Technology Collaboration Programme
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International Energy Agency
Photovoltaic Power Systems Programme

Task 17 PV and Transport

PVPS

Expert survey on technical requirements of PV-powered passenger vehicles 2024

Report IEA-PVPS T17-03:2024

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The 25 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance, the Solar Energy Industries Association, the Solar Energy Research Institute of Singapore and Enercity SA are also members.

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What is IEA PVPS Task 17

The objective of Task 17 of the IEA Photovoltaic Power Systems Programme is to deploy PV in the transport sector, which will contribute to reducing CO_2 emissions of the sector and enhance PV market expansions. The results contribute to clarifying the potential of utilization of PV in transport and to proposal on how to proceed toward realizing the concepts.

Task 17's scope includes PV-powered vehicles such as PLDVs (passenger light duty vehicles), LCVs (light commercial vehicles), HDVs (heavy duty vehicles) and other vehicles, as well as PV applications for electric systems and infrastructures, such as charging infrastructure with PV, battery and other power management systems.

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COVER PICTURE

TNO Curved PV Car Hood

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INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Expert survey on technical requirements of PV-powered passenger vehicles

IEA PVPS
Task 17
PV and Transport

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LIST OF ABBREVIATIONS

CBS	Centraal Bureau voor Statistiek (Netherlands)
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
c-Si	Crystalline silicon
GaAs	Gallium Arsenide
IBC	Interdigitated Back Contact
IEA	International Energy Agency
IEC	International Electrotechnical Commission
III-IV	3-5 PV technology
MPPT	Maximum power point tracker
PV	Photovoltaic
TNO	The Netherlands Organisation for Applied Scientific Research
VIPV	Vehicle Integrated Photovoltaics

EXECUTIVE SUMMARY

Following on from the previously published PVPS Task 17 technical report 'State of the art and expected benefits of VIPV' this report presents an overview of the technical requirements and challenges for successful adoption of VIPV technology.

As VIPV grows in interest as a topic, a survey of world experts to gain insights into what the community considers important in the transition of VIPV from niche to a mainstream and accepted technological application was conducted by TNO (The Netherlands Organisation for Applied Scientific Research).

The survey, in which 110 experts in this field were asked about various aspects of VIPV, provided valuable insights into what areas are important for the adoption of VIPV, and what these experts believe users may be prepared to sacrifice in PV yield to achieve a preferred result in the aesthetics of the vehicle.

The choice to survey VIPV experts of course means that the results may be biased in favour of VIPV technology and not representative of the general preferences of car buyers or early adopters. However, these experts do have extensive knowledge of the technical aspects of VIPV, and so the responses are very well informed.

A. Survey methodology and participants

The survey was conducted using the Survalyzer software. and consisted of 31 questions with 4 sub-questions and took approximately 15 minutes to complete. The experts invited to complete the survey were from 4 continents (Europe, Asia, Australia and North America). They were given 3 weeks to complete the survey. Overall 70 people responded to the survey; a 64% response rate. Care was taken to develop questions to eliminate surveyor bias and the responses to the survey were completely anonymous. Survey responders were given the option to choose N/A for any questions that they felt they did not have sufficient expertise to answer. This leads to an average of 40 countable responses for most questions. A great majority of the responders were from Europe >75%, approximately 20% from Asia and small percentage from North America.

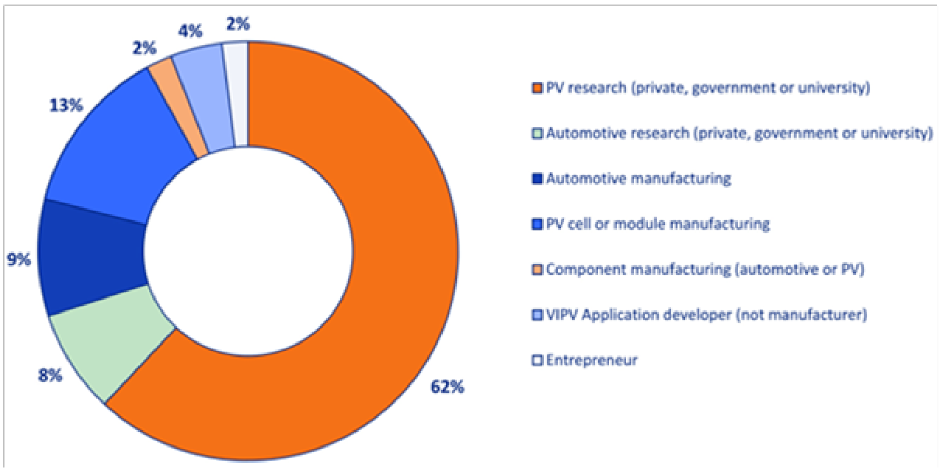

Figure 1. Participants per sector

B. PV Technology

Crystalline silicon, c-Si, technology is seen as the dominant choice now for VIPV, however by 2030 respondents expect tandem and thin film technology to grow.

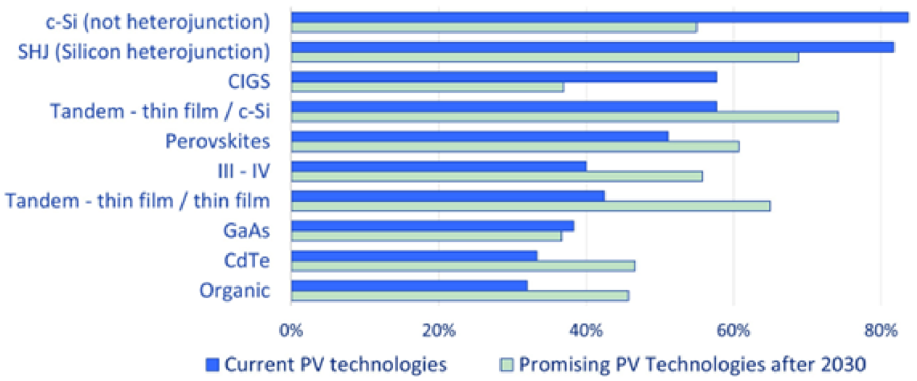

Figure 2. PV technology now and in 2030

C. Most important system properties

Range extension, km/year, efficiency and cost were ranked as very important or important. Colour was the least important property out of those selected.

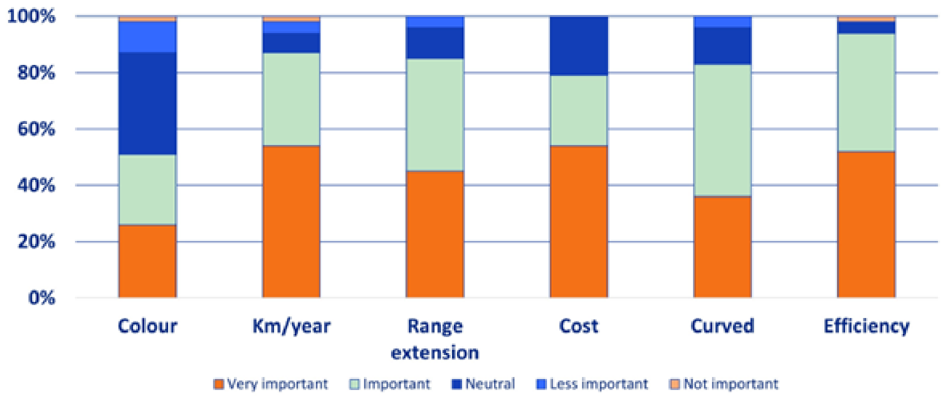

Figure 3. Most important system properties.

D. Summary of key results

Some of the key results were:

- c-Si is the dominant technology now with tandem (thin film / c-Si) expected to grow in the future.
- PV appearance: a preference for no metal on the front – IBC technology was indicated.
- Efficiency, km/year and range extension were the most important system properties.
- Minimum lifetime should be 10-15 years.
- Biggest technical bottleneck – complexity of manufacture.
- Most important benefit – reduced need for charging.

1 INTRODUCTION

Following on from the previously published T17 technical report 'State of the art and expected benefits of PV-powered vehicles' [1] this report presents an overview of the technical requirements and challenges for successful adoption of VIPV technology.

As VIPV grows in interest as a topic, a survey of world experts to gain insights into what the community considers important in the transition of VIPV from niche to a mainstream and accepted technological application was conducted by TNO (The Netherlands Organisation for Applied Scientific Research).

The survey, in which 110 experts in this field were asked about various aspects of VIPV, provided valuable insights into what areas are important for the adoption of VIPV, and what these experts believe users may be prepared to sacrifice in PV yield to achieve a preferred result in the aesthetics of the vehicle.

The choice to survey VIPV experts of course means that the results may be biased in favour of VIPV technology and not representative of the general preferences of car buyers or early adopters. However, these experts do have extensive knowledge of the technical aspects of VIPV, and so the responses are very well informed.

Some of the key results were:

- c-Si is the dominant technology now with tandem (thin film / c-Si) expected to grow in the future.
- PV appearance: a preference for no metal on the front – IBC technology was indicated.
- Efficiency, km/year and range extension were the most important system properties.
- Minimum lifetime should be 10-15 years.
- Biggest technical bottleneck – complexity of manufacture.
- Most important benefit – reduced need for charging.

2 SURVEY RESULTS ON TECHNICAL REQUIREMENTS FOR VIPV

2.1 Survey methodology

The survey was conducted in November 2021 using the Survalyzer software [2], and consisted of 31 questions with 4 sub-questions and took approximately 15 minutes to complete. The survey was sent out to 110 experts in VIPV including individuals from industry, academia, research institutes, consultancy and representing people from 5 continents (Europe, Asia, Australia, North America, and South America). The responders were given 3 weeks to complete the survey. Overall 70 people responded to the survey; a 64% response rate. Care was taken to develop questions to eliminate surveyor bias or preferences through consultation with experts from TNO Human Machine Teaming Research Group with expertise in Statistical Analysis. The responses to the survey were completely anonymous. Survey responders were given the option to choose N/A for any questions that they felt they did not have sufficient expertise to answer. The completed questions in the incomplete responses are also included in our results. This leads to an average of 40 countable responses for most questions. A great majority of the responders were from Europe >75%, approximately 20% from Asia and small percentage from North America.

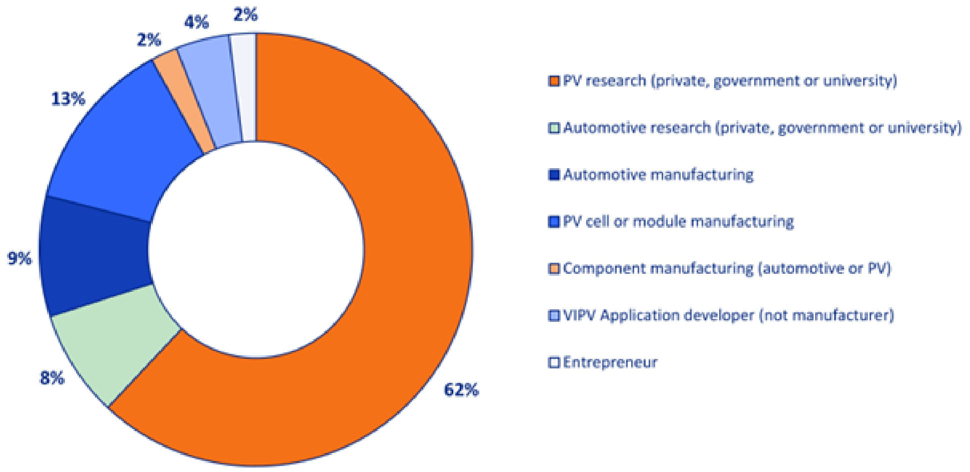

Fig. 2.1-1 Breakdown of the survey respondents by sector, clearly the PV community were well represented. (Q34 of the survey: 47 answers, missing 23, N/A 0)

The survey was split into 5 topic sections:

- PV technology
- VIPV system
- Safety and reliability
- Benefits
- Technical bottlenecks and progress

Table 2.1 Questions in this survey

PV Technology
Question 1: What are the top 5 PV cell technologies you would use today for VIPV - rank in order from 1 to 5, where 1 is your top choice.
Question 2: What are the 5 most promising PV cell technologies for the future (2030) application of VIPV - rank in order from 1 to 5, where 1 is your top choice.
Question 3: Assuming c-Si cell technology: Which front side (visible) PV cell metallisation is most appropriate for VIPV. Rank your choices.
Question 4: Please enter which other cell metallisation you would like to consider
Question 5: Which cell interconnection design is most appropriate for VIPV. Rank your choices.
Question 6: Please enter which other cell interconnection you would like to consider.
Question 7: Assuming PV is integrated into the roof, bonnet, boot and doors of a passenger car. Which PV cover material is the most likely candidate for each of these passenger car components.
Question 8: What would you consider the maximum thickness of glass allowed for the VIPV (mm)
Question 9: Which finish is most appropriate for each of these passenger car VIPV components?
VIPV system
Question 10: How much metal can be visible from the front of the VIPV?
Question 11: When considering the colour of the PV element are deep blue and black colours enough?
Question 12: If deep blue and black are not enough, how much performance can be sacrificed for more colour choice?
Question 13: What would you consider to be the minimum required bending radius, in metres, for the VIPV element?
Question 14: With 3m2 space available for PV on the roof of a vehicle - what is the minimum encapsulated cell efficiency that would be required for VIPV?
Question 15: Various properties of VIPV are given below. Please rate these in terms of how important you think they are for successful VIPV products.
Question 16: Today: What is the maximum allowable manufacturing and installation cost, in USD/Wp, for a fully integrated PV system (Battery management system, wiring, power components, PV components, etc. and excl. body panels)
Question 17: In 2030: What will be the maximum allowable manufacturing and installation cost, in USD/Wp, for a fully integrated PV system (Battery management system, wiring, power components, PV components, etc. and excl. body panels)
Question 18: Today: What is the maximum allowable added manufacturing cost in USD/Wp for PV components (cells, modules, DMPPTs)?

Question 19: In 2030: What will be the maximum allowable added manufacturing cost in USD/Wp for PV components (cells, modules, DMPPTs)?

Question 20: What is the maximum extra weight allowable for PV components installed on a passenger vehicle?

Safety and reliability

Question 21: What is the minimum lifetime required for a VIPV system?

Question 22: What can the maximum voltage of the VIPV system be?

Question 23: Visible failures: In case of visible damage or physical failure of the VIPV system how should it be replaced or repaired.

Question 24: Performance failures: In the case of performance failures of the VIPV system how should it be replaced or repaired.

Question 25: As the PV element will be part of the vehicle how would you rate the following aspects in terms of importance?

Question 26: In terms of flammability will there be extra requirements for VIPV above what is already required for electric vehicles? And what might these be?

Benefits

Question 27: Most important benefit: Rank the listed possible benefits of VIPV in order of importance for a successful market and adoption of VIPV on passenger vehicles.

Question 28: Today: When considering the cost and benefits of VIPV, what is a reasonable payback time in years for a VIPV system?

Questions 29: In 2030: When considering the cost and benefits of VIPV, what will be a reasonable payback time in years for a VIPV system?

Question 30: Energy contribution: What percentage of the energy consumption of a passenger car should be provided by the PV?

Question 31: When considering range extension: how many extra km per day (annual average) would be a minimum requirement.

Technical bottlenecks and progress

Question 32: Technical bottlenecks: What do you see as the biggest technical bottlenecks to large scale rollout of VIPV?

Question 33: Market bottlenecks: What do you see as the biggest market bottlenecks to large scale rollout of VIPV?

Question 34: Finally we would like to ask which of the industries listed below best describes where you work?

2.2 PV technology

Questions 1 & 2: What are the top PV cell technologies you would use today and in 2030 for VIPV? - rank in order from 1 to 5, where 1 is your top choice.
(Number of Responses: 41 / Missing: 18 / N/A: 11)

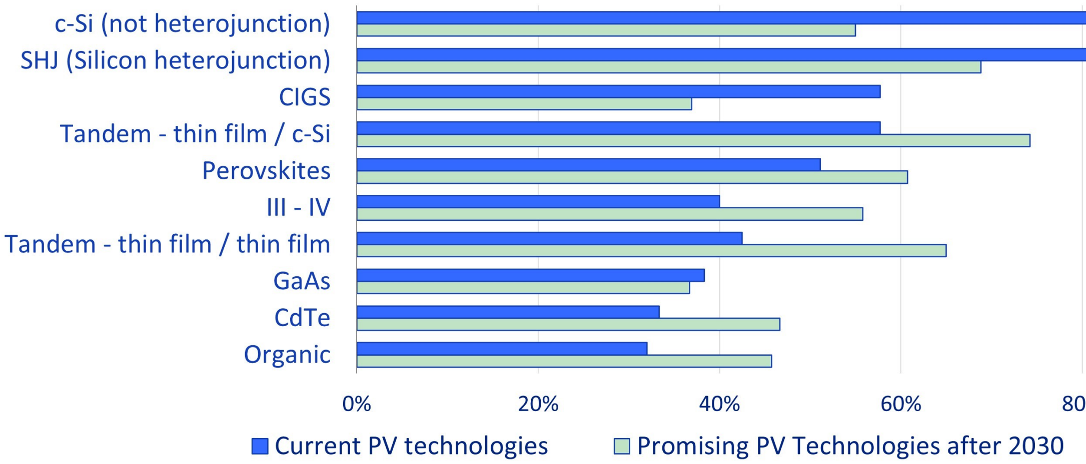

Fig. 2.2-1 PV cell technologies, this chart shows the weighted ranking by respondents for the most appropriate PV technologies for today, and the most promising by 2030.

In terms of cell technologies, for today, the crystalline silicon is leading, however by 2030 perovskites and tandem, both thin-film / c-Si and thin-film / thin-film are more prominent than c-Si alone.

Recent efficiency tables published in Progress in Photovoltaics [3], Report that Tandem thin film/c-Si (Perovskite/c-Si) already pass c-Si HJT in efficiency (laboratory scale) with 33.9% compared to 26.8%.

Currently, a variety of PV technologies are employed in prototype and commercial VIPV applications, Lightyear and Sono Motors work with c-Si, Toyota and Nissan use Sharp III-V technology and as reported in previous Task 17 publication, other technologies being employed include CIGS by Flixbus and Volvo Renault [1, 4 and 5].

Questions 3: Assuming c-Si cell technology: Which front side (visible) PV cell metallisation is most appropriate for VIPV? Rank your choices.
(Number of Responses: 38 / Missing: 18 / N/A: 14)

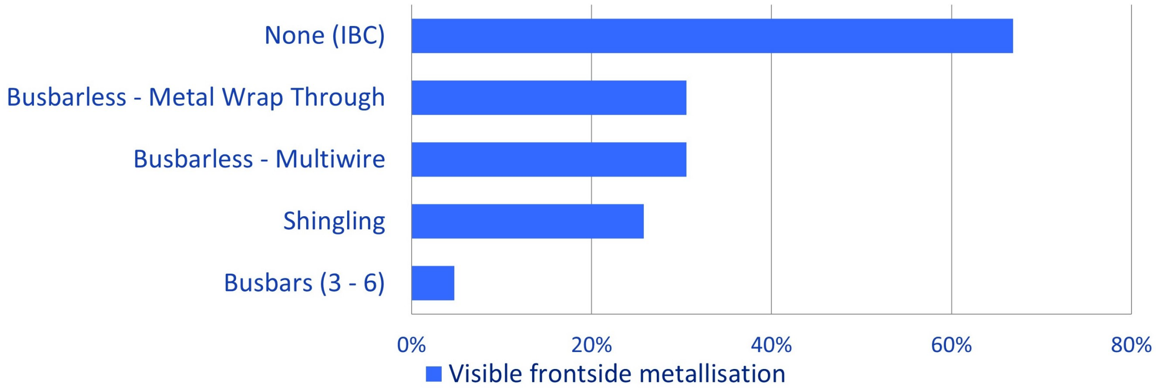

Fig. 2.2-2 Ranking of front side metallisation – for c-Si technologies. The preferred metallisation is none – i.e. IBC technology and then going down the list the metallisation becomes more visible.

The most popular visible metallisation of choice is none, respondents prefer not to see any metal – which logically leads to IBC being the favoured answer. A supplementary question (**Question 4**) asked respondents what other cell metallisation they would like to consider – there were no responses.

Question 5: Which cell interconnection design is most appropriate for VIPV? Rank your choices.
(Number of Responses: 38 / Missing: 18 / N/A: 14)

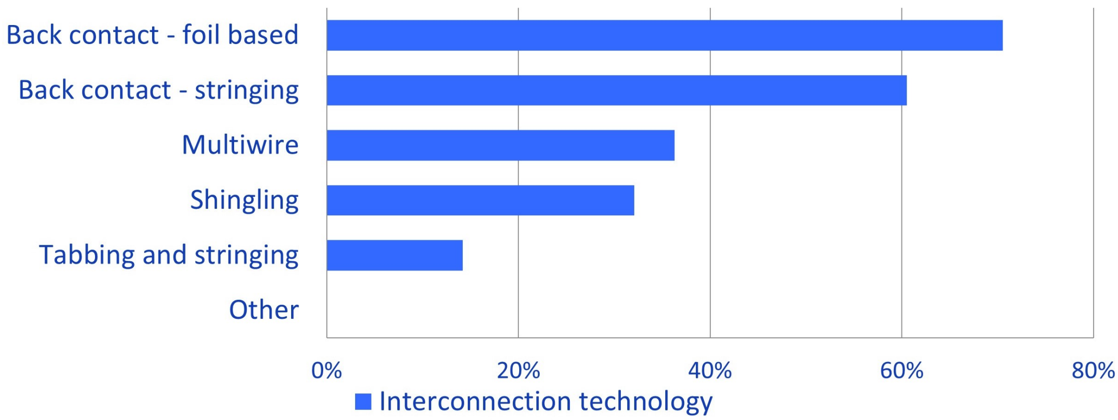

Fig. 2.2-3 Ranking of interconnection design.

A supplementary question (**Question 6**) asked what other interconnection technology could be considered; there were no responses.

Question 3 and Question 5 were very similar however differing in attention with the former (Question 3) focussed on appearance and the latter (Question 5) focussed on technology. The interconnection technology has implications for the visual appearance but also for the flexibility of design and cell layout. The preferred technology was back contact in both cases

Question 7: Assuming PV is integrated into the roof, bonnet, boot and doors of a passenger car. Which PV cover material is the most likely candidate for each of these passenger car components?
(Number of Responses: 45 / Missing: 18 / N/A: 7)

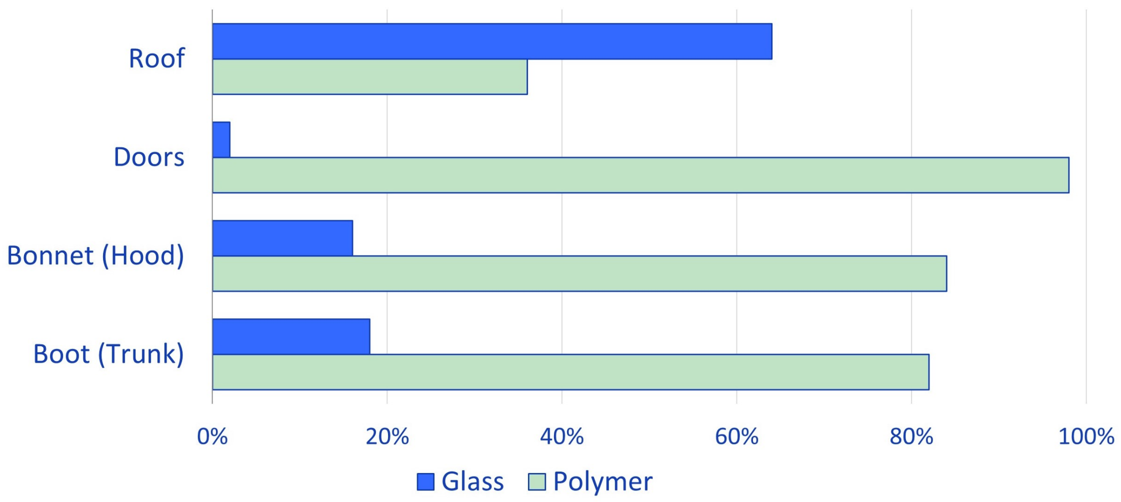

Fig. 2.2-4 Cover material for different vehicle elements. For the roof, glass is preferred, but for the doors, bonnet and boot, polymer is preferred.

The choice of cover material has implications for weight, safety and reliability and for visual appearance. VIPV not only needs to meet PV safety standards but also automotive safety standards. A recent publication proposes a safety qualification procedure for VIPV systems. The proposal considers pedestrian and electrical safety [6]. Work is also being undertaken on the development of lightweight, polymer based, VIPV elements, as the reduced weight is better for vehicle efficiency and the polymer front is thought to make it easier to build curved modules [7].

Question 8: What would you consider the maximum thickness of glass allowed for the VIPV in mm.
(Number of Responses: 30 / Missing: 40 / N/A: 0)

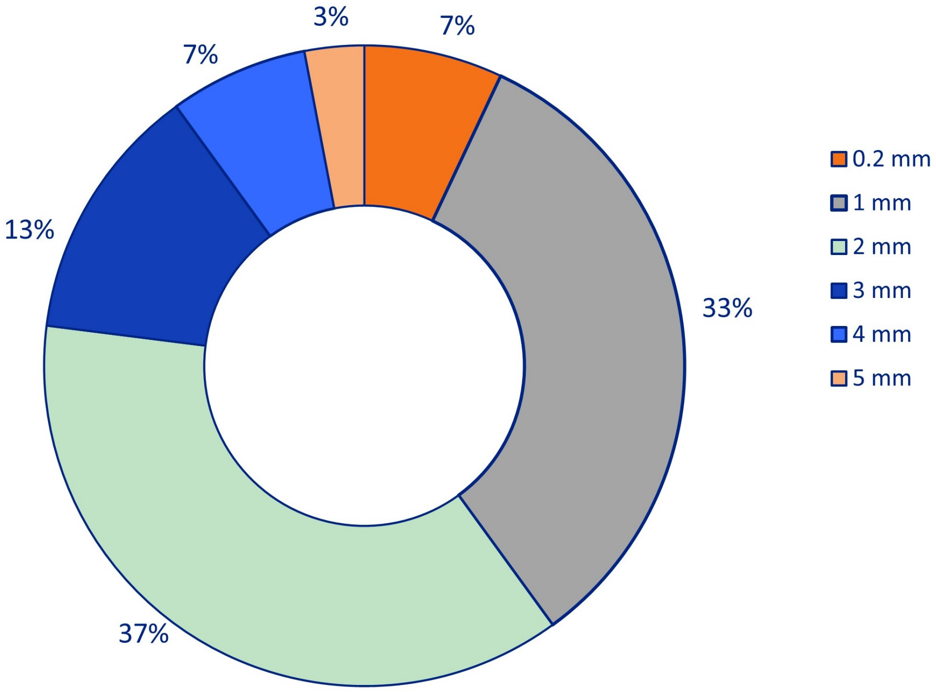

Fig. 2.2-5 Maximum glass thickness – respondents say 1 mm or 2 mm is the preferred thickness – this undoubtedly comes from the need to reduce any extra weight.

The thickness of the glass will significantly impact the weight of the element, and in turn the energy required to move the car. A study by Patel et al. [8] has suggested that an IBC VIPV element and additional electronics weighing between 3 and 7 kg would add between 0.1 and 0.3 Wh/km to the energy consumption of a large passenger car but a heavy (38kg) CdTe VAPV (Vehicle Added PV) element, with glass / glass construction, could add around 1.45 Wh/km to the consumption. Extrapolating these results gives an average of around 0.04 Wh/km extra energy requirement per extra kg. This value is also in agreement with Weiss et al [9].

Questions 9: Which finish is most appropriate for each of these passenger car VIPV components?
(Number of Responses: 37 / Missing: 18 / N/A: 15)

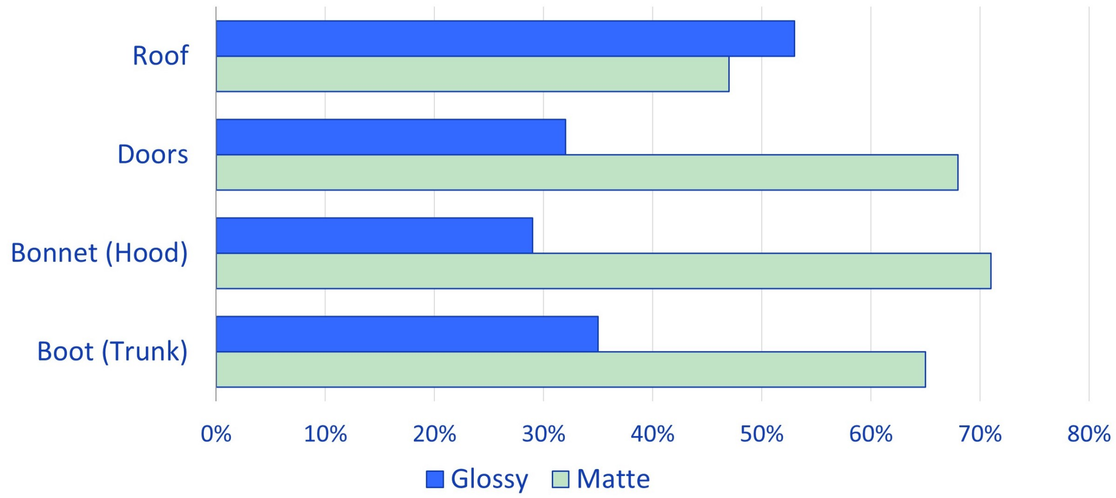

Fig. 2.2-6 Cover material finish – Matte or glossy? A clear preference for a matte finish on all surfaces except the roof – where there is a more even split.

Here we could conclude that a glossy finish is most likely glass, and the matte most likely polymer – in that way the response reflects the response to question 7. Although here we see for the roof a more even split between glossy and matte.

2.3 VIPV System

Question 10: How much metal can be visible from the front of the VIPV?
(Number of Responses: 40 / Missing: 22 / N/A: 8)

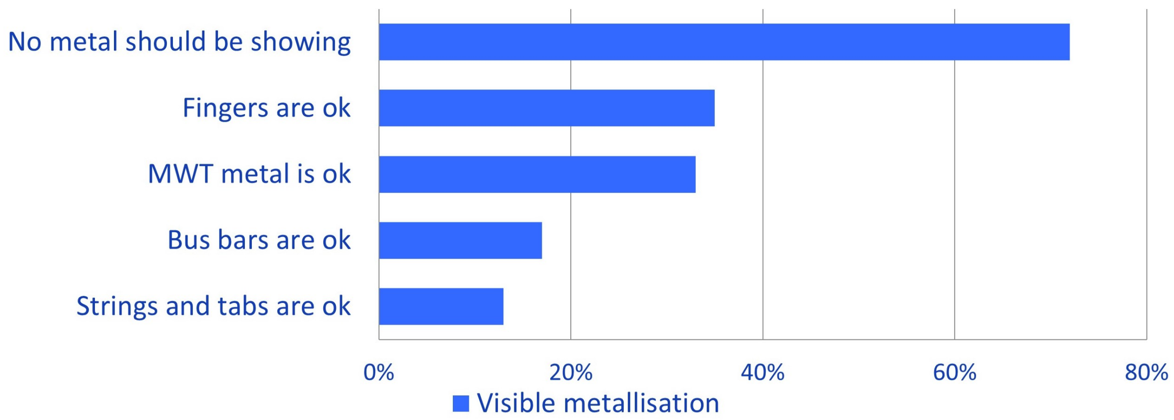

Fig. 2.3-1 Ranking of visible metal, similar to question 3, this result shows that less metal showing is best.

Question 10, like Question 3 is about aesthetics and the preferred appearance of the PV elements. Again it is confirmed that as little as possible visible metal is desired for an appealing result.

Question 11: When considering the colour of the PV element, are deep blue and black colours enough?
(Number of Responses: 48 / Missing: 22 / N/A: 0)

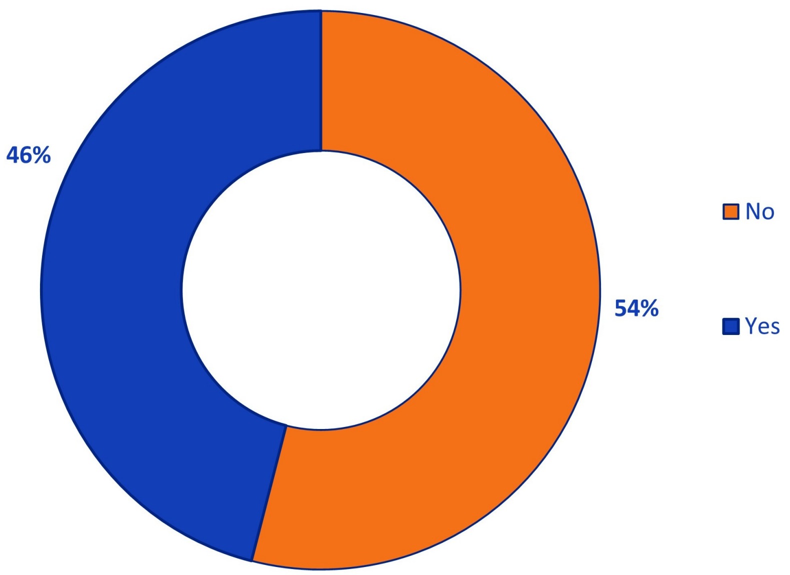

Fig. 2.3-2 Colour of PV element – equal split between blue/black and other colours. (Number of answers:48, missing: 22, N/A: 0)

Question 12: If deep blue and black are not enough, how much performance can be sacrificed for more colour choice? (Number of Responses: 22 / Missing: 44 / N/A: 4)

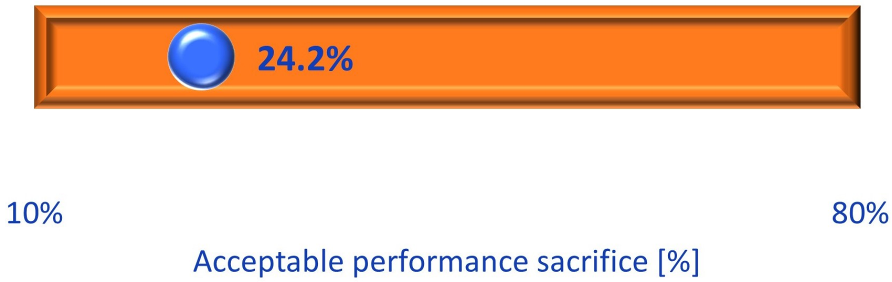

Fig. 2.3-3 An acceptable performance sacrifice to allow for more colour choice.

In terms of colour, there is a fairly even split between repsondents who say deep blue and black colours are enough for the VIPV element and those that do not. However those that wish to have more colour choice answered a supplementary question asking what would they be willing to sacrifice in terms of relative performance to have more colour choice. The responses ranged from 10% up to 80% with the average result being 24.2%. Implying that it would be acceptable to have a 20% efficient PV element reduced to 15% efficient to achieve the colour required. An Australian study exploring consumer preferences reported that people were prepared to pay approximately 1 800 USD to be able to have the PV colour match the colour of the vehicle [10].

Questions 13: What would you consider to be the minimum required bending radius, in metres, for the VIPV element? (Number of Responses: 34 / Missing: 22 / N/A: 14)

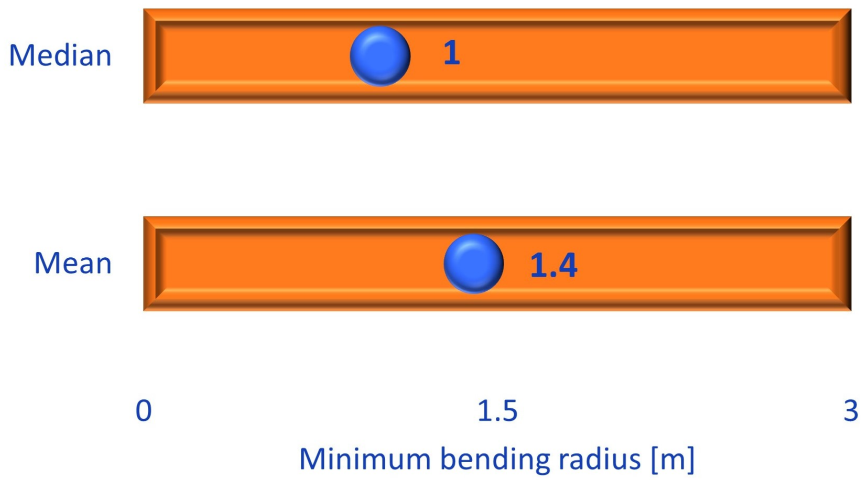

Fig. 2.3-4 Minimum bending radius – what kind of curvature is required for VIPV, to follow the lines of the vehicle a certain two or three dimensional bending will be required.

The bending radius will influence the aesthetics and how the PV element can blend into the shape of the vehicle, but it will also impact the performance. Araki et al. [11] have quantified the effect in terms of a curve correction factor. Fig. 2.3-5, taken from their article, shows how as the curve shape increases (bending radius decreases) the curve correction factor also drops, which in turn reduces the expected output power of the PV component.

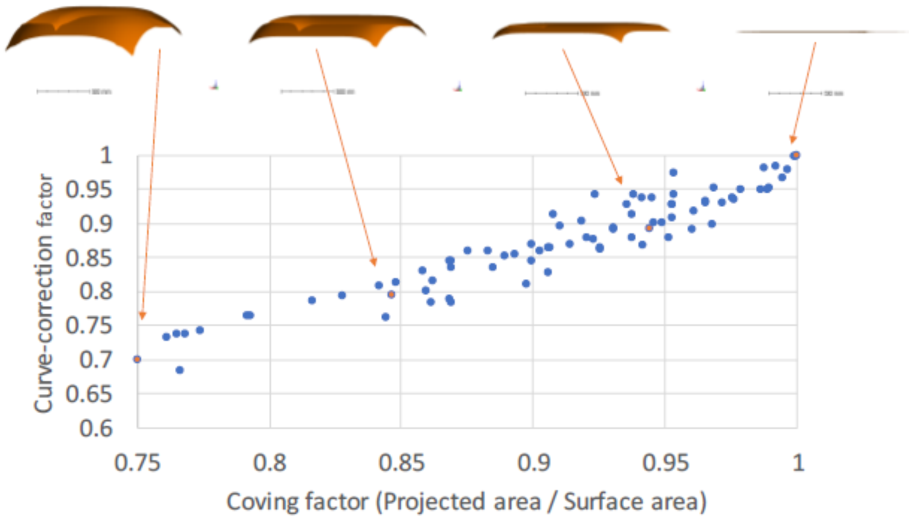

Fig. 2.3-5 Curve correction factor vs Representative shape (after Araki et al [11]) here we see as the shape becomes more curved (lower bending radius) the correction factor also drops and the power generation drops with it.

Another consideration for the effect of a small bending radius is the ease of manufacture of PV elements.

Question 14: With 3 m^2space available for PV on the roof of a vehicle - what is the minimum encapsulated cell efficiency that would be required for VIPV?
(Number of Responses: 42 / Missing: 22 / N/A: 6)

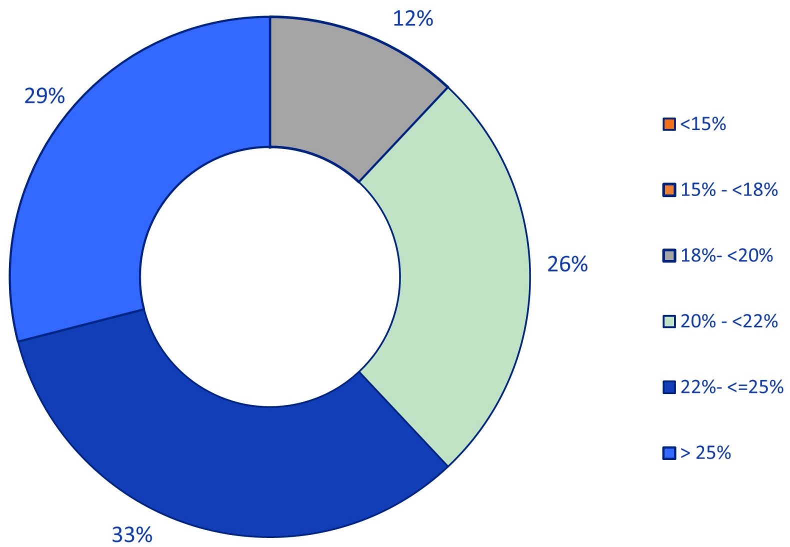

Fig. 2.3-6 Minimum PV efficiency, assuming 3m² space available. The chart shows the % of respondents for the different efficiency ranges.

When considering efficiency requirements no respondents answered that it should be lower than 18% (540 Wp), most selected the 20 to 22% range (600 Wp to 660 Wp). But there were also responses for all the bins above that, with 29% of respondents saying the efficiency should be higher than 25% (750 Wp). This will impact the technology employed and the costs.

Question 15: Various properties of VIPV are given below, Please rate these in terms of how important you think they are for successful VIPV products. (Number of Responses: 48 / Missing: 22 / N/A: 0)

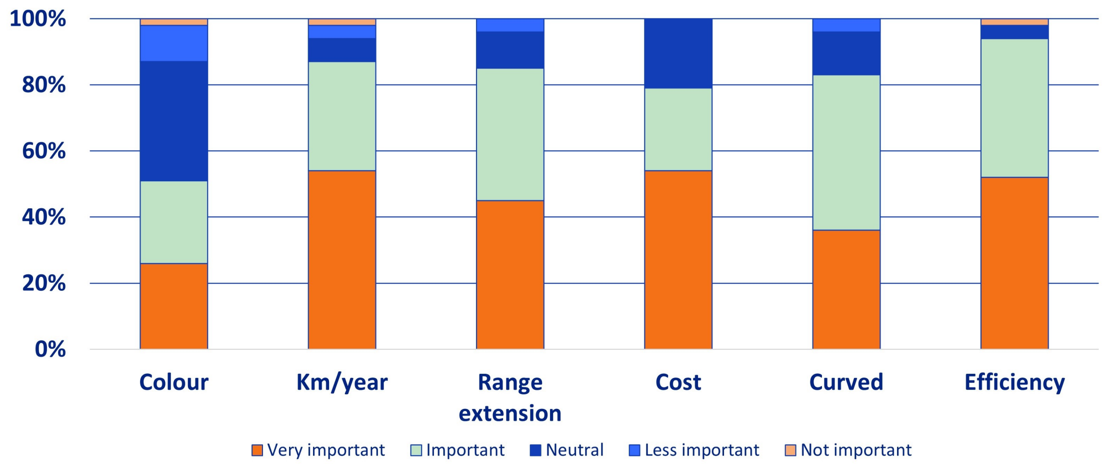

Fig. 2.3-7 Importance of various properties of VIPV. Efficiency, km/year and Range extension are the top three properties with respect to importance.

Question 15 shows how important respondents think various aspects of VIPV are: the top three are efficiency, Km/year and Range Extension with having a curved surface coming in 4th place. Cost and colour and considered less important.

Questions 16 & 17: Today and in 2030: What is the maximum allowable manufacturing and installation cost, in USD/Wp, for a fully integrated PV system (Battery Management System, wiring, power components, PV components, etc. and excl. body panels) (Q16 Number of Responses: 34 / Missing: 22 / N/A: 14, & Q17 Number of Responses: 33 / Missing: 22 / N/A: 15)

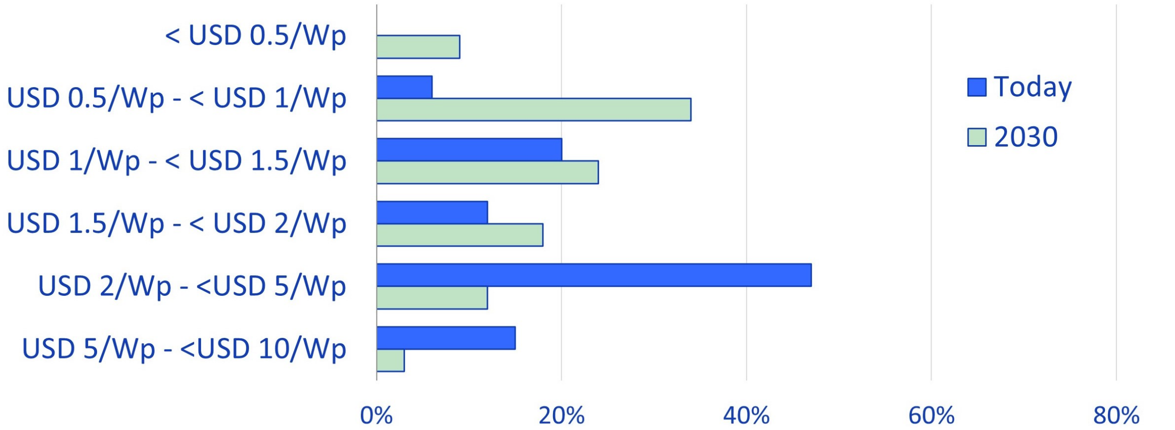

Fig. 2.3-8 Manufacturing and installations costs in USD/Wp for fully integrated system, now and in 2030

Questions 16 and 17 ask respondents to consider what is an allowable manufacturing cost for a VIPV system, now and in 2030. Fig. 2.3-8 shows that today an acceptable cost is between 2 and 5 USD/Wp, however by 2030 this should drop to between 0.5 to 1.5 USD/Wp.

Questions 18 & 19: Today and in 2030: What is the maximum allowable added manufacturing cost in USD/Wp for PV components (cells, modules, DMPPTs)? (Number of Responses: 32 / Missing: 22 / N/A: 16)

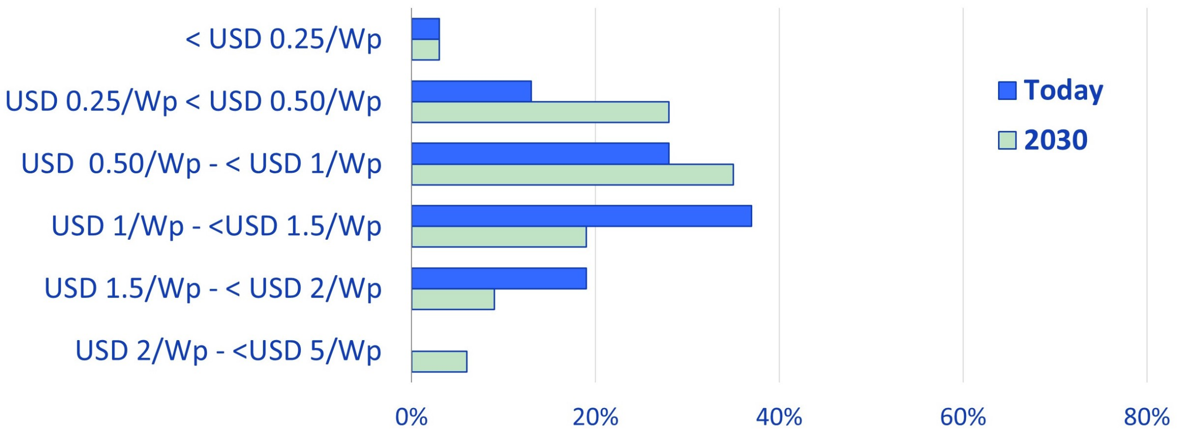

Fig. 2.3-9 Maximum allowable added manufacturing cost in USD/Wp for PV components (cells, modules, DMPPTs), now and in 2030

Most respondents thought 1 to 1.5 USD/Wp would be an allowable extra cost for the PV components, but in 2030 this should drop to 0.5 – 1.0 USD/Wp. A study by Heinrich et al. [12] compared the manufacturing costs of 3 different PV technologies for vehicle integration and came to an average cost of 0.38 EUR/Wp, or 0.41 USD/Wp for the PV component. As a point of comparison NREL report a 2022 residential PV system cost of 3.16 USD/Wp [13] which is in line with the response to Question 17.

Questions 20: What is the maximum extra weight allowable for PV components installed on a passenger vehicle? (Number of Responses: 36 / Missing: 22 / N/A: 12)

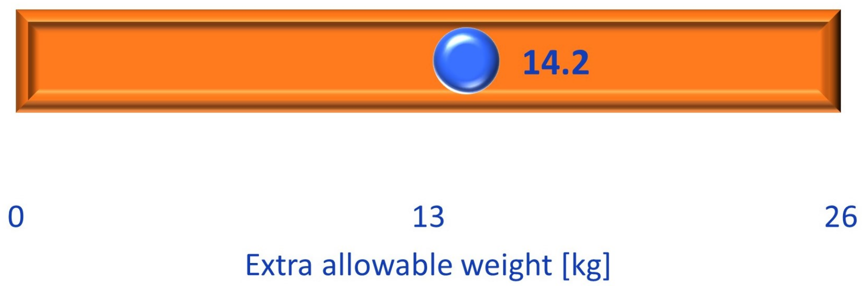

Fig. 2.3-10 Allowable extra weight for VIPV system

As earlier discussed, extrapolating the results of Patel et al [9], and having a value of 0.04 extra Wh/km energy consumption per kg, an extra weight of 14.2 kg would result in an extra energy use of 5.7 Wh/km. As an example of the effect of this. A Tesla Model 3 from 2021, [14] has an efficiency of 142 Wh/km, this extra energy use would take it to 148 Wh/km, an increase of 4%. However, with the extra range the PV could supply it may be possible to reduce the battery size and weight – thereby lowering the energy consumption.

2.4 Safety and Reliability

Questions 21: What is the minimum lifetime required for a VIPV system? (Number of Responses: 46 / Missing: 23 / N/A: 1)

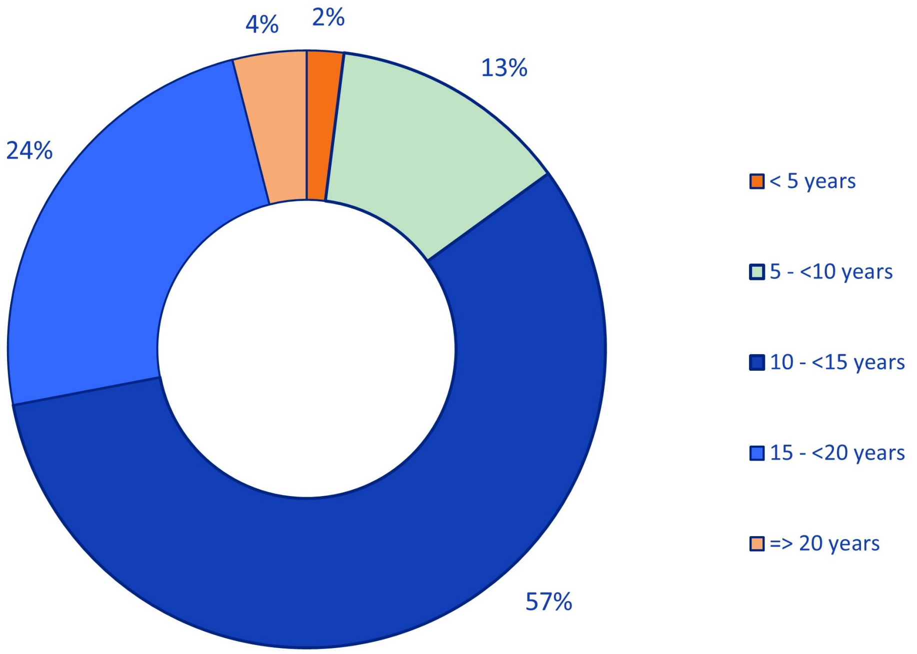

Fig. 2.4-1 Minimum required lifetime for a VIPV system

A lifetime for the VIPV system of 10-15 years was selected by 57% of the respondents with a further 24% selecting 15-20 years. While typically PV manufacturers give a 20 – 30 year warranty on PV modules this result is in line with the average age of passenger cars being taken out of circulation. Using the Netherlands as an example, the CBS (Centraal Bureau voor de Statistiek) figures show that in 2022 the average age of cars taken out of circulation was 19 years [15].

Questions 22: What can the maximum voltage of the VIPV system be? (Number of Responses: 28 / Missing: 23 / N/A: 19)

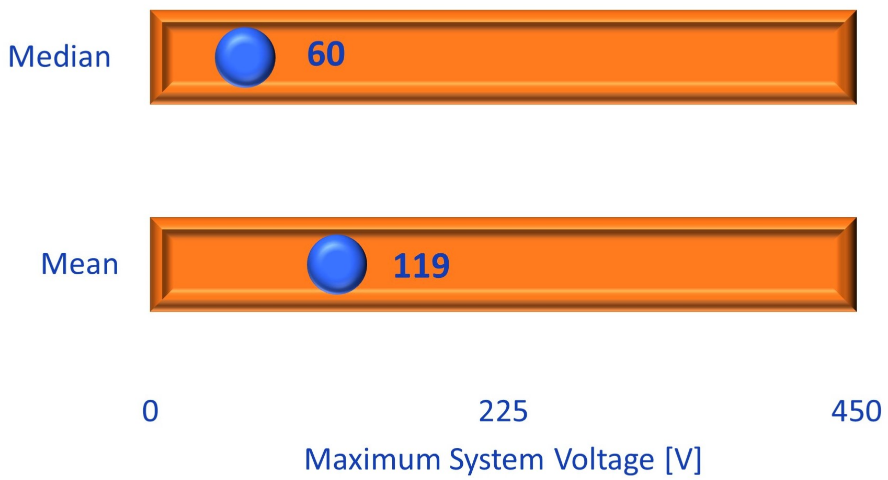

Fig. 2.4-2 Maximum system voltage – between 0 and 450V, the median response was 60 Volts (in line with safety requirements), and the average was 119 Volts.

The new Low-Voltage level of 48 V has become established in addition to the 12/24 V and high-voltage levels. This value stays below the 60 V DC demanded by the current standard ECE-R100 [6,16]. However, the power train of an electrical vehicle can have voltages as high as 800V. The PV component should adhere to the 60 V DC limit for any elements that could become exposed and contacted in an accident.

Question 23: Visible failures: In case of visible damage or physical failure of the VIPV system how should it be replaced or repaired?
(Number of Responses: 43 / Missing: 23 / N/A: 4)

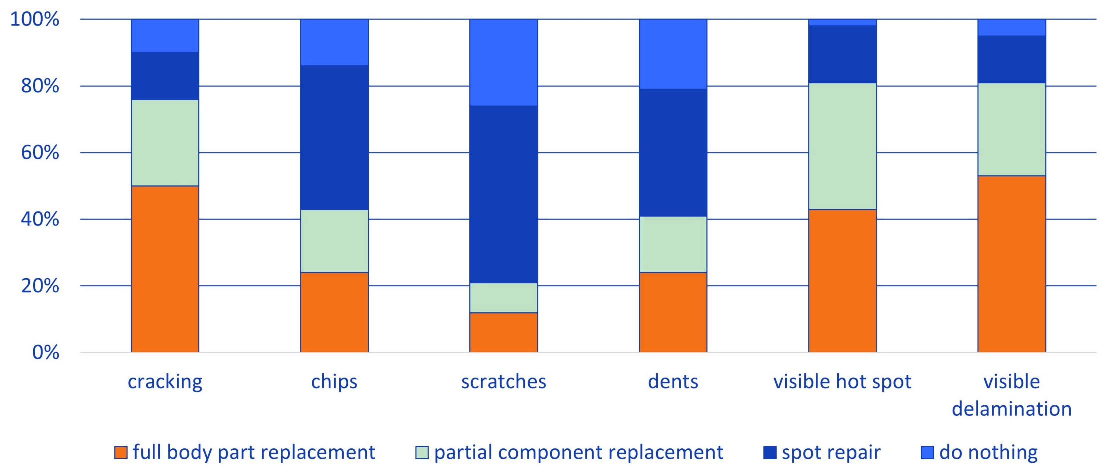

Fig. 2.4-3 Visible failures and repair methods

Question 24: Performance failures: In the case of performance failures of the VIPV system how should it be replaced or repaired?
(Number of Responses: 40 / Missing: 23 / N/A: 7)

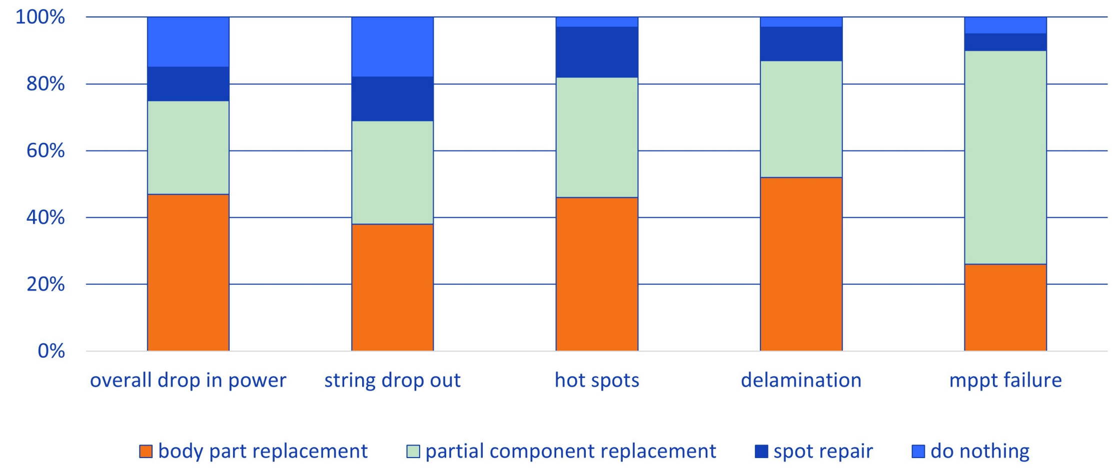

Fig. 2.4-4 Performance failures and repair methods

Questions 23 and 24 are looking at the repairability requirements and methods for VIPV systems. Firstly in Question 23 visible failures are considered, for cracking, visible hot spots and visible delamination of the VIPV element, body part replacement is the preferred method of repair. For chips, scratches and dents, spot repairs are considered appropriate methods of repair. In Question 24 performance failures are considered. Body part replacement or partial component replacement are considered as the most likely methods to repair all of the named failure modes. MPPT failure would most likely be solved by partial component replacement but the other issues will rely more on body part replacement.

Question 25: As the PV element will be part of the vehicle how would you rate the following aspects in terms of importance?
(Number of Responses: 46 / Missing: 23 / N/A: 1)

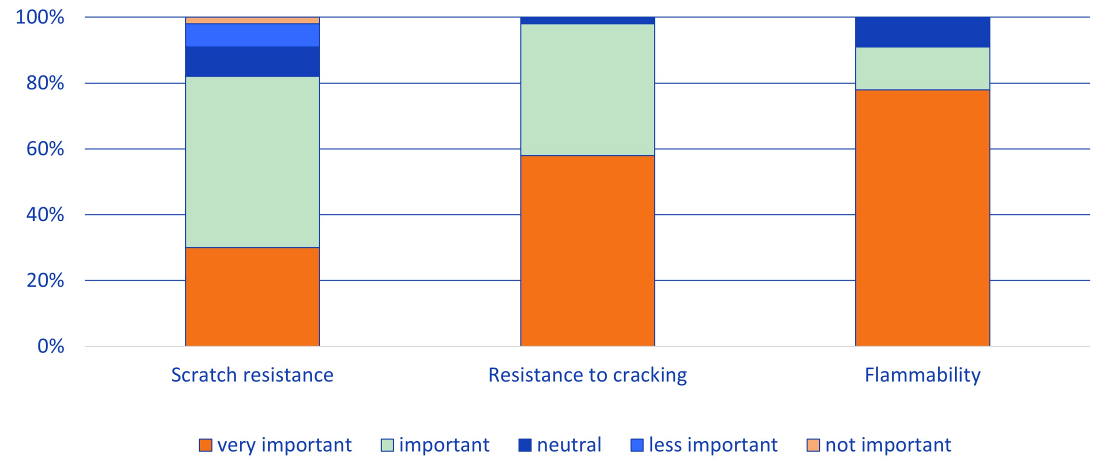

Fig. 2.4-5 Importance of various aspects of the PV element as part of the vehicle, scratch resistance, cracking resistance and flammability

In question 25 respondents have been asked to rate the importance of three issues that have safety implications for VIPV, these are: scratch resistance, resistance to cracking and flammability. Flammability is a very serious consideration for the PV element, and all three aspects are considered very important or important.

Questions 26: In terms of flammability will there be extra requirements for VIPV above what is already required for electric vehicles? And what might these be? (Number of Responses: 12 / Missing: 23 / N/A: 35)

As a follow up to Question 25 in Question 26 respondents were asked to state in words what the extra requirements might be for VIPV above those already in place for EVs with respect to flammability. Respondents pointed out the need to considerate material based toxins in the PV components, potential hot spot development and need for multiple backups for hot spot protection. About half of the respondents also felt that the current PV and EV norms would be sufficient however from the perspective of flammability safety.

Responses are shown in Table 2.2.

Table 2.2 Response texts to question 26.

Texts
I guess not. Should just fulfil all safety norms.
No extra requirements needed.
Protection against partial shadowing - more By-pass diodes and even in the case of the failure of the By-pass diode another security measure.
meet PV standards as well as vehicle standards
Release of poisonous gas Electric shock in case of failure of PV
Should be extended to the whole PV system
With EV's the focus is on the battery, with VIPV you have additional materials and contacts that could incinerate.
Not sure
No
Electrical safety (and thus also fire safety) for all exposed (surface = PV) parts
Take care of the pv-caused heat related hazards e.g. hot spots. A Module-BOM that can resist the maximum hot spot temperatures should be considered.
No

2.5 Benefits

One of the main selling points of VIPV are the benefits for the end user. In this section respondents were asked about the importance of various benefits, covering the areas of: cost, CO_2 reduction and convenience.

Question 27: Most important benefit: Rank the listed possible benefits of VIPV in order of importance for a successful market and adoption of VIPV on passenger vehicles.
(Number of Responses: 46 / Missing: 23 / N/A: 1)

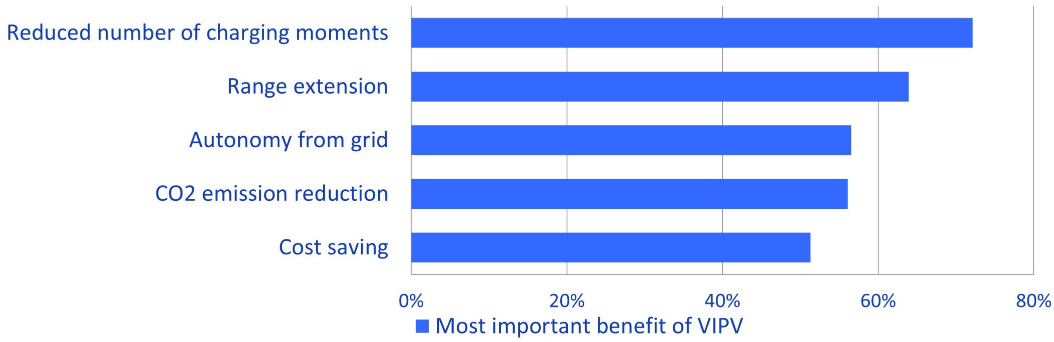

Fig. 2.5-1 Ranking of the most important benefits

The reduced number of charging moments and range extension were considered the most important benefits of VIPV. Autonomy from the grid and CO_2 reduction came next and finally cost saving was the least named.

VIPV will mean extra costs as discussed in previous questions 16-19, with the next Questions, 28 and 29, respondents were asked about reasonable payback times for VIPV systems, the answers were for today and in 2030. In today's environment 8 years was considered reasonable, however, in 2030 this is reduced to 5 years.

Questions 28 & 29: Today and 2030: When considering the cost and benefits of VIPV, what is a reasonable payback time in years for a VIPV system?
(Number of Responses: 42 / Missing: 23 / N/A: 5)

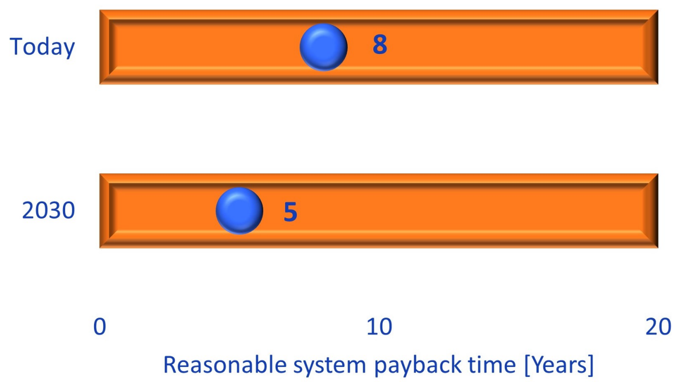

Fig. 2.5-2 Reasonable payback time in years – today an average of 8 years, and in 2030 this is reduced to 5 years.

Question 30: Energy contribution: What percentage of the energy consumption of a passenger car should be provided by the PV? (Number of Responses: 41 / Missing: 23 / N/A: 6)

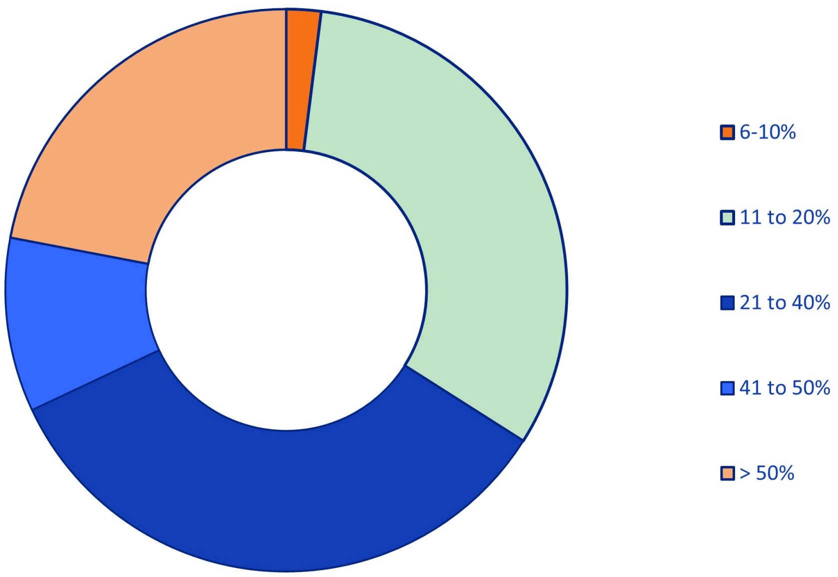

Fig. 2.5-3 Energy contribution by PV

Question 30 looks at the energy to be delivered by the VIPV system and how much of the total energy requirements should be expected from the PV.

Question 31: When considering range extension: how many kilometres per day (annual average) would be a minimum requirement? (Number of Responses: 39 / Missing: 23 / N/A: 8)

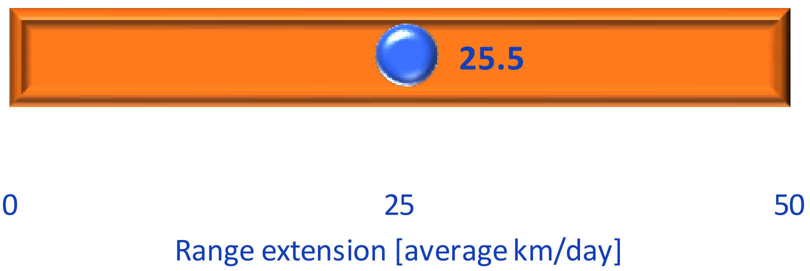

Fig. 2.5-4 Minimum requirement for range extension km/day based on average annual km.

Question 31 considers the important benefit of Range Extension, respondents were asked what the minimum requirement would be in terms of km/day. A figure of 25.5 km/day was the resulting average response, which represents around 9 300 km/year, this may be optimistic for a standard electric vehicle. Considering the modelled results from the previously published T17 report where range extension was estimated at best around 6 700 km/year for Morocco and 6 000 km/year for both Spain and Australia for existing electric vehicles [1]. It all depends very much on the area and efficiency of the PV, the location and the efficiency of the vehicles. Vehicles specifically designed as solar electric vehicles, for example the Lightyear Zero, was designed to provide up to 70 km/day [17] and the Sono motors Sion had claimed to provide 35 km/day in optimal conditions [18].

2.6 Technical and Market Bottlenecks

Question 32: Technical bottlenecks: What do you see as the biggest technical bottlenecks to large scale rollout of VIPV? (Number of Responses: 43 / Missing: 23 / N/A: 4)

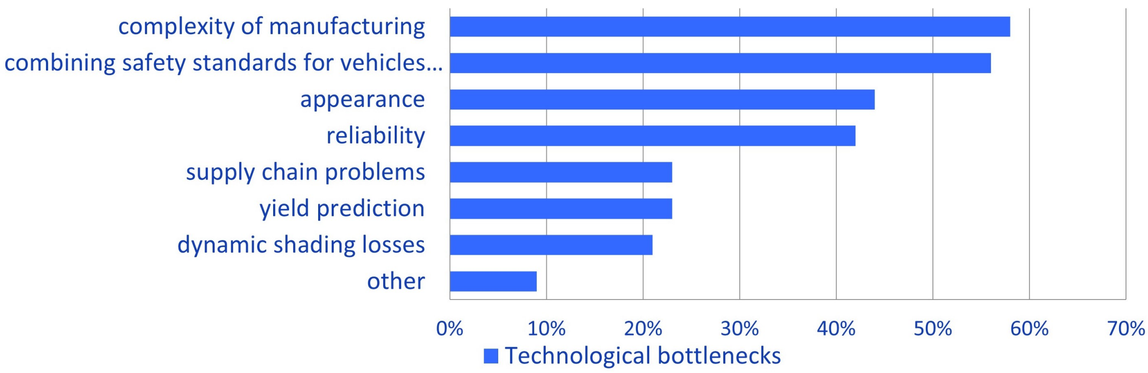

Fig. 2.6-1 Technical bottlenecks ranked

Table 2.3 Response texts to 'other' for question 32

Texts
Weight, loss of features like glass roof and body design shape limitations
Cost
Energy storage and utilisation within the vehicle
Solar cells market and constant changes. Time in automotive is longer than in PV cell production. How to handle the changes?

Question 33: Market bottlenecks: What do you see as the biggest market bottlenecks to large scale rollout of VIPV?
(Number of Responses: 44 / Missing: 23 / N/A: 3)

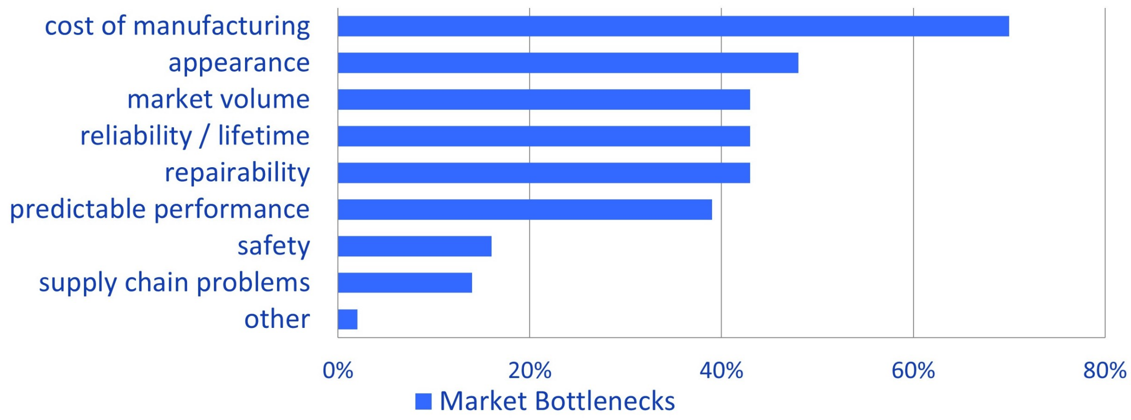

Fig. 2.6-2 Market bottlenecks – ranked

Table 2.4 Text response to 'other' for question 33.

Texts
Affordability as most people buy second hand cars

These final two questions asked about the expected technical and market bottlenecks. In Question 32, regarding the technical bottlenecks, respondents see the complexity of manufacturing and combining PV and vehicle safety standards as the biggest issues. Followed closely by appearance and reliability. Less of an issue are: supply chain problems, yield prediction and dynamic shading losses.

For Question 33, the biggest market bottleneck is considered to be cost of manufacturing, with to a slightly lesser degree: appearance, market volume, reliability, repairability and predictable performance, all sitting around 40% of the maximum possible.

3 SUMMARY AND CONCLUSIONS

In conclusion, the survey results provide valuable insights into the preferences and expectations of respondents regarding Vehicle-Integrated Photovoltaics (VIPV). Silicon PV technology is currently the preferred technical solution, but the community foresees tandems as a superior technology in 2030.

The desire for minimal visibility of metal on the front side of cells, coupled with a preference for glass on roof components and polymer on other surfaces, indicates a strong aesthetic consideration in VIPV design. A matte surface appearance is favoured across most surfaces, except for the roof, where preferences for matte and glossy are nearly equal. Respondents emphasize the importance of diverse colors for PV panels, even if it means sacrificing a portion of power performance, up to 24%. The flexibility of PV module technology, with the ability to conform to a minimum radius of curvature and a focus on efficiency, is crucial for its integration into vehicles.

Cost, contribution to vehicle mileage, and safety considerations, particularly flammability, are identified as paramount factors for VIPV products. The survey outlines specific cost targets for VIPV systems, aiming for a reduction in manufacturing and installation costs by 2030 by as much as 60%. This will require not only economies of scale for production but also the development of new production technologies and innovations.

In terms of lifetime expectations, respondents suggest a minimum of 10-15 years, with repair methods focusing on spot repairs for visible damage and full body replacement parts for performance failures. The market outlook emphasizes the importance of ‘’convenience’’ benefits like reducing charging moments and extending vehicle range, while cost savings are considered less crucial. This is particularly interesting as it has proven difficult to quantify the value of these benefits for market introduction.

Looking ahead, the expansion of the survey beyond researchers in PV and automotive research to include more industry professionals is recommended for a comprehensive understanding of VIPV preferences and requirements. Overall, these survey findings serve as a valuable foundation for the future development and integration of VIPV systems, aligning with evolving technological trends and user expectations.

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