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Office of Energy Efficiency & Renewable Energy
U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585
RE: DE-FOA-0002790: Request for Information on Challenges and Opportunities for Vehicle Photovoltaics

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INTRODUCTION

Thank you for the opportunity to provide insight on technical and commercial challenges and opportunities for vehicle photovoltaic systems. The Information Technology and Innovation Foundation (ITIF), the leading think tank for science and technology policy, is a non-profit, non-partisan research and educational institute. Its mission is to formulate, evaluate, and promote policy solutions that accelerate innovation and boost productivity to spur growth, opportunity, and progress. Clean energy, climate innovation, and industrial policies are some of ITIF's primary issue areas.

The United States trails behind Europe and China in the adoption of on-road electric vehicles, but it is nonetheless underway. Decarbonizing the rest of the transportation sector (namely, any subsector outside of the on-road light-duty vehicle subsector) has received comparatively less attention from DOE. Although vehicle-integrated photovoltaic (VIPV) and vehicle-added photovoltaic (VAPV) strategies could in principle complement policies that impact the transportation sector and have climate benefits, the likelihood of breakthroughs that significantly improve upon current VIPV and VAPV products (which provide only a few miles per day) is low. DOE's highest RD&D priorities should focus on decarbonizing the off-road and heavy-duty transportation segments, which have proven to be much harder to abate to date and are less likely to be impacted by VIPV and VAPV strategies.

If they were to proceed, RD&D and commercialization efforts on VIPV/VAPV technologies need to apply beyond the on-road light-duty vehicle subsector. Current technologies are compatible with only battery-electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs), and hybrid electric vehicles (HEVs). Current trends for heavy-duty vehicles, aviation, and shipping appear to favor alternative fuels such as green hydrogen and green ammonia instead of battery-electric drivetrains.

CATEGORY 1: STATE OF THE INDUSTRY AND KEY DOMESTIC MARKETS

Category 1.1

Light-duty passenger vehicles, recreational vehicles (RVs), and buses are the most promising segments for vehicle PV systems despite the PV systems' current limitations. The passenger vehicle segment shows the highest potential given it has the most matured electric vehicle market compared to other transportation segments. Commault et al. (2021) noted that the number of car-integrated PV projects from 2015 to 2020 increased at least three times compared to the previous 5-year periods when EV sales began to take off.[1] At present, VIPV/VAPV technologies work best with lighter vehicles as they require lower energy consumption (kWh/miles). For example, Toyota Prius Prime (curb weight = 3,365 pounds-3,375 pounds) has an electric-only range of 25 miles with an 8.8 kWh battery, yielding an energy consumption of about 0.33 kWh/miles.[2] Meanwhile, an electric Scania truck (GVWR Class 8) has a usable battery capacity of 468 kWh that provides a range of 250 km (155 miles), which means its energy consumption is over 2 kWh/miles.[3] These data points suggest that the efficacy of VIPV/VAPV reduces significantly as the weight of the vehicle increases, even if the heavier vehicle has a greater surface area.

Despite their higher weight than passenger vehicles, RVs including motorhomes (Class A, B, and C) are also promising for vehicle PV systems due to their mostly flat surfaces and RV PV systems can provide auxiliary uses such as bidirectional charging and emergency backup power.

The RFI identified that medium- and heavy-duty utility vehicles also show high potential. However, it did not make a distinction between single-unit trucks and combination trucks. This distinction is important for three major reasons. First, a single-unit truck that travels locally with a home base to return to daily has an annual average VMT similar to a passenger vehicle, whereas the average annual VMT of a combination truck (which is typically Class 7 or 8) is about 60,000/year, or five times of a single-unit truck's annual VMT.[4] The potential range generated from VIPV on the heavier combination trucks is likely too little to be of practical use. Second, while battery-electric trucks might make sense for single-unit trucks, currently, FCEV market growth occurring in heavier vehicles with high daily use is deemed more likely, but VIPV projects are tested on BEV and PHEV vehicles.[5] Finally, a combination truck consists of the tractor, axles, and trailer (which is mounted over the tractor axle) or shipping container separately. Since a tractor makes up a small portion of the vehicle's total length and surface area, the application of VIPV/VAPV technologies is significantly limited. Also, it is not feasible to apply a PV system on the trailers or shipping containers. Although a truck trailer or a shipping container has a large surface area, making it ideal for VIPV/VAPV applications, the rough nature of shipping and handling of it (especially in water or rail transit) presents additional challenges in terms of reliability and durability of the PV system.

Although not explicitly identified in the RFI, off-road low-speed vehicles such as golf carts, in which electric versions are readily available and the market CAGR is expected to grow by 3.5% from 2021 to 2027, are also very compatible with vehicle PV systems.[6]

Overall, applications of VIPV/VAPV products are limited to on-road non-heavy-duty vehicles. To expand these products to other vehicle segments, DOE should study the relationship between battery and PV and the key use cases of VIPV/VAPV products (e.g., charging the vehicle battery a bit more versus substituting for the grid.) If it is the latter case, then it would make more sense to simply improve the grid.

Category 1.2

The passenger vehicle segment has the largest market opportunity for VIPV/VAPV since it is the largest segment (by number of vehicles) and accounts for the largest share of GHG emissions in transportation. In addition, since the electric vehicle market is the most mature (mainstream) in passenger vehicles, the segment also offers the highest market penetration potential. The medium-duty vehicle segment has the next largest market opportunity.

CATEGORY 2: PRODUCT REQUIREMENTS

Category 2.1

There are various PV products already available on the market, from bendable and lightweight thin PV modules to vehicles with solar roofs. For PV modules, available products fall into three main types: flexible, curved, and light rigid. Flexible PV modules, which are primarily made of crystalline silicon (c-Si) or copper iridium gallium selenide (CIGS) solar cells, can be added to existing vehicles (allowing for easy integration) and are typically thinner than light rigid PV modules. Commercially available light rigid modules are flat panels also commonly made of crystalline silicon. Rigid solar panels are heavier than flexible solar panels, encased in glass, and may have a metal frame. Finally, curved PV modules are heavier than light rigid or flexible PV modules and are covered with glass-glass or glass-back sheet.

Some automobile manufacturers offer commercially available EVs with rooftop solar panels, as pointed out in the RFI. For example, the Hyundai SONATA hybrid's rooftop solar panel, available only for the Limited trim, can provide about 2 miles of driving range a day.[7] This meager range is still an improvement compared to Toyota Prius' rooftop solar panel, available since 2012, which provided no driving range but rather ancillary functions. Otherwise, most car models mentioned in the RFI are still in the pre-production stage.

Category 2.2

In addition to the requirements already identified in the RFI—weight, size, form factor, flexibility, resistance to vibration, visual appearance, and power conversion efficiency—other key product requirements include temperature gradients, maximum temperature tolerance, and resistance to scratches, crashes, and mechanical shocks.

Different market segments will prioritize different requirements. For example, aesthetics is a very high priority for the passenger vehicle segment and perhaps off-road and neighborhood EV segments while reliability and supply chain integration would be more important than aesthetics for the medium- and heavy-duty vehicle segment. Weight is an important factor but for different reasons. Lighter vehicles require a lower amount of electricity needed for traction. The additional weight of VIPV/VAPV modules could completely offset the additional driving range provided to a passenger car. Indeed, the curb weight of the Hyundai SONATA hybrid's Limited trim (the only option in which the solar roof is available) is 180 pounds more than the basic

Blue trim. With a combined fuel economy of 47 MPG, even with the optimal usage of the solar roof, the Limited trim would likely still be less efficient than the Blue trim, which has a combined fuel economy of 52 MPG.

Category 2.3

Mono/poly c-Si, Interdigitated Back Contact (IBC), CIGS, and plastic solar cells are common PV cell technologies on the market. Gallium Arsenide (GaAs) based solar cells belong to III-V group compounds and are commonly used in the aerospace industry, may be appropriate for VIPV/VAPV applications due to their high efficiency. However, deployment of solar modules with GaAs solar cells (single-junction cells and multi-junction cells) is less common due to its relatively high cost. So far, market-ready VIPV applications have been mostly limited to the passenger vehicle segment, which may also explain the low deployment of GaAs cells. Therefore, GaAs cell technologies would align better with heavy-duty segments.

Perovskite solar cells also show potential for VIPV applications due to the significant performance improvements in efficiency, weight, flexibility, and price over silicon solar cells. However, the technology is far from being commercialized as perovskite solar cells are sensitive to oxygen, moisture, and heat.

Category 2.5

The RFI focuses primarily on the product requirement and integration of VIPV/VAPV technologies. However, research, development, and demonstration (RD&D) efforts should also consider the end-of-life opportunities and challenges. For example, standard solar PV modules have an estimated useful life of 25 to 30 years (and can still be used beyond that with reduced efficiency) while the average life span of cars, trucks, and buses is less, implying opportunities for repurposing the modules for second uses. There are also no regulations or standards for recycling and waste materials recovery. Future RD&D efforts on VIPV/VAPV should give these issues consideration.

Another challenge to vehicle PV integration is the reduced solar yield from transformation losses due to driving patterns. Improvements in solar predictions and advanced charging controls may help to mitigate the issue. A high voltage battery for the electric drivetrain is more conducive to increasing solar yield (the utilization of generated power) but presents safety concerns and transformation losses.

CATEGORY 3: KEY BARRIERS AND PERCEPTIONS

Category 3.1

Range and cost are the major barriers to the adoption of VIPV/VAPV technologies. For example, Hyundai SONATA hybrid's rooftop solar is only available in the most expensive option, the Limited trim, which has a capacity of 205W and provides a driving range of 2 miles per day or 700 miles per year for MY 2022.[8] Assuming a 12,000 VMT per year, the solar roof system provides 5.8% of the VMT. Since the vehicle is an HEV, this translates to a 5.8% discount at the pump—decent but perhaps insignificant to a household's budget.

The solar roof system itself costs about $1,100 (in 2020 and likely more in 2022).[9] The SONATA's Limited trim has a combined fuel economy of 47 MPG. Finally, the average retail cost of gasoline (regular in conventional areas) to consumers was $2.074/gallon in 2020 and $2.908/gallon in 2021.[10] These data points suggest even with a 0% discount rate, the payback period would be 35.6 years and 25.4 years, respectively. Even if a high retail gasoline cost of $6.201/gallon, the cost of regular grade in reformulated areas in California in June 2022, is assumed, the payback period is still 11.9 years (a 5% discount rate would increase the payback period to 21 years). Since the average age of vehicles on-road is about 12 years, the payback period is simply too long with current technologies.

Note that this example illustrates the optimal usage case. Often, passenger cars are parked in garages or the shade, reducing the yield of the VIPV system.

Category 3.3

Beyond the barriers already identified in the RFI, additional barriers impeding the adoption of VIPV/VAPV technologies exist. Perhaps the most apparent barrier is the issue pertaining to the general maintenance and replacement process of the VIPV/VAPV system arising from general wear and tear, accidents, and vandalism. Replacing or repairing the system—as well as the reimbursements of the costs incurred by consumers—whether through warranty or insurance, should be simple and relatively seamless akin to replacing and repairing a windshield.

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