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POTENTIAL AND CHALLENGES OF VEHICLE INTEGRATED PHOTOVOLTAICS FOR PASSENGER CARS

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ABSTRACT: We provide a general overview on vehicle integrated photovoltaics (VIPV) for passenger cars. Historic examples are reviewed to demonstrate that VIPV can provide an economic benefit due to the current and unique setting of very low solar cell costs and ambitious goals for electric vehicles. Subsequently, four guiding questions are addressed: 1. Which benefits are offered by VIPV, 2. Which potential costs are related to VIPV, 3. What are the challenges of VIPV and 4. What is the future potential of VIPV? It is shown that with a typical roof (1.7 – 2 m²) of a car equipped with solar cells, a solar driving distance of up to 1900-3400 km/year can be achieved and the cost for manufacturing such a solar module is estimated to be below 120 €/piece. Furthermore, using the full potential of solar integration in cars, a solar driving distance in the range of the yearly average driving distance of passenger cars in Germany (15,000 km/a) could be theoretically covered by VIPV.
Keywords: Vehicle Integrated PV (VIPV), Module integration, Module manufacturing

1 INTRODUCTION

Vehicle integrated Photovoltaics (VIPV) has shown the potential to fulfill the dream of free travelling since the first solar car race (“Tour de Sol” [1]) took place in 1985 in Switzerland (see Fig. 1).

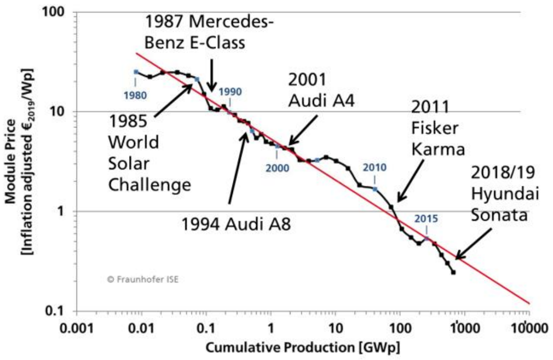

Figure 1: Examples of VIPV over the years down the PV learning curve [2].

This race, where cars are powered by solar energy alone (now continued as e.g. “World Solar Challenge”), forecasted the great potential of VIPV and it took no more than 2 years until the first prototypes of VIPV were investigated by car manufactures such as Audi [3], Mercedes-Benz (Daimler) [4] and suppliers such as Webasto [5], and asolar (a2solar) [6].

At that time solar cells and modules costs were around 100 times the current ones (see Fig. 1), hence the market penetration was very low. The introduction of CO_2 reduction targets for passenger cars and the consideration of eco innovations such as solar roofs as CO_2 credits by the European Union in 2009 [7] was still not able to help for a significant deployment of VIPV. The possible reasons are manifold, but probably the most prominent hurdle was that the potential benefits of a solar roof such as a relative cooling of the cabin while parking, slight reduction of the charging time of the starter battery, or the eco-friendly image of the user/fleet operator; were valued too little compared to the elevated costs of a solar roof. Additionally, many solar roofs were offered as part of another product, such as a retractable roof, since this allowed an easier manufacturing and integration into the vehicle. However, this adds onto the costs and only customers who are interested into a retractable roof where potentially offered the choice of an additional solar option. This changed substantially in 2011 when the Fisker Karma [6] was presented. For the first time a large solar car roof with 120 W was part of a series production vehicle. Unfortunately, the car did not become a great success. With the exception of the Toyota Prius [8], it took almost eight years until only recently many new and old car manufactures have announced to explore the option of a solar car roof. As an example, Hyundai is already offering a solar roof as part of the “limited” edition of the Hyundai Sonata [9]. Further examples include the Start-ups Sono Motors [10] and Lightyear [11] which plan to equip not only the roof but also other vehicle body parts.

But why is there a recent renaissance of vehicle integrated photovoltaics? Firstly, the power which can potentially be generated on a car roof has increased substantially due to the continuous improvement of the solar cell and module technology, leading to higher efficiency modules [12]. Therefore, not only a cooling of the passenger cabin could be provided by the solar roof, but even a significant extension of the driving distance could be feasible. Secondly, the cost of solar cells has decreased rapidly, specifically in the last 10-15 years, which also decreases the cost of a solar car roof [€/Wp]. Thirdly, the market share of hybrid or fully electric cars, where solar energy could be directly used for the propulsion of the car, has taken off within the last few years and the International Energy Agency (IEA) expects that by 2030, 44 million electric vehicles will be sold each year worldwide [13].

Assuming an average roof size of 2 m² and a module power of 200 W/m², this accounts for a potential market size of solar modules of 18 GW/year globally if all new electric vehicles were to be equipped with a solar roof. Compared to the overall solar market, with a current size of 131 GW [2], this is much more than a niche market, which gives the potential for several application-focused manufactures to produce high-value solar modules specifically targeted to vehicle manufactures.

In this work we analyze the potential and the challenges of VIPV modules. Based on a selection of electric vehicles and an estimation of the potential generated power of a solar roof, we discuss the added benefits of a solar car roof. Manufactured prototypes are introduced and key questions of vehicle manufacturers are answered. Finally, we provide an outlook beyond current technology and the roof area of cars.

2 METHODS

2.1 Potential solar range

We start with an analysis of the currently available electric vehicles and compare the largest available battery size of each series, the consumption and the respective range. Additionally, we collect data on the roof size of the vehicles. We only consider the roof area of the vehicles for the equipment with solar cells for two reasons: Firstly, the roof provides a rather simple technological implementation; the curvature is quite low, glass roofs with a similar layout such as solar roofs are already available and manufacturers have already produced and sold solar roofs. Secondly, the yield on the car roof is potentially the highest relative to other surfaces of the car since the area is quite large, the orientation of the roof is favorable and, due to low curvature, the mismatch between cells may also not be significant.

Based on a calculated module output power for the roof areas we perform yield estimations. Irradiation data of Freiburg, Germany was obtained from SolarGIS s.r.o. This dataset provides an average of yearly irradiation at different locations taking into account the solar irradiation and the weather. We decided to use the 10-year average from 2006 till 2015 for our calculations. We assume a horizontal module without any curvature and no additional shading by houses, trees, etc. A system efficiency factor of 88% is used, which is calculated based on PV power plants and taking into account effects such as (e.g.) soiling, temperature, cabling. We further assume that the generated power can be fully used for the propulsion of the car. This would strongly depend on the available battery capacity throughout the day; therefore a charging of the high voltage battery by the solar module in a fully or hybrid electric car would be more beneficial.

2.2 Module manufacturing

To investigate manufacturing hurdles and potential manufacturing costs, we manufactured car roofs with integrated solar cells based on the panoramic roof of a Peugot 308SW. We used this roof, since it is one of the largest available panoramic car roofs made out of one continuous glass laminate. The area of the panoramic roof is around 1.6 m². Low-iron glass shaped in the same way as the panoramic roof has been provided by Carlex. The outer glass was coated using the MorphoColor® coating technology developed at Fraunhofer ISE [14]. The MorphoColor® coating allows the cell layer to be hidden behind a color layer with a transmission of 93% in the spectral response range of the PV cells. The coating can be chosen freely from a wide range of colors.

The manufacturing of the solar car roof is done with a conventional plate-membrane laminator (E-LAPV, Bürkle) which we modified to be able to work with substrates up to a height of 12 cm. A transparent PVB-layer is used as encapsulant in front of the cell matrix and a black PVB layer behind the cell matrix. As cell layout we use three configurations: 5-busbar half cells, shingled strings and the matrix shingled configuration where we can avoid non-active area between strings [15]. The used cells have an efficiency of 20.4%. One manufactured module is IV-measured and we perform thermal cycling (TC) testing, and damp heat (DH) testing according to IEC 61215. During TC200 the module is exposed to 200 cycles of temperature between -40 °C and 80°C. During DH1000 the module temperature is kept at 85 °C under a humidity of 85% for 1000 h. The I-V characterization is performed at Fraunhofer ISE’s CalLal facility, such that the module is in the same horizontal plane as when equipped in a car and the focus is adjusted to the largest horizontal area of the module. Note that losses from the curvature are already incorporated into the IV data with this measurement setup.

3 RESULTS

3.1 Potential solar range

Table I provides an overview of the different vehicle types, with the respective key characteristics. The roof area between the vehicles differs significantly. Depending on the overall design of the vehicle, larger roof areas are available for e.g. cars with a larger cabin size or station wagons. For the vehicles marked with an * (Tesla Model 3 and Volkswagen ID3), an extended roof area is considered. The Tesla Model 3 has a very small roof but a large rear window extending the roof significantly. We have added this area as available roof area for solar cells. The Volkswagen ID3 has a sizeable roof which extends into a rear spoiler. We have also included the area of the rear spoiler for calculations. The potential nominal solar power was calculated from the roof area assuming a module efficiency of 20%. It is shown that modules with significant power output up to 538 W_p can be integrated in currently available electric vehicle roof areas.

The generated energy yield potential in Freiburg over

Table I: Different vehicle types with their respective consumption, largest available battery capacity, range, roof area, potential solar power, yearly yield in Freiburg, Germany and respective generated range potential considering the consumption. The * marks where an extended roof area was considered.

Vehicle	**Consumption [kWh/ 100km]**	**Battery capacity [kWh]**	**Range [km]**	**Roof area [m²]**	**Potential Solar power [W_p]**	**Generated Energy/ year (Freiburg) [kWh/a]**	**Solar range / year [km]**
Audi e-tron	24	95	436	2.3	460	495	2063
BYD e6	21.5	80	400	2.2	440	473	2200
Chevrolet Bolt EV	16	60	380	2.0	400	430	2688
Hyundai Ioniq Electric	13.8	38.2	311	2.2	440	473	3428
Daimler EQC	23.5	80	390	2.1	420	452	1923
Nissan Leaf	20	40	270	1.8	360	387	1935
Tesla Model 3	16	75	560	2.5*	500	538	3363
Volkswagen ID3	14	77	550	1.9*	380	409	2921
BMW i3	13.1	37.9	359	1.9	380	409	3122
Renault ZOE	17.7	52	386	1.7	340	366	2068

the duration of a year as well as the respective potential range, considering the consumption, is shown as well. Assuming a scenario without shading and a vehicle in Freiburg, the solar yield provides a significant increase in potential range of more than 1900 and up to 3400 km per year. Figure 2 provides a graphical view on the potential solar range depending on the roof area and consumption for the different vehicles. This accounts for 13 – 23% of the yearly average driving distance of a car in Germany (15.000 km, KBA statistics) [16]. Assuming the solar power can be fully utilized for propulsion, this directly translates into a consumption reduction of 13-23%.

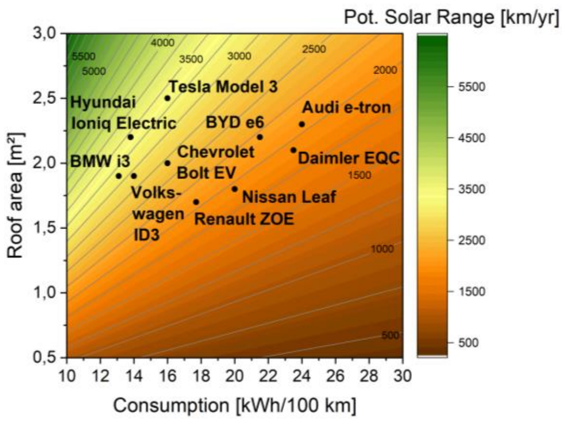

Figure 2: Potential solar range in Freiburg, Germany for different electric vehicles depending on available horizontal roof area and consumption.

The provided figures in Table I and Fig. 2 show a theoretical potential of the current technology. Curvature of the module, losses due to shading and needed utility power for battery charging are not considered as well as a reduced yield because of non-optimal utilization of solar potential if the battery is full.

The influence of curvature is also discussed in this conference [17]. Yield reduction because of shading strongly depends on the driving pattern and vehicle location. While a full solar cadaster for the German road network is currently under development in the research project PV2Go [18], we estimate the losses due to shading with a typical daily driving pattern. Figure 3 shows two scenarios of cars travelling and parking in Freiburg: Firstly, a car (2 m² roof area) which does not receive any shading at all (blue columns). This amounts to a generated power of 450 kWh/a or 1880 – 3450 km solar range per year depending on the car's consumption.

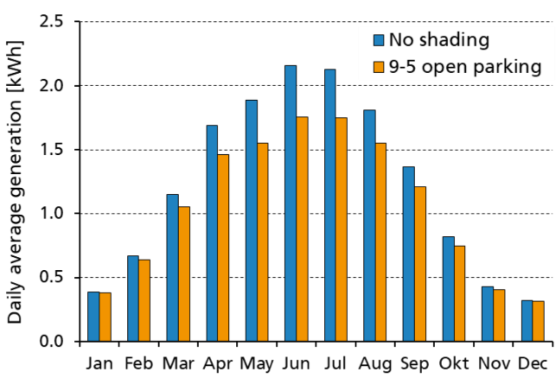

Figure 3: Daily average generation for each month of a car with 2m² roof area in two different scenarios.

In the second scenario (orange columns) we assume a person living in Freiburg and parking in an underground parking lot, but working in an office with an open parking lot. This means that the car is fully exposed to the sun during office hours (9am - 5pm) but 100% shaded during all other hours of the day. For the yearly yield we also assume generation only during weekdays, therefore the car only harvests solar energy 5 days of the week. Here the generated power amounts to 266 kWh/a which still relates to 1100 - 2030 km solar range per year (or ~60% of scenario 1). Figure 3 also shows that daily generation during the winter months of the 9-5 scenario is still quite similar to the no-shading scenario, but for the summer months a daily yield reduction of 22% is observed.

Further solar yield reductions due to the battery charging efficiency, transformation losses and non-optimal utilization of generated power depend strongly on the system design and driving patterns. An intelligent battery control and charging management is required. Utilization of solar generated power may be further expanded by using advanced charging controls and solar predictions.

3.2 Module manufacturing

Figure 4 shows two manufactured prototypes of the solar car roof. The solar car roof on the left side uses the matrix configuration of the solar cells and a "dense" MorphoColor® coating offering a very effective hiding of the solar cells, while the solar car roof on the right uses the string shingled configuration and a less saturated MorphoColor® coating such that the individual cells are slightly visible (thick brighter stripes from left to right within the module).

Figure 4: Manufactured module prototypes.

I-V measurements of a string shingled module show that the achieved module power is 266 W with a voltage of 196 V and current of 1.72 A.

After accelerated aging of a string shingled module no degradation is observed. Fig. 5 shows electroluminescence (EL) measurements before aging, after TC200 and the subsequent DH1000. A slight increase in inhomogeneity of the EL pattern is observed, however, I-V measurements confirm that module power alterations were within the measurement tolerance.

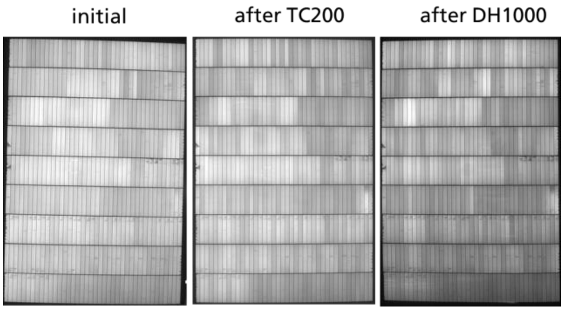

Figure 5: EL measurement before aging, after TC200 and after DH1000.

Table II shows a comparison of the three interconnection technologies (half cell interconnection with 2 mm gap, string-shingled and matrix-shingled technology [19]). We use market-available PERC cell efficiencies, and calculate the number of cells which can fit into the used module geometry. The module output power is calculated based on the cell efficiency, number of cells and an estimate cell to module (CTM_{power}) factor of 0.96. The provided manufacturing costs are based on module production line costs [20] and are calculated for a yearly production of 50,000 modules for 5 years, with an adjusted component list and specialized equipment for a dedicated VIPV module production.

Table II: Comparison of the different solar cell interconnection technologies.

Interconnection technology	**Cell efficiency [%]**	**Number of cells**	**Rectangular module area m²**	**Calc. module power [W_p]**	**Manufacturing costs [€/module]**
Half cells	22.1	108	1.38	279	107
String shingled	22	360	1.38	311	112
Matrix shingled	22	366	1.41	316	115

Table II shows that while the half cell technology has the lowest manufacturing costs, the module power is significantly lower than for both shingled technologies. The reason is that the gaps between the solar cells decrease the active area (cell area). The largest active area could be achieved for the matrix shingled configuration.

4 SUMMARY

To summarize the results we would like to discuss the three main questions which are often raised when introducing VIPV to manufactures and suppliers:

1. Which benefits are offered by VIPV?

The main benefit of VIPV for potential users and fleet operators is a solar range of 13-23% of the yearly average driving range of cars in Germany (15,000 km). This also relates to reduced charging times of vehicles (around 1 charging stop less per month during the summer months) and an increased range during sunny days. Hybrid cars may also profit from VIPV due to a reduced fuel consumption. Even for conventional cars with internal combustion engine, a significant amount of fuel savings could be achieved as the solar roof could reduce the demand for the alternator to run. Further potential is seen in cooling of the passenger cabin during summer months. Secondary benefits are reduced CO_2 emissions as compared to receiving power from the grid, and a relief for the power grid due to lower charging requirements if many cars are equipped with solar energy.

2. Which potential costs are related to VIPV?

The manufacturing costs for a VIPV module of 1.6 m² are below 120 €/piece considering a production of 50,000 modules per year (~15 MW) for at least 5 years.

3. What are the challenges of VIPV?

The main technological challenge is the utilization of the generated power. For a high utilization, the high voltage drive-train battery is preferred; however this could lead to significant transformation losses and potentially safety concerns. Additionally, the battery management system needs to be setup such that the charging can utilize most of the PV power and the battery self-consumption does not lead to significant losses. Further challenges arise e.g. due to the curvature of the car roof. A strong curvature may lead to a significant irradiance mismatch and resulting cell power which could reduce the yield of the module. The overall achievable yield strongly depends on the driving patterns of individuals. However, for the scenario of open parking during office hours and only 5 days per week, the achievable range is still very significant. Lastly, module and cell technology needs to provide highest yield but also a premium aesthetical appearance and durability.

5 OUTLOOK

So far the presented results only considered the roof area of a car and currently available crystalline silicon-based solar cell technology. However, a car has additional surfaces that can potentially be equipped with solar modules. Figure 6 shows the different integration levels of VIPV for cars and the respective available surfaces for equipment with solar modules.

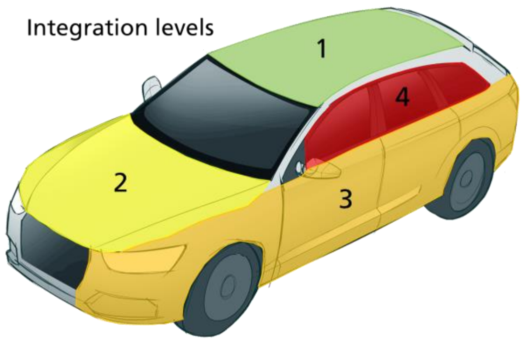

Figure 6: Possible integration levels on a vehicle depending on the vehicle body surface.

Integration level 1 is the integration on the car roof, which is just a slight deviation from a standard glass/glass module setup. In accordance with Table 1, we assume an area of 2 m² as available for solar module integration. In Integration level 2 (hood and trunk), the available area is larger, however, the requirements regarding safety, durability (i.e. scratch resistance) and curvature are much more demanding, therefore different and new module technologies need to be applied. Here we propose 3 m² as additional available area. For comparison, the Lightyear One uses 5 m² as area for solar modules including the roof [11]. For integration level 3, which considers all non-transparent surfaces such as the sides of the car, the safety requirements are similar to integration level 2 but the yield is significantly lower. Here we calculate with an addition of 3 m², vertical module configuration and assume only half of it generates power at each time since they are installed on opposite sides of the car. Last but not least, in integration level 4 also transparent car surfaces are considered, since it might be possible to use e.g. organic solar technologies which are partially transparent but still capable of delivering power [21]. These would even further expand the available area on the car and increase the yearly power output. We calculate a total hypothetical area of 10 m² used for solar modules, however for the transparent areas (2 m²) we consider a reduced efficiency of the cells and also assume vertical modules. The different integration levels, the area and the related performance ratio by integration level are listed in Table III. The * marks the areas where we consider that only half of the available module configuration can generate power at once.

Table III: Comparison of the different solar cell interconnection technologies.

Integration level	Area [m²]	PR [%]	Efficiency [%]	Efficiency (new cell techn.) [%]
1	2	88	20	30
2	3	88	20	30
3	3*	60	20	30
4	2*	60	8	15

Figure 7 shows an overview on how the different integration levels may increase the potential driving distance. Considering also a reduction in consumption and future solar cell technologies with an efficiency of 30% (achievable with cell technologies such as perovskite-Si-tandem [22, 23] or III-V-Si-tandem [24]) a yearly driving range of ~15,000 km with solar energy is achievable. For a car operating in e.g. Spain or California, the yearly driving range provided by solar may be even further increased by 50% (Spain) or 60% (California) due to the higher solar irradiation levels.

The results shown in Fig. 7 demonstrate that the mean yearly driving range of a car operated in Germany could be covered by VIPV alone, calculatedly. However, in practical terms, the generated power by VIPV during summer months would exceed the energy demand for driving and, consequently, little charging during summer months would be necessary already for integration level 2. During winter months, and even with the highest yield possible, external charging stops will still be required.

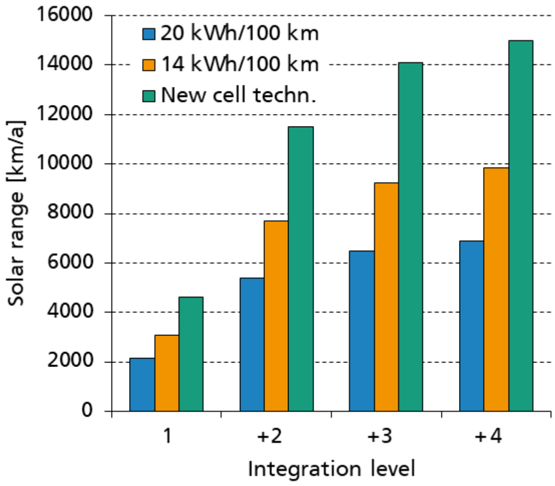

Figure 7: Solar range depending on the integration level, vehicle consumption and solar cell technology for a vehicle operated in Freiburg, Germany.

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