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THE INTERNATIONAL TECHNOLOGY ROADMAP FOR PHOTOVOLTAICS AND THE SIGNIFICANCE OF ITS DECADE-LONG PROJECTIONS

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ABSTRACT: The International Technology Roadmap for Photovoltaics (ITRPV) is a leading roadmap in the PV community. Ever since its first edition has been published in 2010, the ITRPV has succeeded to provide the technology projections in crystalline silicon PV technology covering a wide scope in the PV value chain. The projection data obtained from contributing experts and institutions are processed and published by the German Mechanical Engineering Industry Association (VDMA). In this paper, the projection accuracy of each of eight frequently reported projected topics is studied. The projected topics include: (a) multicrystalline silicon (mc-Si) wafer thickness, (b) mc-Si ingot mass, (c) bulk recombination current density, (d) emitter sheet resistance, (e) finger width, (f) silver amount per cell, (g) screen printing throughput rate, in addition (h) the market share of half cells is studied. The method includes the calculation of the deviation of each year's projection from the reference value for each of the chosen topics. Projection absolute percentage deviations (PAPD) are calculated as the time-dependent projection accuracy measure. Based on this approach, finger width projections show the highest accuracy by having a PAPD as a function of time accuracy slope of (1.5 ± 0.1) %/year. Half cells' market share is the least accurately projected topic featuring a PAPD accuracy slope as a function of time to be (8.1 ± 0.2) %/year. Results of the accuracy study (results of the "past") provide insights for future expected values.

Keywords: International Technology Roadmap for Photovoltaics (ITRPV), forecasting, technology roadmap, projections, projection accuracy

1 INTRODUCTION

The objective of a technology roadmap is to analyze an existing technology situation, to identify future trends and development targets, as well as formulate requirements to meet the targets. From an industry vantage point, following a roadmap will increase market competitiveness via development of comprehensive solutions that tackle existing product limitations causing higher costs, low technology deployment and inefficiency. The International Technology Roadmap for Photovoltaic (ITRPV) [1,2], first introduced in 2010 by SEMI PV group, provides the photovoltaics (PV) community with yearly reports projecting the development of key value chain items (materials, processes, and products). The ITRPV result graphs cover technical aspects of the PV value chain, and are often taken as guidance for the technological progress in the field. As shown in Fig. 1, the ITRPV report has developed year by year reaching a latest version of the ITRPV (11th Edition, 2020) using input data from a total of 55 different contributing companies and research institutes from all around the world. To obtain the result graphs of the projections, the data provided by expert contributors is then processed anonymously by the German Mechanical Engineering Industry Association (VDMA) which also ensures the publication of the report. The results in the report are median projected values from filled questionnaires' of professional expectations.

The ITRPV is by far the main PV roadmap among existing ones which focuses mainly on projected topics for crystalline silicon PV technologies with different technology readiness levels [3]. According to Bray and Garcia [4], technology roadmapping process includes three essential phases, briefly stated as: (i) preliminary phase of defining the leadership, scope and boundaries of the roadmap, (ii) creating the technology roadmap report, and (iii) follow-up activity including the critique and validation of the roadmap; see Fig. 2. The ITRPV team has succeeded to instigate, create, and review the yearly reports, fulfilling the first two phases of roadmapping. Additionally a brief review of projection differences of some topics are also shown in Ref. [5] followed by a quantitative projection accuracy study in Ref. [6].

To further enhance the third phase of roadmapping, the regular update studying the prediction accuracy of the projections is beneficial. By that, the trust in the current and future ITRPV editions' projections is even further enriched.

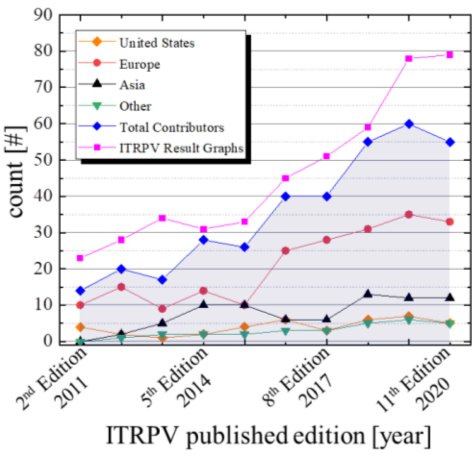

Figure 1: The development of ITRPV shown in the increasing number of contributing companies/institutes in addition to the number of result graphs (mainly projections) throughout the published report editions' years. The increase of result graphs to 79 in the 11th edition shows the growth of the roadmap's scope. Contributions of European collaborators are the highest in each of the editions (with the exception of the 5th edition in 2014).

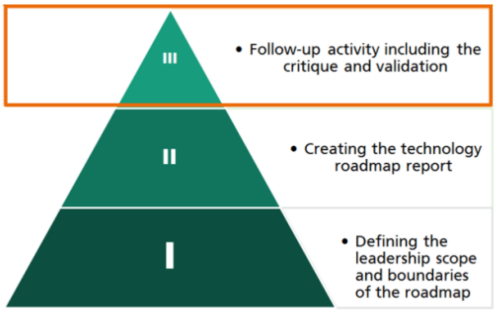

Figure 2: The three essential phases of technology roadmapping. Own figure drawn according to Ref. [4] definitions.

In this work, the projection accuracy of the ITRPV reports' selected projections is studied throughout its decade of existence.

2 APPROACH

An accuracy study for the significance of the reports' projections for eight of the most frequently discussed topics is performed by using forecasting/projection accuracy studies and statistical methods [7,8]. This quantitative approach reinforces the third essential phase of roadmapping, aiming to enhance the prediction accuracy and further criticize and validate specific projections stated in the different reports. The flow chart of the adopted methodology for the accuracy study is shown in Fig. 3. First, topics are chosen based on their frequency in all the studied report editions (2nd until 11th edition). Data points from the projection graphs are collected. Data points for the years not found in the projection graphs are deduced from linear interpolation between existing data for the projected years before and after. The projection absolute deviations (PAD) of each topic at each year is calculated from the differences of projected values P to the reference values Y (proven values since they are "projections of the past").

$$PAD = |P - Y| \qquad (1)$$

As an example, the reference value of the 10th edition projection of 2019 value would be taken from the 11th edition data of the 2019 value. This then corresponds to the 1-year projection time span reference.

From that, projection absolute percentage deviation (PAPD), an accuracy measure, is calculated as follows:

$$PAPD = \frac{PAD\,.\,(100\%)}{Y} \qquad (2)$$

The average PAPD from all the considered editions for each topic as a function of each projection time span is obtained. An expected trend shows that projections in the near future are easier to project than farther ones. Based on the trends of each studied topic, the accuracies can be ranked according to the PAPD dependency on the time scale of the prediction.

The obtained accuracy results can then be used to form expected ranges of future predictions by creating upper and lower projection accuracy limits. These limits are placed by considering the slope of the PAPD as a function of time, with the assumption that the behavior would be expected in the future.

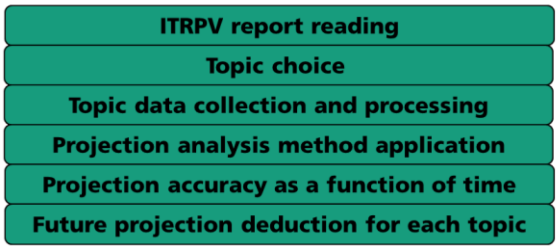

Figure 3: The sequence flow of the approach adopted in the projection accuracy study. (Figure adapted from Ref. [6]).

However, the nature of the results is purely statistical, and in some cases might be discussed further by considering physical constraints.

3 RESULTS AND DISCUSSION

The chosen studied topics are: (a) *p*-type multicrystalline silicon (mc-Si) wafer thickness for Al-BSF, (b) mc-Si ingot mass, (c) bulk recombination current density, (d) emitter sheet resistance, (e) finger width, (f) silver amount per cell, (g) screen printing throughput rate, in addition (h) the market share of half cells is studied. The first six studied topics (a-f) have been included in all studied editions, fulfilling the requirement of data availability to the maximum extend. Screen printing throughput (g) as well as market share of half cells (h) are also studied as examples of process and products, respectively.

3.1 Time-dependent projection accuracy

For each of the studied topics and based on the adopted approach, the PAPD as a function of prediction time scale is plotted; shown in Fig. 4.

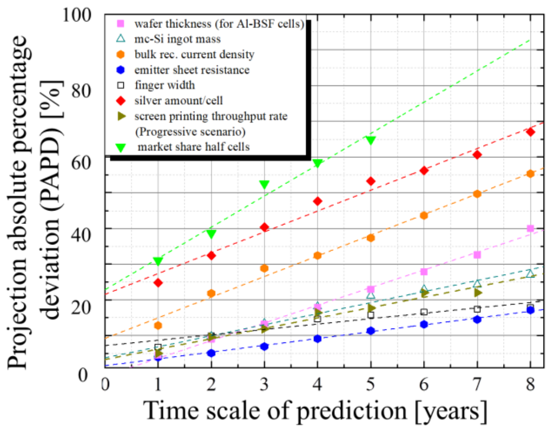

Figure 4: Projection absolute percentage deviation (PAPD) as a function of the time span of the predictions for each of the studied topics within the analyzed report editions (2nd until 11th edition). The linear fits show the trend of the accuracy deviation of each topic. Steeper slopes indicate a higher inaccuracy in the projection, noticeably showing that projecting a larger time scale (in years) is susceptible to higher deviations. Some topics have been projected more accurately than others.

A clear trend of the drop in accuracy (increase in PAPD) is observed with the increase of projection time scale. As expected, this behavior is observed on all the projected topics' accuracies per projected time scale. This explicitly shows that the near future expectations are easier to meet in comparison to longer time span ones.

To differentiate accurately projected topics from less accurately projected ones, the slope of the PAPD vs. projection time scale plots can be considered as an indication. Considering the data points in this work a linear fit can describe the dependency of the PAPD on the time frame of the projection. Topics that are more accurately projected throughout the years feature lower slopes. Consequently, the topics can be ranked in a decreasing order of accuracy (highest to lowest accuracy); as shown in Table I, depending on the values of the slopes.

Table I. Projection accuracy summary of studied topics listed in a decreasing order "rank" of accuracy.

Studied topic	Time-dependent projection accuracy (%/year)	Accuracy rank
Finger width	1.5 ± 0.1	1
Emitter sheet resistance	1.9 ± 0.5	2
Screen printing throughput	2.9 ± 0.2	3
mc-Si ingot mass	3.1 ± 0.1	4
mc-Si wafer thickness for Al-BSF cells	4.9 ± 0.1	5
Bulk recombination current density	5.7 ± 0.1	6
Silver amount per cell	5.8 ± 0.1	7
Half cells market share	8.1 ± 0.2	8

3.2 Future projections and accuracy ranges

For each of the topics and based on the approach in this work, upper and lower limits can be drawn. Since these limits have sometimes only statistical meaning, additional constraints can be placed based on common knowledge of possible known physical limits. Additionally, some values within the upper or lower limits of the future projections are already achieved in previous/current versions. As a result, these "forbidden" or already achieved projected values are marked in "grey" in the upcoming projection plots, showing their exclusion from the sole statistical result.

(a) Multicrystalline silicon wafer thickness

The projections of the wafer thickness in this case are mainly focused on the application on Al-BSF. This projection has been presented ever since the first editions of the ITRPV. Back then mc-Si wafer based Al-BSF cells were dominating the PV market. Currently, with the advancement of the monocrystalline PERC cell concepts and market share, the relevance of the mc-Si wafer thickness reduction for Al-BSF application has substantially decreased. However, an expected minimum in the latest edition is seen to be around 160 µm; see Fig. 5.

Considering the deviations of the previous projections and applying them on the future ones, the purely statistical nature of the study creates upper limit that are higher than already achieved wafer thickness values. Since such wafer thickness values have already been achieved, it is not expected to have higher wafer thickness values in the future marked, therefore this area is marked in "grey".

The report is developed in such a way, that it has been more specific when it comes to prediction topics. Unlike the PV industry a decade ago, the advancements in the cell and module architectures as well as materials and processes used upon a larger window of discussed topics. For that reason, it is quite evident that in each result plot of the ITRPV report, several topics are being included. Taking the example of wafer thickness; not only the wafer thickness of *p*-type mc-Si for Al-BSF cells is provided, but also the wafer thickness of *p*-type mc-Si for passivated emitter and rear (PERx) cells. Additionally, the *p*-type mono-Si wafer thicknesses are also included for both Al-BSF and PERx cells. Similarly, another plot in the current ITRPV edition not only includes *n*-type wafer thickness for PERx cells, but also that of interdigitated back contact (IBC) and silicon heterojunction (SHJ) cells. This clearly shows the commitment towards finding specific solutions based on necessary detailed projections, imaging the current and future state of the technologies. Future projection accuracy studies should include each of those projected topics independently.

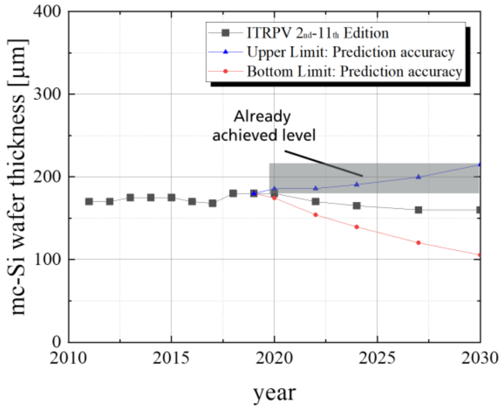

Figure 5: The projected values of the mc-Si wafer thickness for Al-BSF cells from the 11th edition ITRPV 2020. The plot includes expected upper and lower limits based on the accuracy study of the past projections.

(b) Multicrystalline silicon ingot mass

It is obvious that the mc-Si ingot mass is expected to increase. This is clearly motivated by the increase of crystallization process throughput. The latest edition of ITRPV expects a 1600 kg mc-Si ingot mass in 2030; see Fig. 6. The upper and lower limits of the projection based on the projection accuracy study are included.

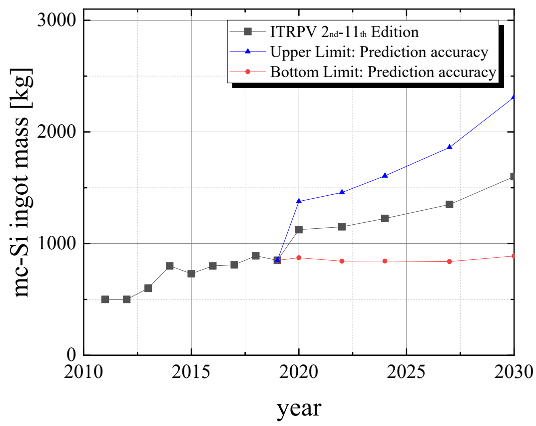

Figure 6: The projected values of the mc-Si ingot from the 11th edition ITRPV 2020. The plot includes expected upper and lower limits based on the accuracy study of the past projections.

The latest editions of the ITRPV also include projections of crystal growth ingot mass of the cast-mono-Si and Czochralski-grown mono-Si, can be analysed in upcoming accuracy studies.

(c) Bulk recombination current density

The bulk recombination current density for *p*-type mc-Si is also expected to decrease; see Fig. 7. The projected value is 62.5 fA/cm^2 for the year 2030. Since the statistical nature of the projection accuracy study doesn't account for the physical limits, the considered deviations in the future lead to a significantly lower limit. The region marked in grey is not expected to be attained as it shows either values that have been already achieved or are too low to achieve.

The current version of the ITRPV includes the projections of the bulk recombination current density of the *p*-type mono-Si as well as the front and the rear recombination current density. Projection accuracy studies for those topics are also possible in the future, especially with the increase of the number of editions and hence the increase of the data points to be considered.

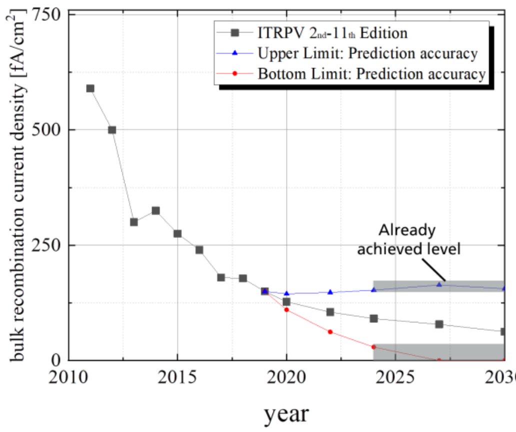

Figure 7: The projected values of the bulk recombination current density from the 11th edition ITRPV 2020. The plot includes expected upper and lower limits based on the accuracy study of the past projections.

(d) Emitter sheet resistance

The projected values of the homogeneous emitter sheet resistance for phosphorous doping have been projected to reach 140 Ohm/sq in 2030; see Fig. 8. The deduced upper limit shows possible progressive scenario with an expected 2024 value of around 140 Ohm/sq,

The current edition also includes projections of the selective emitters for *p*-type cells and emitter sheet resistance of *n*-type cells. The projection accuracy of these topics can be studied with the advancement of the report editions and the availability of the data in upcoming reports.

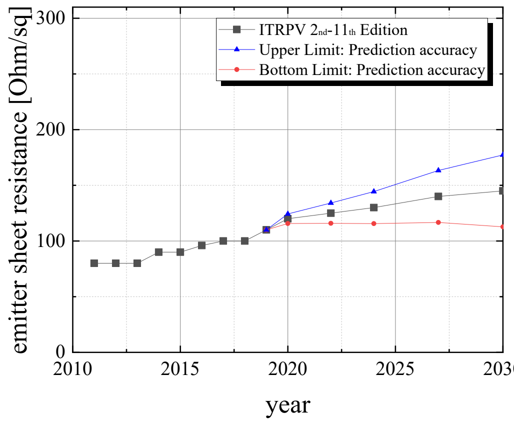

Figure 8: The projected values of the homogeneous emitter sheet resistance for phosphorous doping from the 11th edition ITRPV 2020. The plot includes expected upper and lower limits based on the accuracy study of the past projections.

(e) Finger width

The finger width is seen to decrease to a value of 20 µm in 2030; see Fig. 9. This topic is extremely well projected in the available reports. This is clearly shown by the projection accuracy results; see Table 1. The upper and lower limits deduced from the projection accuracy shows a quite narrow area in between those limits, mainly due to the high projection accuracy.

Current research shows the clear trend towards finer finger widths [9]. This can be realized by advancements in screen printing technology [10] or by using alternative approaches such as dispensing and inkjet printing [11].

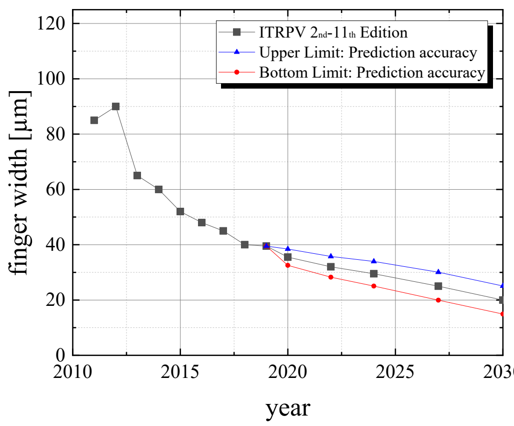

Figure 9: The projected values of the finger width from the 11th edition ITRPV 2020. The plot includes expected upper and lower limits based on the accuracy study of the past projections.

(f) Silver amount per cell

Silver amount per cell is an essential projected topic, especially due to its impact on the cell production costs. The projections show a strong reduction in the amount of silver used per cell, with the latest report projecting a silver amount reaching 0.05 g/cell; see Fig. 10.

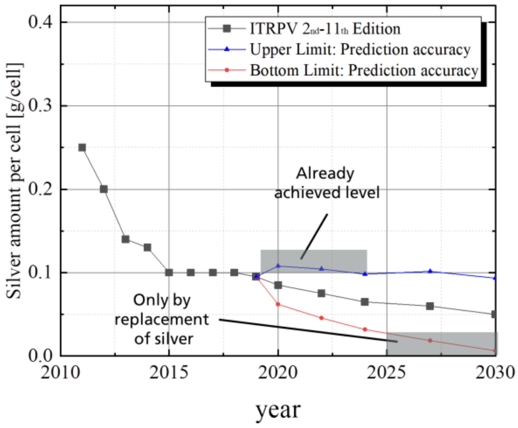

Figure 10: The projected values of silver amount per cell from the 11th edition ITRPV 2020. The plot includes expected upper and lower limits based on the accuracy study of the past projections.

Based on the approach, the bottom limit projects even lower values that might be achieved with the total/partial replacement of silver in upcoming cell concepts.

(g) Screen printing throughput rate

It is evident that the screen printing equipment throughput rate has reached a current value of 7000 cells/hour and is expected to increase further in the upcoming years. The ITRPV report expects a progressive increase of throughput rate resulting in up to 15000 cells/hour by 2030; see Fig. 11. This increase in throughput is driven by advancements in screen printing technology. For high throughout rates, rotational screen printing as well as dispensing are also seen as possible metallization technologies allowing such productivity advancements [12,13].

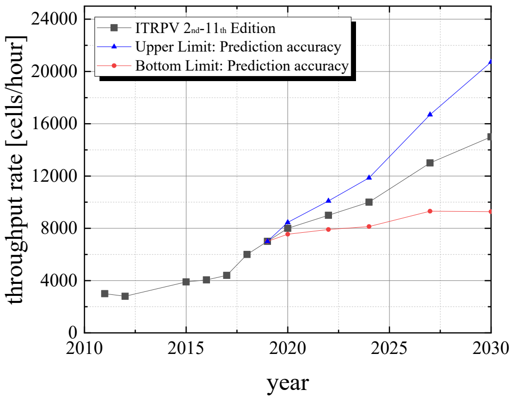

Figure 11: The projected values of screen printing throughput rate from the 11th edition ITRPV 2020. The plot includes expected upper and lower limits based on the accuracy study of the past projections.

In general screen printing is expected to remain the main metallization technology. The development of the technology remains towards finer fingers, lower silver consumption and higher process throughputs, all those without leading to resistive losses.

(h) Market share of half cells

The predictions of the market share of half cells started in the year of 2015. Due to the advantages of applying separated cells, which is clearly seen on module level, concepts based on half cells [14,15] and shingle cells [16–18] are subject of increasing interest in the upcoming years. This is shown by the projected market share of more than 60% by 2030; see Fig. 12. This goes hand-in-hand with the projected increase in used wafer sizes [19]. Since the projection accuracy of half cells market share is seen to be the lowest among the studied topics in this work, this makes it quite difficult to deduce upper and lower projection accuracy limits. Nevertheless, recent record modules by leading cell and module manufacturers include half cell or separated cell architectures [20–22].

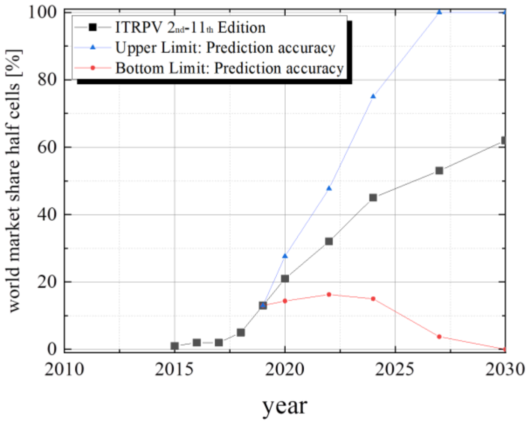

Figure 12: The projected values of the market share of half cells from the 11th edition ITRPV 2020. The plot includes expected upper and lower limits based on the accuracy study of the past projections.

4 SUMMARY

Ever since its establishment, the International Technology Roadmap for Photovoltaics (ITRPV) has grown year after year in terms of number of contributors and discussed topics (results). The report includes projected topics covering mainly crystalline PV technology value chain items. As a roadmap follow-up phase, the understanding of the report can be enhanced by studying the accuracy of the projections in comparison to current reference values. This also supports the differentiation between accurately projected topics from less accurately projected ones.

This paper investigates the accuracy of the projections of frequently discussed topics from the 2nd Edition up to the 11th Edition (current) chosen topics by comparing projections of the past with reference values of the present. The projection accuracy of eight topics is analysed: (a) multicrystalline silicon (mc-Si) wafer thickness (for aluminum back surface field), (b) mc-Si ingot mass, (c) bulk recombination current density; (d) emitter sheet resistance, (e) finger width, (f) silver amount per cell, (g) progressive scenario screen printing throughput rate, in addition (h) the market share of half cells are studied. For each of the studied topics the projection absolute percentage deviation (PAPD) from reference values is calculated and deduced as a function of projection time scale. As a result, the time-dependent projection accuracy per chosen topic is obtained.

Based on the adopted approach, the topic finger width features the highest projection accuracy showing a PAPD as a function of time scale slope (1.5 ± 0.1) %/year, while the half cell market share projection is the least accurately projected topic attaining (8.1 ± 0.2) %/year. Considering the time-dependent projection accuracy, expected future projection ranges (upper and lower limits) are obtained for each of the discussed topics. Studying the projection accuracy of the ITRPV topics enhances the understanding of the developments in the market as projected by experts.

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REFERENCES

[1] VDMA, International Technology Roadmap for Photovoltaic: Results 2019 - 11th Edition 2020.

[2] M. Fischer, A. Metz, S. Raithel, SEMI International Technology Roadmap for Photovoltaics (ITRPV) – Challenges in c-Si Technology for Suppliers and Manufacturers, 27th EUPVSEC (2012). https://doi.org/10.4229/27thEUPVSEC2012-2BP.1.1.

[3] P. Baliozian, S. Mourad, D. Morse, S. Kim, L. Friedrich, R. Preu, Photovoltaic Development Standardizing Based on Roadmaps and Technology Readiness Levels, 32nd EUPVSEC (2016). https://doi.org/10.4229/EUPVSEC20162016-7EO.2.2.

[4] O. H. Bray, M. L. Garcia, Technology roadmapping: the integration of strategic and technology planning for competitiveness, in: Innovation in Technology Management. The Key to Global Leadership. PICMET '97, Portland, OR, USA, IEEE, 27-31 July 1997, pp. 25–28.

[5] M. Fischer, International Technology Roadmap for Photovoltaic, Seventh Edition, March 2016, Malaysia, 2016.

[6] P. Baliozian, J. Trube, M. Fischer, S. Al-Hajjawi, R. G. Yadav, R. S. Nold, R. Preu, Accuracy and Significance of the Projections in the International Technology Roadmap for Photovoltaic (ITRPV). 33rd European Photovoltaic Solar Energy Conference and Exhibition; 280-285 / 33rd European Photovoltaic Solar Energy Conference and Exhibition; 280-285, 33rd EUPVSEC, Amsterdam, The Netherlands (2017). https://doi.org/10.4229/EUPVSEC20172017-2AO.6.1.

[7] A.K. R. Hyndman, Another look at measures of Forecast Accuracy., Department of Econometrics and Business statistics Monash University and Department of Decision Sciences and Management Information Systems Miami University (2005).

[8] J. Hoover, How to Track Forecast Accuracy to Guide Process Improvement, Foresight: The International Journal of Applied Forecasting. (2009).

[9] S. Tepner, L. Ney, M. Linse, A. Lorenz, M. Pospischil, K. Masuri, F. Clement, Screen Pattern Simulation for an Improved Front-Side Ag-Electrode Metallization of Si-Solar Cells, Prog. Photovolt: Res. Appl. (2020). https://doi.org/10.1002/pip.3313.

[10] S. Tepner, L. Ney, M. Linse, A. Lorenz, M. Pospischil, F. Clement, Studying Knotless Screen Patterns for Fine Line Screen Printing of Si-Solar Cells, IEEE J. Photovoltaics 10 (2020) 319–325. https://doi.org/10.1109/JPHOTOV.2019.2959939.

[11] M. Pospischil, T. Riebe, A. Jimenez, M. Kuchler, S. Tepner, T. Geipel, D. Ourinson, T. Fellmeth, M. Breitenbücher, T. Buck, M. Dhamrin, F. Clement, Applications of parallel dispensing in PV metallization, AIP Conference Proceedings (2019) 20005. https://doi.org/10.1063/1.5125870.

[12] A. Lorenz, M. Linse, H. Frintrup, M. Jeitler, A. Mette, M. Lehner, R. Greutmann, H. Brocker, M. König, D. Erath, F. Clement, Screen Printed Thick Film Metallization of Silicon Solar Cells - Recent Developments and Future Perspectives, 35th European Photovoltaic Solar Energy Conference and Exhibition (2018) 819–824. https://doi.org/10.4229/35THEUPVSEC20182018-2DV.3.65.

[13] S. Tepner, N. Wengenmeyr, M. Linse, A. Lorenz, M. Pospischil, F. Clement, The Link between Ag-Paste Rheology and Screen Printed Metallization of Si Solar Cells, Adv. Mater. Technol. (2020). https://doi.org/10.1002/admt.202000654.

[14] S. Guo, J. Schneider, F. Lu, H. Hanifi, M. Turek, M. Dyrba, I. M. Peters, Investigation of the short-circuit current increase for PV modules using halved silicon wafer solar cells, Solar Energy Materials and Solar Cells 133 (2015) 240–247. https://doi.org/10.1016/j.solmat.2014.11.012.

[15] Hanwha Q CELLS, Q.PEAK Duo-G5 315-330, 2019. https://www.q-cells.de/produkte/solarmodule/qpeak-duo-g5.html (accessed 7 October 2019).

[16] P. Baliozian, E Lohmüller, T. Fellmeth, N. Wöhrle, A. Krieg, R. Preu, Bifacial p-type silicon shingle solar cells - the "pSPEER" concept, Solar RRL (2018). https://doi.org/10.1002/solr.201700171.

[17] P. Baliozian, N. Klasen, N. Wöhrle, C. Kutter, H. Stolzenburg, A. Münzer, P. Saint-Cast, M. Mittag, E. Lohmüller, T. Fellmeth, M. Al-Akash, A. Kraft, M. Heinrich, A. Richter, A. Fell, A. Spribille, H. Neuhaus, and R. Preu, PERC-Based Shingle Solar Cells and Modules at Fraunhofer ISE, Photovoltaics International (2019).

[18] P. Baliozian, M. Al-Akash, E. Lohmüller, A. Richter, T. Fellmeth, A. Münzer, N. Wöhrle, P. Saint-Cast, H. Stolzenburg, A. Spribille, and R. Preu, Postmetallization "Passivated Edge Technology" for Separated Silicon Solar Cells, IEEE J. Photovoltaics (2020) 390–397. https://doi.org/10.1109/JPHOTOV.2019.2959946.

[19] RENA Technologies GmbH, Wafer Wet Chemical Surface Treatment from M0 to M6 & M12, 2020. https://www.rena.com/en/products/large-wafer-wet-processing (accessed 11 May 2020).

[20] E. Bellini and M. Willuhn, 500 W-plus panel race intensifies with JA Solar's new module, Risen's

first shipments, 2020. https://www.pv-magazine.com/2020/05/11/500-w-plus-panel-race-intensifies-with-ja-solars-new-module-and-risens-first-shipment/.
[21] E. Bellini, Jinko Solar bringt Modul mit Rekordleistung von 580 Watt auf den Markt, 2020. https://www.pv-magazine.de/2020/05/15/jinko-solar-bringt-modul-mit-rekordleistung-von-580-watt-auf-den-markt/.
[22] E. Bellini, Trina unveils two 500 W bifacial solar modules, 2020. https://www.pv-magazine.com/2020/02/27/trina-unveils-two-500-w-bifacial-solar-modules/.