HIGH-VOLTAGE VEHICLE INTEGRATED PHOTOVOLTAIC SYSTEM CONCEPT AND DEMONSTRATOR TRUCK

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ABSTRACT: Certain commercial vehicles feature large roof areas that can be easily equipped with lightweight photovoltaic (PV) modules to harvest solar energy. Typically, heavy commercial vehicles (>12 t trucks and semi-trailer) can be fitted with an installed photovoltaic power of 3 kW_p to 7 kW_p with today's mainstream cell technologies integrated on the roof, and harvest significant amounts of energy. Therefore, a high voltage photovoltaic system can significantly reduce the amount and the cross-section area of the cables, and therefore cost and weight. This is why we propose a high voltage photovoltaic system concept for commercial application. The difference to conventional automotive high voltage systems, which are controlled by a central unit, is that within the photovoltaic array, high voltage is present whenever the PV modules are illuminated, and hence need to be considered under power at all times. To comply with safety standards and reduce the risks linked to high voltages (e.g. after an accident), we present a smart junction box with integrated disconnector that automatically separates the serial connection of the modules in order to lower the voltage into the range of safety extra-low voltage. The developed VIPV system is able to feed in solar energy during operation and in standby mode. We present a 15-t demonstrator truck, a Framo E-165, equipped with the abovementioned VIPV system and show yield calculations based on an energy yield model.
Keywords: DC-DC Converter, High-Voltage System, Vehicle-Integrated Photovoltaic (VIPV), Standalone PV

1 INTRODUCTION

Equipping vehicles with photovoltaic (PV) systems is seen as having a great potential for reducing CO_2 emissions in the transport sector, while also leading to further self-sufficiency from fossil fuels [1–4]. In the REPowerEU plan of the European Union, it is targeted to achieve a cross-sectoral expansion of PV to 320 GW by 2025 and 600 GW by 2030, as part of which Vehicle Integrated PV (VIPV) serves [4,5]. The Potential of vehicle-integrated photovoltaic (VIPV) on trucks has been estimated to 90 GW in the EU [4] and previous studies have looked at fuel savings of diesel-powered refrigeration trucks using irradiance measurements in the EU, USA [6] and calculations for Germany [7] and Australia [8]. Since then, cost of c-Si cells and modules have decreased further, so the implementation of solar cells on the roof of commercial trucks has become more economically attractive [6]. Additionally, with the accelerating transition from internal combustion engine drivetrains towards battery or fuel-cell electric drive trains, it is easier to utilize and store the solar energy harvested from VIPV within the vehicle. Recently, several parties (e.g. Sono Motors GmbH in cooperation with Chereau S.A.S.) are investigating VIPV Systems for diverse vehicle types, such as cooling trailers or heavy duty vehicles [9,10].
In this document we present the concept and introduce the several components to realize a photovoltaic system which is equipped on the roof of a demonstrator truck and feeds into the high-voltage battery of the vehicle, with an example given in Figure 1.

Figure 1: Demonstrator truck with integrated photovoltaic modules in the roof

2 SYSYTEM CONCEPT OF HIGH VOLTAGE INTEGRATION

This chapter introduces the relevant components to realize a high-voltage integration of the demonstrator's PV system. The system consists of a box-body integrated photovoltaic module array that feeds directly into the **high voltage battery** and is, to the authors' knowledge, the world's first integrated PV system for trucks operating fully in the high voltage infrastructure. Within the array, each module is dimensioned to comply with **IEC 61730** and Safety Extra Low Voltage (SELV) at all reasonable operation modes (up to 1000 W/m² at -20°C). Depending on the photovoltaic array size, system voltages can reach 400 - 800 V. Within the PV array, all modules are connected in series via their individual smart junction box with integrated connectors.

Superior to the smart junction box, the array is controlled with an automotive compliant SiC-based, transformer-less DC/DC converter. The DC/DC converter features a superfast Maximum Power Point (MPP) tracking technology that adjusts to the new MPP in under 1 ms to mitigate impacts of dynamic shading while driving. The DC/DC converter is connected to the vehicle control system as a subordinate via redundant communications and adjusts its power to the system parameters, only supplying the HV system when the feed-in release is granted. Therefore, the DC/DC converter is embedded in the vehicle's high voltage interlock circuit and can be galvanically separated from the high voltage DC link via manual service disconnect switches in case of emergency or maintenance. The VIPV system feeds into the high voltage (800 V) drive train battery via the DC link. In general, the system is designed as an extension of the electric truck, which enables an effortless adaptation to any make or model using the developed soft- and hardware interface.

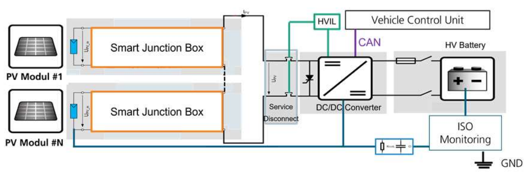

Figure 2: VIPV system concept developed in the project "Lade-PV"

2.1 Lightweight PV modules

PV modules for integration into vehicles must withstand harsh environmental conditions and are required to be lightweight to reduce load-related CO_2 emissions of the vehicle. Previous work presented some approaches to achieve the various constraints [4,11]. The PV modules used in the LadePV demonstrator truck, designed at Fraunhofer ISE and produced by SUNSET Energietechnik GmbH, feature a rated I_{SC} of 9.7 A and a V_{OC} of 28.56 V at Standard Testing Conditions (STC). The module configuration is shown in *Figure 3*.

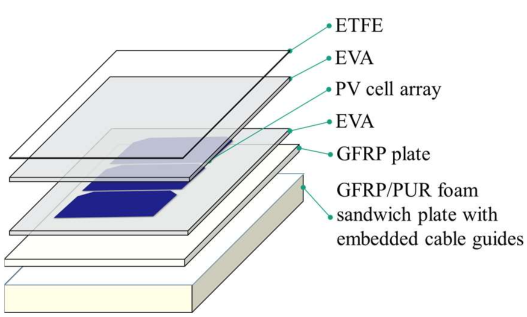

Figure 3: Proposed light-weight PV module configuration for integration on top of a GFRP/PUR foam sandwich structure [2,4]

2.2 Photovoltaic Array Featuring Smart Junction Box

For effectively conducting the harvested current to the DC/DC converter, all panels are connected in a series string, which allows to minimize the cross-section area of the cable. Furthermore, the installation has been designed to keep electromagnetic coupling between cables and modules at a minimum. A total of 14 Modules were attached on the roof of the demo truck, resulting in a maximum PV system voltage of 399.84 V at 25°C. The installed PV array can reach a power of 3.2 kW_P at STC, hence all components in the system are rated according to this value.

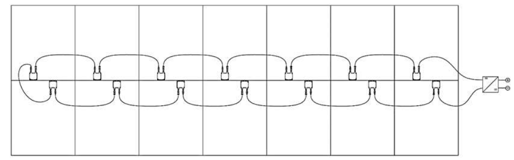

Figure 4: Schematic of wiring between PV modules and DC/DC converter

Open contact points could occur during an accident or because of cable damage, which might constitute a safety hazard, particularly if it happens where the full voltage of the string is tangible. This is not an acceptable scenario according to the ECE-R100 standard for electric vehicles, therefore it must be guaranteed that, for example, in the event of a cable defect, the string voltage is reduced to a non-hazardous level (<60 VDC) as quickly as possible [12]. Therefore, in the following states of the vehicle, the PV string has to switch into open state to ensure safe conditions:

- Separated contacts e.g. cable break, loosened plugs, faulty insulation
- Vehicle involved in an accident
- Maintenance of the vehicle
- HV circuit of the vehicle is not connected
- DC/DC converter is not active

To assure a safety level 2 (SELV) in such scenarios, a transistor-based smart switch circuit has been developed and implemented in every junction box of each PV module. In combination with the DC/DC converter, this smart junction box constantly monitors the parameters prevailing in the string and thus can separate and reconnect the series interconnection at module level accordingly via switches. In this way, a maximum of 60 VDC per single module is present at open contacts during the above-mentioned cases. Furthermore, the smart junction box features active bypass diodes to guarantee safe operating conditions of the PV modules when shading occurs.

2.3 DC/DC on board converter with fast MPPT

Among the PV components, a DC/DC converter was developed by M&P Motion Control and Power Electronics GmbH, that supplies the HV battery of an electrically powered truck with the harvested solar energy. This converter is connected between the photovoltaic module array (input) and the HV DC link of the truck (output). The hardware architecture of the converter is built on fast-switching, wide bandgap SiC MOSFETS in the power stage, allowing in- and output voltages of up to 900 V. This way a high efficiency of 98% is achieved at nominal power of 3.2 kW. Hence, the dimensions of the converter can be kept relatively small at 350x590x180mm without active cooling.

Besides transferring the energy, the converter adjusts the global operating point of the PV array by MPPT with the vehicle in both static and dynamic states. For this reason, an ultra-fast Incremental Conductance algorithm was developed to optimize energy harvest in dynamic mode by settling to the MPP of the PV array in 1ms. Communication to the truck's control unit is built via Controller Area Network (CAN) such that the converter acts as a slave via redundant communication. Hence, the DC/DC converter is integrated into the safety concept of the control unit and adjusts its power to the system parameters, and only supplies the HV system when the feed-in release is granted. Moreover, a connector for an external solar irradiance sensor is provided. Considering the information on actual irradiance, the PV system can ramp-up the vehicle's DC link in stationary state. Moreover, the converter is transformer-less, so the insulation monitoring device of the vehicle is able to detect faulty insulation in the PV circuit and therefore prevent hazardous failure states.

Figure 5: Automotive-compliant prototype of the developed DC/DC converter for LadePV

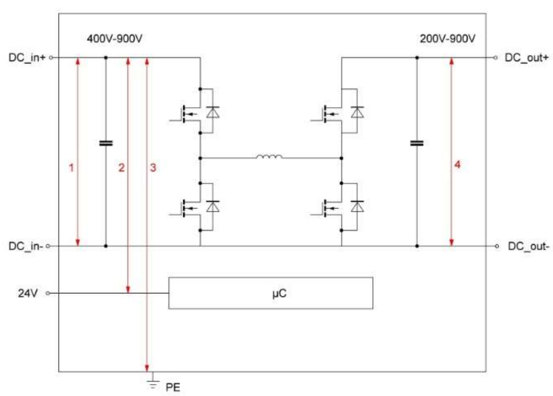

Figure 6: Schematic Overview of the developed DC/DC converter

Table I: Datasheet of the DC/DC on board converter

	Value	Unit
Nominal Power	3.2	kW
Max Input Voltage	900	V (DC)
Output Voltage	0-900	V (DC)
Efficiency (max.)	98	%
Current rating	10	A
Dimensions	350x590x180	mm
MPPT Settling	1	ms
Communication Interfaces	CAN, Ethernet	

3 SIMULATION BASED MODEL FOR HARVESTED ENERGY IN THE ELECTRIC TRUCK

3.1 Setup of a digital twin for energy prognosis

A digital twin for the demonstrator truck was created in IVIsion to allow an estimation of the energy harvested by the PV system. IVIsion is an in-house tool developed at Fraunhofer IVI for determining the driving dynamics and energy requirements of road and rail vehicles. The prognosis tool features a model for the relevant actuators and electrical loads connected to the on-board system. The solar radiation, which depends on the time of day, location, and direction of travel, is also modeled, making IVIsion particularly suitable for simulating VIPV.

Furthermore, the parametric basis of the model is extended by including conversion-efficiencies for the PV components such as PV modules, cables, and the DC/DC converter. Thereby, the modeling for the Framo E-165 includes the energy flow for major components of the drivetrain such as engine, gearing, power electronics, HV and LV system, but also auxiliary systems of the vehicle such as cooling and compressed air infrastructure [13].

The hourly-averaged annual global irradiation dataset for the location Freiburg (Breisgau) in Germany, acquired from the climate data center by the German Weather Service (DWD), was taken as input parameter for the irradiation perceived to the PV modules. For a more realistic approximation, the user profile, which considers the usage and operational patterns of the vehicle, was aligned with the logistic partner responsible for testing the demonstrator truck, resulting in a driving time between 05:00 and 10:00 on operational days. In the evening from 20:00 the truck is then recharged from the grid. An explanatory user profile taken from the simulation is shown in Figure 7, with an additional focus on the state of charge (SoC).

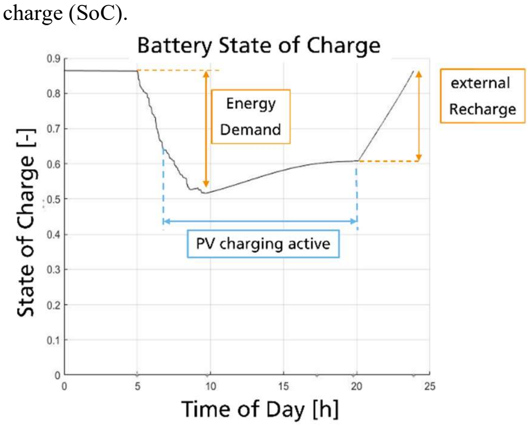

Figure 7: Simulated State of Charge for a given day in summer, taken form IVIsion

3.2 Results of the energy prognosis

Two simulation scenarios are set in IVIsion for every month considering the obtained user profile. One considers an electric truck based on the model for the Framo E-165 without integrated PV; in the second scenario the truck is equipped with a solar system as described in the previous chapter. Additionally, the energy demand of auxiliary actuators for stationary scenario is approximated to around 54 W in July, while in winter 19 W are considered. Considering the hourly-average irradiation data for the given location, a prognosed solar yield is calculated for every month in the second scenario. The results of the prognosed energy demand for the two scenarios and the solar yield are shown in Figure 9.

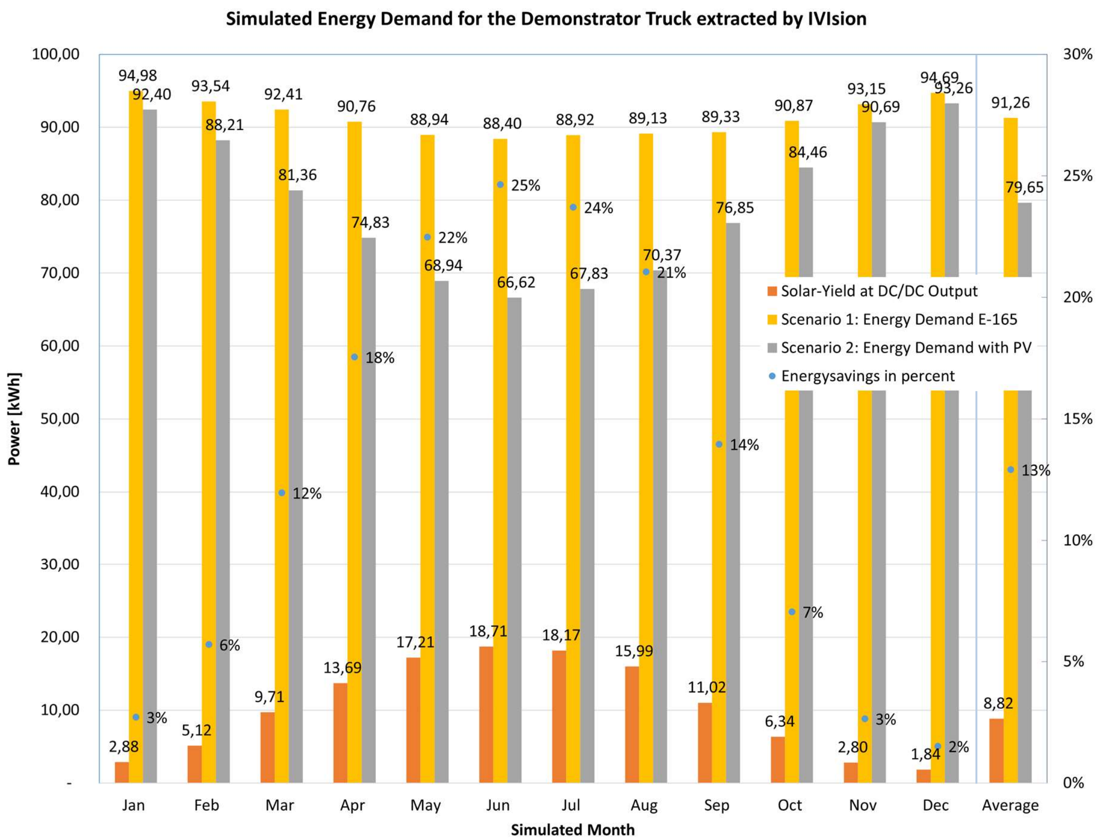

Figure 8: Simulated average solar yield in kWh (orange) and related energy savings in percent (blue) per day for every month. Based on the digital twin of the demonstrator in IVIsion and hourly-averaged irradiation data for Freiburg im Breisgau

As shown in Figure 9, comparing the energy demand of the simulation scenario for the truck without PV system and the demonstrator results in the latter expecting yearly energy savings at the charging station of 13% in average. In both scenarios, the boosted auxiliary energy demand while charging from the grid is included, a factor not considered in previous studies that focused mainly on the energy savings resulting from the additional solar range [14]. To further analyze the impact of this factor in the energy calculations, the model takes vacations and weekends into account, such that a total of 250 days of operation are considered, while the solar charging is simulated for the whole year.

Within the framework of the partner project PV2Go [15], five trucks have been equipped with irradiation sensors to create and validate a solar irradiation atlas for German traffic routes. As the shading profile of the assumed routes is yet unknown, the energy model neglects influence of shading to the vehicle but is likely to be extended in the future.

4 MONITORING OF THE DEMONSTRATOR

To collect data under real world conditions, the demonstrator truck was equipped with the described PV system in October 2021, and ever since operated by the electronic wholesaler Alexander Bürkle GmbH. Energy yield of the PV system and irradiation measurements are tracked in parallel by the datalogger STW TCG-4 with an integrated 4G antenna. In this way, the operation state of the truck can be monitored remotely, and a continuous validation of the energy prognosis is possible.

4.1 Outdoor exposure of the demonstrator:

Within the system ramp-up and operation period, different challenges had to be overcome to realize a smooth operation between the retrofitted PV system and the vehicle control unit. One of the major requirements from **ECE-R100** and **VDE C 0140-479-1:2007-05** concerning the insulation of all components in a vehicle, is to guarantee a critical minimum limit for the insulation of 100 Ω/V. To accomplish this, the Battery Management System (BMS) integrated isolation monitoring device tracks the electrical insulation R_{iso} continuously and forces the vehicle control unit to block driving permission if the measured value is below the limit. Furthermore, a warn signal is sent if the insulation drops below 500 Ω/V. As the maximum system voltage of the battery is 760 V in our demonstrator, the following limits are respectively programmed in the BMS for these safety conditions.

$$\mathrm{R}_{iso_{min}} \geq 760\,V \cdot 100\,\Omega/V \geq \mathbf{76\,k\Omega}$$
$$\mathrm{R}_{iso_{warn}} \geq 760\,V \cdot 500\,\Omega/V \geq \mathbf{380\,k\Omega}$$

Industrialized PV module requirements as per **DIN EN 61646; DIN IEC 61215** and **DIN VDE 0126-1-1** set a $\mathrm{R}_{iso} > \mathbf{40\,M\Omega \cdot m^2}$ or a total minimum of at least $\mathbf{200\,k}\Omega$. However, as the temperature in the module rises during operation, and especially under the influence of moisture, the insulation might drop to as low as 90% of its initial value [16]. Since conventional insulation monitors measure the entire parallel impedance of a vehicle, the influence of moisture on the measured value is even stronger. More specifically, in our demonstrator setup a value of $125\,k\Omega$ is seen by the insulation monitoring system when water has pooled on the modules, even though the modules were measured individually in dry conditions and show an average value of $1.6\,M\Omega$. Furthermore, Wang et al. proposed a settling time of approximately 30 s before the first insulation measurement to avoid parasitic capacitive disturbances of PV modules on isolation monitoring devices [16].

In November 2021 the driving permission appeared to be locked by the insulation monitoring system. It was found through error diagnostics that one of the PV modules suffered a major fracture in one of the full cells, as shown in the electroluminescence (EL) image in Figure 11. The damage was determined to have been caused by accidental heavy mechanical impact while servicing the vehicle. This was determined to be the source of the loss of insulation and, therefore, the entire module was taken off the PV array. Similar faults have not been observed since.

Figure 9 Close-up of EL measurement to a damaged PV module on the solar roof taken by a daylight EL camera.

Aside from the effect of moisture on the modules, the temperature behavior when exposed to solar irradiation was also measured with an InfraTec VarioCAM infrared (IR) camera with a FPA microbolometer. A sample IR image is shown in Figure 12, which shows that the PV array's temperature behaves homogenously, and the measured temperature of the cells is approximately 64,4°C at the 08th of July around 1:30 pm. According to the weather station nearby, at the University of Freiburg, an irradiation intensity of 913 W/m² and a temperature of 19.8°C are present at this specific time.

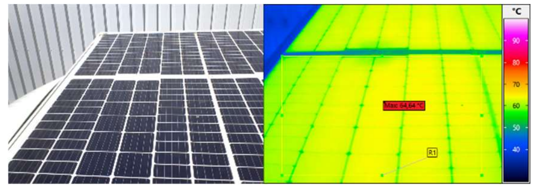

Figure 10: Picture and sample IR image of a PV module of the demonstrator truck, which is exposed to solar irradiation on 8th July 2022 at 1:30 pm in Freiburg, Germany.

4.2 Energy measurements of the demonstrator in operation

First measurement data revealed that the behavior of the user, e.g. the charging-profile, needs to fit the assumptions of the energy prognosis. As can be inferred from the measurements in Figure 13 of the exemplified case from 28th of May, the electric truck is plugged to the charging station directly after its delivery service around 2:30 pm. It must be noted that, when the vehicles battery is above 60% of SoC, the control unit deregulates the energy transfer provided by the PV system, this SoC percentage has been arbitrary chosen by the vehicle manufacturer and will be adjusted at a later stage. Under these circumstances, the total harvested energy sums up to 10.23 kWh, whereas in the energy prognosis, the assumed user profile considers that the vehicle is only charged after sunset, which optimizes the transfer of available PV energy.

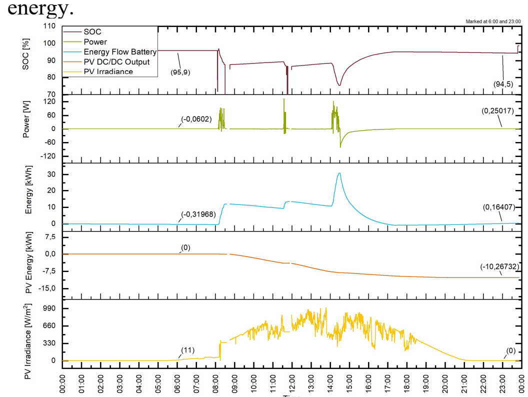

Figure 11: Plotted data for SOC, power-demand, energy flow from the battery, PV energy output at DC/DC for the sample case from 28th of May 2022

Figure 14 shows the measurements on the 19th of July, in which the usage profile aligns closely with the assumed profile in the simulation. The harvested PV energy on this day totaled 15.2 kWh. Throughout this specific day the vehicle was driven twice and consumed a total amount of 62.5 kWh for the trips. Accounting for the secondary consumers and the continuous energy consumption of the vehicle while in PV charge mode (e.g. HVIL safety system, monitoring), a total charge boost from SOC of 66.5% to 73.9% is achieved between 9:40 am and 7:00 pm. This results in a positive balance of 10.9 kWh that were charged into the battery. In this case, the solar coverage factor equals to 17.45% for this day. Accounting for the total energy transferred to the drive train versus the consumed energy for driving, a potential solar coverage factor of 24.3% was possible.

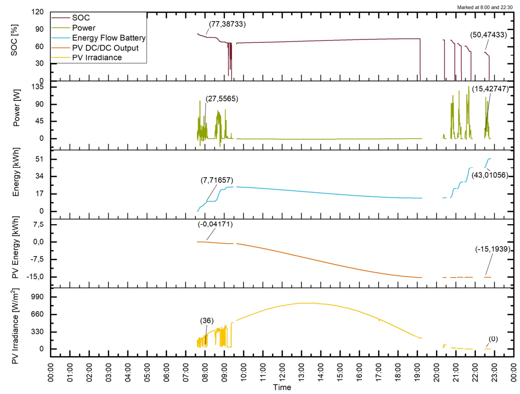

Figure 12: Plotted data for SOC, power-demand, energy flow from the battery, PV energy output at DC/DC for the sample case from 19th of July, 2022 with clear sky

Considering the area-under-curve (AUC) of the irradiation data, a total solar energy of 7.8 kWh/m² was available on the 19th of July. Under these circumstances, an active PV area of 13.34 m² would perceive approximately 104 kWh throughout the day. Considering factors for cell efficiency at 20%; a cell-to-module CTM loss of 98%; the DC/DC overall performance ratio of 98.5%; a MPPT tracking efficiency of 98%; and a temperature coefficient of -0.35%/°C with a cell temperature of around 65°C [4], a total energy harvest of 16.84 kWh is theoretically possible which is close to the simulated average for July of 18.17 kWh. The difference of 10% in the measured yield suggests that partial shading, dirt or other factors e.g. none optimal component behavior might have affected the actual power yield. Nonetheless, the chain efficiency from the PV array to the DC/DC output can be calculated around 73% for this scenario.

4.3 Validation of the energy prognosis model in stationary conditions (reference scenario)

To evaluate the installed system in parallel with the simulated energy model, a reference scenario in stationary conditions was set for the measurement of the energy yield. A parking lot was found, which excludes the effect of shading produced by surroundings (such as buildings or trees). With a relatively low SoC of around 28.9% as starting point, the vehicle was positioned to guarantee enough headroom for charging the battery with solar energy for a few days. During the observed period, beginning on Friday 01st of July around 11:20 am and ending on Friday 8th of July 1:00 pm, the PV system was able to harvest and deliver 150.68 kWh into the drivetrain of the vehicle, which translates to an average of 21.53 kWh/day. The measured amount of energy fed into the powertrain is in line with the predictions of the energy model for the month of July, which gives an average of 18.2 kWh/day transferred to the battery.

Within this period the SoC raised to 88.0 % after the seven days, which represents an increase in charge of 13.86 kWh/day. The charge that went into the battery as compared to the energy transferred into the drivetrain differs mainly because of the standby power consumption in the demonstrator, which is measured between 400 - 500 W while parking, which is also in line with other investigations [17,18]. In the energy prognosis, a mean standby consumption of 54 W is assumed for July. The actual power demand shows that this is an underestimation. As can be seen in Figure 15, the PV system was also able to fully charge within the following two days. Note that, within the reference week, the datalogger stopped operation from the 2nd of July, around 10:00 am, and began to operate again on the 6th of July around 16:25 pm. Nevertheless, the PV system operated as expected and the information of the supplied energy in between is taken from the SOC change, as well as the internal power meter of the DC/DC converter.

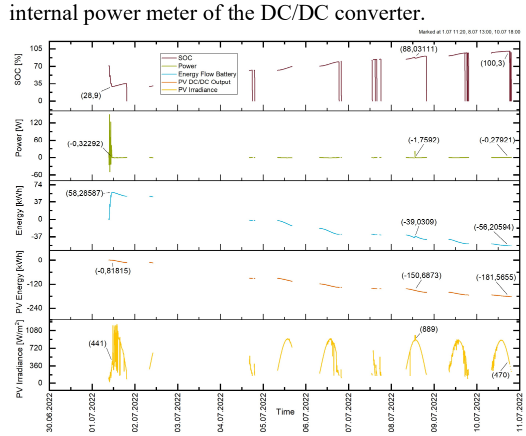

Figure 13: Plotted data for SOC, power-demand, energy flow from the battery, PV energy output at DC/DC for the static reference period in between 1st and 11th of July 2022

5 SUMMARY AND DISCUSSION

We presented a successfully and complete integration of the PV system into the vehicle's safety routine within our demonstrator. This approach of feeding into the HV system enhances the chain efficiency from PV module to the vehicle's battery, as well as shrinking the demand for various electrical converters. Another advantage is the high battery capacity available in electrified trucks, which avoids the expansion of the LV battery and therefore minimizes the additional weight and resources.

The reference measurement scenario exceeds and thereby validates the assumption on solar yield in the prognosed model by IVIsion. indicating the model holds for stationary and unshaded conditions.

Whereas, on the provided data of the 19th July, the approximated energy harvest overestimates the measured yield by 19.5 %. This is partly explained by the assumption made in simulation, which are based on average loss factors determined in laboratory environment compared to a specific day. Additionally, shading may also have been present during this day on the vehicle and even further, module losses such as the turned off module (see Fig. 11) and further losses due to degradation may also play a role. However, this last effect may be only very little since the stationary conditions over a week showed an overperformance of the harvested energy, compared to the average in simulation.

On the contrary, the relatively high standby losses result from the vehicle's concept, which is based on the conversion from a diesel to an electric vehicle. The auxiliary aggregates are intersected and are completely booted up by the control unit in the charging state. This indicates, there is still the need to optimize the system functions regarding PV charging, to achieve the prognosed solar coverage also in the battery during parking throughout the whole year.

Even though, the demonstrator vehicle was not optimized in energy consumption and the prototype components can be optimized further, the implementation of direct feed into the high voltage intermediate circuit shows a promising chain efficiency of 73% for an exemplary day in summer. This result outperforms other approaches as for example to contribute the power to a low voltage buffer first [18].

Apart from the requirements on component level, we show that the evaluation of systems performance towards safety aspects should not be underrated in the design phase of VIPV systems. A careful adjustment of e.g. limits for isolation faults is necessary for a smooth but also safe operation. Another major learning and field for further studies is that the focus on system level is necessary, e.g. to optimize the status of continuous power consumption during standby. We showed in simulations and supported by experimental results that an average energy saving of 13% can be achieved if lower standby losses are in place.

6 ACKOWLEDGEMENT

We thank Torsten Peppel, Ralf Nöske and Steffen Margenberg, from M&P Motion Control and Power Electronics GmbH, Dr. Aswin Linsenmeyer from SUNSET Energietechnik GmbH, Stephan Möllinger from Alexander Bürkle GmbH and Rolf Huhn from TBV Kühlfahrzeuge GmbH for exceptional good collaboration within the project “Lade-PV”. Finally, we would like to thank the German Ministry of Economic Affairs and Climate Action (FKZ 03EE1002A “Lade-PV”) for their funding.

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