and Nissan Leaf (24kWh 2013) is 500km and 200km respectively. This corresponds to a fuel use of 12kWh and 17kWh for the Leaf and Model-S respectively for driving 100km. With 0.23€/kWh electricity price in Netherlands and

TABLE 1
COST OF GASOLINE VEHICLE, GRID CHARGED AND SOLAR CHARGED ELECTRIC VEHICLE

	Fuel car	**Grid charged**	**Solar charged**	**Solar carport**
Annual distance (km)	14,300	14,300	14,300	14,300
Fuel price (€/L or €/kWh)	1.69	0.23	0.10	0.28
Fuel use per 100 km (L or kWh)	8.33	15	15	15
Fuel/year (L or kWh)	1,191	2,145	2,145	2,145
Fuel costs/ year	€ 2,013	€ 493	€ 215	€ 601
Saving/year for 1 car	€ 0	€ 1,520	€ 1,798	€ 1,412
Saving/year for 4 cars	€ 0	€ 6,080	€ 7,192	€ 5,648
Savings for 10 years for 4 cars	€ 0	€ 60,800	€ 71,920	€ 56,480
Extra Investment for 4 EV	€ 0	€ 40,000	€ 40,000	€ 40,000
Total benefit 10 years 4 cars	€ 0	€ 20,800	€ 31,920	€ 16,480

TABLE 2
CO2 EMISSIONS AND TAXES WHEN USING GASOLINE VEHICLE, GRID AND SOLAR CHARGED EV

	Fuel car	Grid charged	Solar charged	Solar carport
Motor Taxes/year	€ 912	€ 0	€ 0	€ 0
Vehicle purchase tax	€ 2884	€ 0	€ 0	€ 0
Tax benefit (PV, EV)	No	MIA/ KIA/ EIA	MIA/ KIA/ EIA	MIA/ KIA/ EIA
CO_2 emission (g/km)	109	70.5	0	0
CO_2 emission for 14300 km (kg/yr)	1559	1008	0	0
CO_2 emission for 20,000 km (kg/yr)	2180	1410	0	0

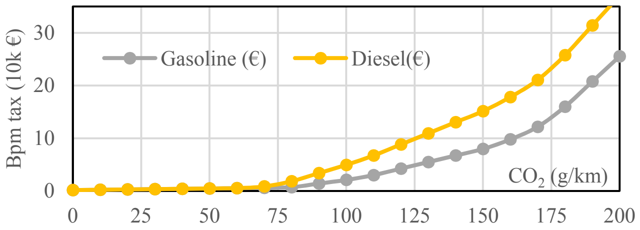

Fig. 3 – Dutch Bpm purchase tax of EV as based on rated CO_2 g/km emissions of the car with an additional surcharge for diesel cars.

fuel use of 15kWh for 100km, it corresponds to €493 fuel cost per year for driving 14,300km as shown in TABLE 1. As mentioned earlier, the EV owner gets an additional financial benefit via zero annual vehicle taxes compared to gasoline cars, which is close to 1000€ giving a net benefit of ~€2500/year in operational costs. For the sake of simplicity, the factors relating to maintenance costs, insurance, depreciation, rate of interest and down time costs that provide the Total Cost of Ownership (TCO) of gasoline car and EV have not been considered in this study.

While most people assume that the CO_2 emissions of an EV are zero, this is not the case in reality. This is because electricity production by itself results in CO_2 emissions. This is especially true in the Netherlands where large amounts of fossil fuels like gas and coal are used in power production. This results in a net CO_2 emission of 470g/kWh as per 2012 estimates [23]. If the energy use of EV is taken to be 15kWh for 100km, this results in a net CO_2 emission of 70.5g/km. So, if the gasoline and EV vehicle usage are compared, it results in:

1. An annual saving of € 1,520 just based on fuel costs
2. CO_2 emissions are reduced on an average by 38.5g/km. This results in annual CO_2 emission reduction of 551kg/car/year for the distance of 14,300km and 770kg/car/year for the total 20,000km driven per year.
3. Tax benefits in the form of zero vehicle taxes for EVs

Considering four EV used over a period of ten years, the net benefit is €60,800 without considering maintenance cost and tax benefits as shown in TABLE 1 (It will be explained later why four EV are taken as reference). In the Dutch market, an EV typically costs €10,000 more than the corresponding gasoline vehicle. If this cost is considered, the net benefit for four cars is €20,800 as shown in TABLE 1. If tax benefits are considered, the gain will be an additional 2844+912*10=11,964€ per car and 47,856€ for four cars. This shows the lifetime economic and environmental benefit of using an EV over gasoline vehicles in the Netherlands. With increased driving range, improved charging infrastructure and lower cost of EV, these benefits are only bound to increase.

III. SOLAR GENERATION POTENTIAL IN NETHERLANDS

An alternative to charging EVs from the grid is to charge the EV from solar panels installed at the workplace. This has several benefits as enumerated in the introduction section. The main benefit is it results in zero CO_2 emission unlike gasoline vehicles or EV charged from grid. Secondly, the cost of PV electricity is less than half of that of conventional electricity from grid as will be shown later.

To evaluate the power and energy generated by a $10kW_p$ PV array in the Netherlands, an accurate measurement of weather data is required. For this purpose, the meteorological data from the Dutch Meteorological Institute (KNMI) is used, which has a resolution of 1 minute [24]. Global and diffused horizontal irradiance, direct normal irradiance and ambient temperature are obtained from KNMI for the years 2011-2013. A $10kW_p$ PV array is modeled in MATLAB using thirty Sun power E20-327 modules rated at 327W [25]. They are connected in 5 parallel strings having 6 modules in series having a combined installed power of 9810W. The power output of the 10kW PV array is estimated as described in [4].

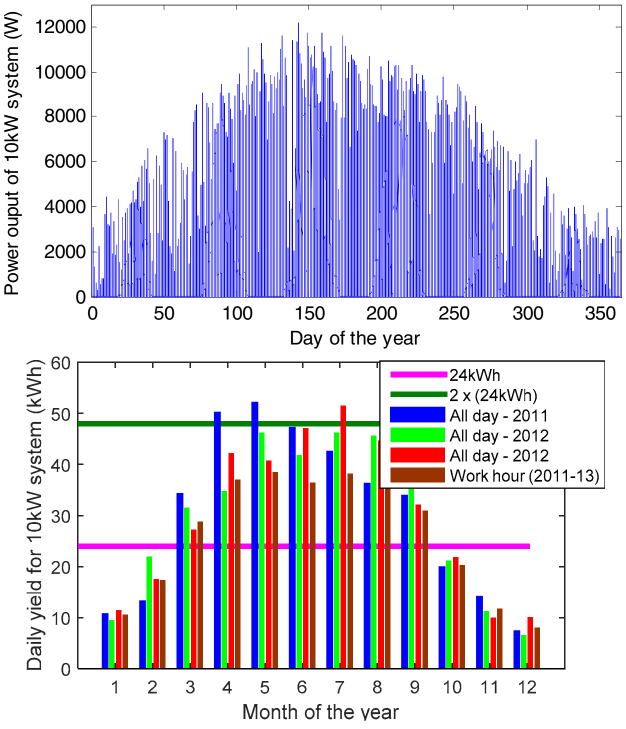

Fig. 2 - Power output of 10kW PV system as a function of time for 2013 (left). Average daily yield of 10kW PV system for different months for 2011-2013 (right). The PV modules were oriented south with a tile of 28°.

TABLE 3
Annual energy yield of 10kW PV system with 28° tilt

	2011	2012	2013	Avg.
Annual yield of PV E_y (kWh) [A]	11039	10753	10876	10890
Annual yield in working hours on all days (kWh) [B]	9682	9469	9541	9564
Annual yield in working hours on weekdays E_{wh_y} (kWh) [C]	6915	6763	6815	6831
% of energy [B/A*100] (%)	87.7	88.0	87.7	87.8
% of energy [C/A*100] (%)	62.6	62.8	62.6	62.7

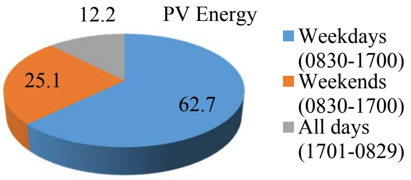

Fig. 4 – Pie chart showing the percentage of annual PV energy production during working and non-working hours on weekdays and weekends

The PV panels are orientated at an optimal orientation of azimuth $A_m=0^o$ (i.e. facing south) and tilt angle $\theta_m=28^o$ that results in maximum energy yield.

Fig. 2 shows the power output of the 10kW PV array with 1 min data resolution, showing the seasonal variation in power output from January to December [4]. Fig. 2 shows the average daily energy yield E_{day} of the system for different months. The yield E_{day} varies from 10kWh/day in winter to about 50kWh/day in summer, nearly a five times variation due to large seasonal impact. The annual energy yield E_y for 2011-2013 period is indicated in TABLE 3 and the average is 10,890kWh/year. It must be remembered that the calculations above have not considered shading due to nearby buildings/trees and installation in non-optimal orientations [26], [27]. The yield would then be appropriately lower based on the location characteristics.

For EV charging from PV, what is vital is the daily PV energy yield during working hours E_{wh}. Here the working hours is considered as the period between 0830hr to 1700hr. Using the model developed, the estimated annual energy yield in the working hours is 9564kWh/year, which corresponds to 87.8% of the total energy yield of the year as seen in TABLE 3. This goes to show the huge potential of charging the EV from PV. However, a small part of this energy cannot be used for EV charging if the EVs are available at workplace only on weekdays and not on weekends. Then the energy available for charging EV from PV during work hours on weekdays is E_{wh_y}=6831kWh/year which is 62.7% of annual yield as shown in Fig. 4. The percentage would be slightly different if the working hours considered are different, for example working hours are 0900 to 1800. This variability is not considered in this analysis as it changes based on the company, location, weather etc.

IV. CHARGING OF EV FROM PV – ROOFTOP PV AND SOLAR CARPORT

Based on the metrological conditions in the Netherlands, it has been shown in [4] that 13kW PV array can be connected to a 10kW inverter resulting in only 3% energy loss in the year. This is due to the low levels of insolation in the Netherlands, a PV panel very rarely produces its full peak power in the year. Therefore a higher peak power PV array can be connected to smaller power rated inverter with minimal losses due to non-MPPT operation [28]. Using a 13kW PV system connected to a 10kW EV-PV charger, 13449 kWh/year is produced in the working hours assuming 5% system losses, as shown in TABLE 4. The corresponding revenues generated from PV energy is 3093€/year based on the electricity price of 0.23€/kWh. The use of smart dynamic charging of EV at variable power can ensure that the PV power is optimally used for EV charging [4], [29].

To install the solar panels for charging the EVs, two options exist – installing the PV on the rooftop or as a solar carport. The most cost efficient solution is to place the panels on a roof of the office/factory building as it only requires low cost racks for mounting. Further, roof top installation eliminates shadow from trees, buildings and other objects. On the other hand, the cost of construction of a carport is much higher than a rooftop installation. But they have the advantage that it has proximity to the EV making the transmission losses lower, it provides shade for the car and creates a ‘green’ image for the workplace.

In terms of cost, PV panels are sold in the Dutch market at 0.75-1 €/W$_p$, inverters for 0.15-0.25€/W$_p$ and roof top mounting kits for 30€/panel [30], [31]. Based on these costs, the cost of a 13kW PV system is 19,700€ as shown in TABLE 4 considering the worst case price of 1€/W$_p$ for PV and 0.25€/W$_p$ for inverter. In comparison, the cost of a solar carport like Orion, Upsolar or Schletter is priced between 2500€-5000€/kW for the physical construction based on the type of structure and material used [31], [32]. For the solar carport developed by the authors, the estimated cost for construction was in the range of 2300€-3250€/kW [7]. For this paper, a mid-value of 3000€/kW is used for the

TABLE 4
Annual revenue from Energy of 13kW PV (5% losses)

	Energy (kWh)	Revenue (€)
Full year	13449	3093
Working hours	11812	2717
Weekdays working hours	8436	1940

TABLE 5
Cost of 13kW PV rooftop system & carport

	Unit cost (€)	Qty.	Cost (€)	Cost (€)
330W PV module	330	40	13,200	13,200
10kW PV inverter	2,500	1	2,500	2,500
Replacement inverter	2,500	1	2,500	2,500
Module mounting	30	50	1,500	0
Solar carport 13kW	39,000	1	0	39,000
Total Cost			19,700	57,200

TABLE 6
Cost of Electricity from 13kW Solar
Rooftop and Carport

	Cost of System (€)	Energy (kWh/year)	Electricity Cost (€/kWh)
Rooftop PV	19,700	13,448	0.097
Solar carport	57,200	13,448	0.28
Grid			0.23

TABLE 7
Number of EV that can be charged by 13kW PV @ workplace

Energy	EV	kWh per 100km	Full charges per year	Distance (km/year)	Cars/year
PV Energy 8436 kWh	Leaf	12	351 of 24kWh	70,300	4.91
	Model S	17	99 of 85kWh	49,625	3.46
Grid Capacity 22100 kWh	Leaf	12	920 of 24kWh	184,000	12.87
	Model S	17	260 of 85kWh	130,000	9.09

calculations in TABLE 5 for cost of solar carport. A 13kW solar carport will hence cost 57,200€, nearly three times as expensive as the rooftop installation.

Based on TABLE 4 and TABLE 5, the cost of the energy generated from PV can be estimated assuming a 15 year lifetime for the PV system. In general, PV panels have a warranted lifetime of 20-25 years with a gradual reduction in performance. Fifteen years is chosen here as a conservative average during which period the reduction in PV performance is neglected. In the 15 years, an inverter would need to be replaced considering its lower lifetime with respect to the panels and this cost has been included in the lifetime costs. This corresponds to an electricity price C_{PV} over the 15 year period of 0.097€/kWh and 0.283€/kWh for the rooftop PV and solar carport respectively, as shown in TABLE 6.

With 8436 kWh of PV energy available per year on weekdays during office hours, the number of times a Nissan Leaf (24kWh battery) and Tesla Model-S (85kWh battery) can be fully charged and the total distance that can be driven on solar energy is shown in TABLE 6. Thus, solar charging at workplace can provide annual charging capability for 70,300 km for a Nissan Leaf and 49,625km for a Model-S. This is a very large number considering that the average amount of kilometers driven by a car on workdays is 14,300km as mentioned earlier. So the energy produced by a 13kW PV system is sufficient to match the driving needs of five small EV like Leaf and three large EV like Tesla Model S for travel requirements on working days. This explains why four EV were chosen for comparison with gasoline vehicles in TABLE 1. The number will remain the same if the working days are considered to be 7 days/week where the additional PV production in the weekend will match the corresponding EV demand.

If only the capacity of the EV charger of 10kW is considered then, 10kW*(8.5h*260days) = 22,100kWh of energy can be delivered by the system over the year. 8,436 kWh or 38% of this energy will be from solar energy. The number of times each of the car can be fully charged and total distance that can be driven using the full 10kW capacity is shown in TABLE 6 exhibiting the possibility to charge nine to thirteen EVs every day. It must be kept in mind that the PV production has a seasonal dependence, so the same amount of 'solar' miles is not spread evenly throughout the year but can only be realized over an annual basis.

To compare the economics of grid charging and solar charging, the electricity price from solar is 0.097€/kWh which is less than half of the grid price of 0.23€/kWh. This difference in electricity price leads to reduction in fuel costs per year by more than half, from €493 to €215 as seen in TABLE 1. However, the larger benefit of solar charging is that the CO_2 emissions are completely zero as the electricity is itself produced from renewable source. The emissions reduce from 109g/km and 70.5g/km for gasoline and grid charged EV to 0g/km for solar charged EV. Further, the energy from a solar carport is 0.05€/kWh more than the grid prices which could be very attractive where the application derives benefits from the car shade and aesthetic appeal. The dual benefit of lower fuel cost and emission make EV charging from PV to be both economical and environmentally beneficial compared to grid charging. Further the installation of PV and use of EV can provide additional tax and governmental benefits in the form of Milieu-investeringsaftrek(MIA), Energie- investeringsaftrek(EIA) and Kleinschaligheids- investeringsaftrek (KIA) in the Netherlands.

V. Impact of Feed-In Tariffs

There has been a renewed push towards motivating users to increase their self-consumption of PV power. This is due to problems in the grid due to large scale PV generation in the form of overvoltage, overloading of lines and reverse flow [8]. Secondly, whole sale energy prices (0.02-0.04€/kWh) are much lower than the retail prices (0.23€/kWh) which has caused grid operators to reduce feed in tariffs for PV to a value much lower than retail prices [33], [34]. Fig. 5 shows the revenues from PV generation which are obtained for different feed-in tariffs ranging from 0 - 0.40€/kWh. The revenues show a big variation ranging from 0 – 5380€/year based on the feed-in tariff. The effect of local load of the workplace on the PV revenues is not considered here so as to consider the PV charging station as an independent entity.

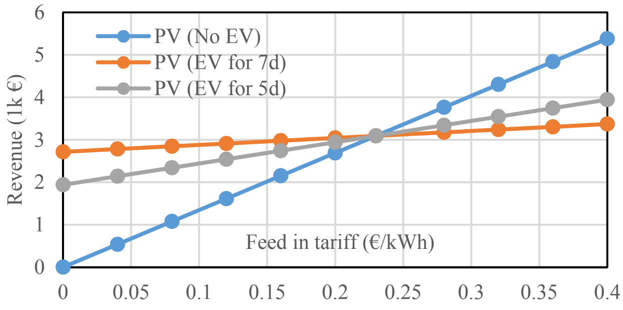

Fig. 5 – Annual PV revenues as a function of feed-in tariffs

With the introduction of EV charging for 7days/week during work hours, 11,812kWh or 87.8% of PV electricity can be annually diverted for EV charging which would have otherwise been purchased from the grid for 2717€ at 0.23€/kWh. With a revenue of 2717€, only the remaining PV power is fed back to the grid (12.2%) resulting in improved PV revenues when the feed-in tariff is <0.23€/kWh as seen in Fig. 5. If EV charging is done only on weekdays during work hours, 8436kWh or 62.7% of PV electricity can be annually used for EV charging which values to €1940 as shown in TABLE 4. Due to lower self-consumption, the revenues are lower than the 7day/week but much higher than having a PV system with no EV charging integrated.

It can thus be seen that by charging EV from PV, the PV self-consumption is increased preventing the economic losses due to lower feed in tariff. Secondly, demand charges at the workplace can be avoided if there is no seasonal variation in PV generation and part of the EV charging power is consistently supplied by PV.

VI. CONCLUSIONS

The economic benefits and CO_2 emission reduction of a solar powered EV charging station for Netherlands have been analyzed in this paper. Driving an electric vehicle instead of a gasoline car to work every day results in an annual saving of €1,520 just based on fuel costs and CO_2 emissions are reduced on an average by 38.5g/km. This results in annual CO_2 emission reduction of 770kg/car/year for a distance of 20,000km. Further, the purchase tax and annual car taxes are zero for an electric as against tax €2844 and €912 respectively for a gasoline car of 1.5ton weight and 109g/km of CO_2 emission. While EVs are cleaner than gasoline car, their usage still results in 70.5g/km of CO_2 on average because the Dutch energy mix for power production is largely based on fossil fuels with 470g/kWh of CO_2 emission.

A truly sustainable way of driving is hence to charge an EV using solar energy. This results in zero CO_2 emission. The electricity price from PV is 10c/kWh, which is less than half of the current grid price of 23c/kWh. Using a 13kW PV, 13448 kWh/year is produced in the working hours. This can provide annual charging capability for 70,300km for Nissan Leaf and 49,620km for a Tesla Model-S. EV charging promotes the self-consumption of PV and this results in increased PV revenues when feed-in tariffs are lower than retail electricity price. Thus the dual benefit of lower fuel cost and emission make EV charging from PV to be both economical and environmentally beneficial.

For future work, the authors recommend the inclusion of factors relating to maintenance costs, insurance, depreciation, rate of interest and that provide the Total Cost of Ownership (TCO) of gasoline car and EV. From the perspective of grid operator, the reduced costs of grid expansion and increased renewable production would be interesting to evaluate.

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