Material Requirement and Resource Availability for Silicon Photovoltaic Laminate Manufacturing in the Next 10 Years

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Abstract— **Material scarcity is a considerable threat to energy transition towards renewables. Photovoltaics (PV) installations are expected to increase rapidly in the next decade, which may increase the amount of material needed. This study created three scenarios (S_1, S_2, & S_3) to evaluate the impacts of potential technology improvements on the quantity of materials necessary for manufacturing silicon PV (Si PV) laminate in the next ten years. Our baseline was similar to previous studies, which applied theoretical models on PV historical data and ignored PV technology improvements that can influence future material projections. S_1 considered only market share and module efficiency, while S_2 covered wafer thickness improvements as well. S_3 was the scenario that more likely will occur in the next decade, which included module efficiency, market share, wafer thickness, glass thickness, and potential replacements such as using perovskite/silicon tandem. The material requirement for Si PV laminate manufacturing in S_3 was 22% to 78% lower than the baseline, S_1, and S_2. The highest material demand is expected to be for solar glass (74 million metric tons) and Metallurgical grade silicon (3 million metric tons) in the next decade. This study showed the importance of considering technology improvements to project the PV material requirement.**

Keywords—silicon photovoltaics, energy materials, resource availability

I. Introduction

The global cumulative PV installation increased from one GW in 2000 to 480 GW in 2018 and is expected to reach 8,519 GW by 2050 [1][2]. PV technologies' contribution to electricity generation from renewable resources was less than one percent in 2010, while it is estimated to increase from 13% in 2018 to 48% by 2050 in the USA [3]. However, the energy transition to renewable energy faces various challenges related to material availability that should be carefully explored [4].

Material scarcity is a potential threat to PV deployment. In 2019, silicon PV (Si PV) was 95% of the PV market [1]. Si PV is anticipated to remain the primary type of PV technology (>50%) until 2040 [5]. Most previous studies on the material need for Si PV used theoretical models such as material flow analysis [6], the total material requirement [7], Hubbert peak [8][9], and historical data to project future material necessary for manufacturing Si PV in the future need. A few studies considered changes in market share and efficiency while ignoring changes in technology and manufacturing [10]–[12].

In this work, we calculated the materials such as metallurgical grade silicon (MG-Si), solar glass, aluminum, copper, lead, silver, and tin needed for manufacturing Si PV laminate to meet the expected global annual Si PV installation in the next ten years. We considered module efficiency, the percentage of Si PV sub-technologies in the PV market, silicon wafer thickness in cells, glass thickness in laminate, sawing techniques, and other potential technology improvements such as using silicon/perovskite tandem.

II. Methods

A. Study scope

This study considered materials necessary for manufacturing Si PV laminate. Fig. 1 shows the study scope, which contains mining raw materials, solar-grade material production, wafering, cell processing, and PV laminate manufacturing. MG-Si is required for producing solar-grade silicon. Silver and aluminum are needed for metallization paste at the cell production stage. Copper, tin, lead, and solar glass are considered for PV laminate.

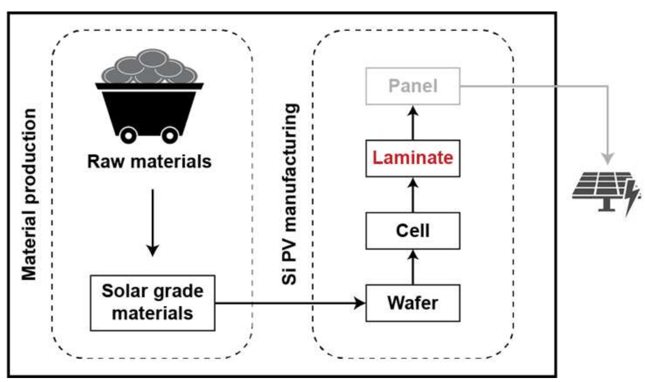

Fig. 1. Study scope

B. Material requirements

Materials necessary to support Si PV were calculated based on data compiled from literature, energy outlooks, and the annual reports of leading Si PV manufacturers. The annual PV installation was based on the 2020 DNV-GL Energy Transition Outlook [13]. PV technology improvements, such as efficiency, wafer thickness, wafer sawing, glass thickness, and material replacement, were determined based on leading manufactures' annual reports and energy outlooks. We identified the required materials for the baseline and three scenarios (S_1, S_2, & S_3) (Table 1). The baseline assumptions were similar to previous PV studies that used theoretical models and PV historical data to calculate the necessary materials for PV manufacturing and ignored technology changes. S_1 and S_2 were similar to previous studies where some part of technology improvement was considered to estimate materials required for making PV. S_3 considered Si PV sub-technologies efficiency and their contribution in the PV market, silicon wafer thickness, glass thickness, sawing techniques, and perovskite/silicon tandem.

Table 1 Scenarios for calculating materials necessary for making Si PV [22]

Scenario	Description				
Baseline	Efficiency, market share, and current PV technologies remain constant until 2031				
				2021	**2031**
S_1	Sub-technology Market share (%)	c-Si*		35.5	28.22
		mc-Si**		64.5	40.61
	Efficiency (%)	c-Si		22	23.5
		mc-Si		19	22
S_2	Sub-technology Market share (%)	c-Si		35.5	28.22
		mc-Si		64.5	40.61
	Efficiency (%)	c-Si		22	23.5
		mc-Si		19	22
	Silicon wafer thickness (µm)	c-Si		170	50
		mc-Si		180	50
S_3	Sub-technology Market share in PV	c-Si	Al-BSF	3.44	0
			Monofacial PERC	14.58	5.82
			Bifacial PERC	14	20.64
			Monofacial HJT	1.05	1.45
			Bifacial HJT	1.01	5.16
			Bifacial perovskite PERC	0.97 (2023)	5.18
		mc-Si	Al-BSF	6.35	0
			Monofacial PERC	26.89	5.8
			Bifacial PERC	25.84	20.64
			Monofacial HJT	1.94	1.45
			Bifacial HJT	1.87	5.16
	Efficiency	Al-BSF c-Si		20	21.5
		Al-BSF mc-Si		19	20
		PERC c-Si		20.7	22.2
		PERC mc-Si		19.5	21.5
		HJT Si		21.5	23
		Si/perovskite tandem		22.5	26
	Silicon wafer thickness (µm)	c-Si		170	50
		mc-Si		180	50
	Glass thickness (mm)	c-Si & mc-Si		4	2

*mono-crystalline silicon (c-Si), **multi-crystalline silicon (mc-Si)

We used a bottom-up approach to determine the required materials for manufacturing Si PV laminate. Fig. 2 shows the six types of Si-based solar cells considered: aluminum back surface field (Al-BSF), monofacial PERC, bifacial PERC, monofacial Si heterojunction (HJT), bifacial HJT, and perovskite/silicon tandem.

C. *Resource availability*

Material availability for Si PV manufacturing was based on the United Nations Comtrade annual reports [13] and the United States Geological Survey Minerals Yearbooks [14]. Annual MG-Si and silica sand production were identified using yearly USGS reports [15].

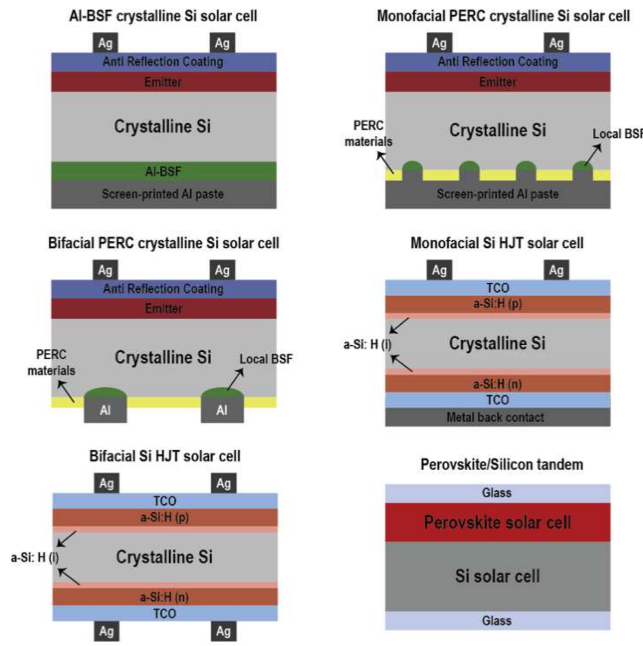

Fig. 2. The typical structures of Si PV. Al-BSF: Aluminum Back Surface Field, PERC: Passivated Emitter and rear Cell, HJT: Heterojunction Technology. [16]–[20]

III. RESULTS AND DISCUSSION

A. *Material requirements*

We projected the required materials for manufacturing Si PV laminate until 2031. Wafer thickness for Si PV was assumed to be 180 µm for mc-Si and 170 µm for c-Si in 2020 [21] and reduced to 50 µm by 2031 [22]. The 2021 market share for c-Si and mc-Si PV was 35.5 % and 64.5%, respectively [23]. The Si PV market share is expected to shrink to 25% for c-Si and mc-Si PV by 2040 [24]. Cadmium telluride (CdTe), copper indium gallium selenide (CIGS/CIS), and amorphous silicon (a-Si) PV will cover the rest of the PV market by 2040 [24]. The efficiency was assumed to improve from 22% (c-Si PV) and 19% (mc-Si PV) [25] to 25% in 2040 [24]. However, this was higher than the Si PV efficiency reported for mass production. For example, the median efficiency of Al-BSF c-Si produced by leading global PV manufacturers was about 20% in 2021 and will reach 21.5% by 2031 [22]. In the 3rd scenario (S_3 – Table 1), we considered market share changes and efficiency improvements for each Si PV sub technology for mass production; Al-BSF, mono facial PERC, bifacial PERC, mono facial HJT, bifacial HJT, and perovskite/silicon (Fig. 2).

Fig. 3. shows the material required for manufacturing Si PV laminate to meet the global PV installation forecasts until 2031. Solar glass and MG-Si will have the highest demand in the next ten years. The baseline shows how material demands are increasing due to the increase in PV installation without

considering any changes in PV technology. Material demand will increase 260% for MG-Si and 250% for solar glass in the next decade (Fig. 3A). The first scenario (S_1 - Fig. 3B) shows how efficiency improvements and market share changes may influence material needs in the next couple of years. For example, in 2031, about 1.04 million metric tons of MG-Si and 13.1 million metric tons of solar glass will be required for the baseline, while it is 0.69 million metric tons of MG-Si and 9.3 million metric tons of solar glass for S_1. For the second scenario (S_2–Fig. 3C), we considered the reduction in wafer thickness. For S_2, the amount of MG-Si was 69% lower than S_1.

The 3rd scenario (Fig. 3D) was based on data collected from mass production in global leading PV manufacturers. Similar to the baseline, S_1, and S_2, MG-Si and solar glass were the primary materials for making Si PV laminate. However, the material demand in 2021 was higher due to the low efficiency of massive Si PV production compared to the Si PV efficiency reported by previous studies. Manufacturing improvements such as the decrease in the thickness of Si wafer and glass as well as using emerging technologies such as perovskite will mitigate material demand. The material demand will be reduced after 2029 due to replacing Al-BSF with other PV technologies with higher efficiency.

Fig. 4. shows material requirements for manufacturing Si PV laminate for sub-technologies in the 3rd scenario. MG-Si and solar glass were the primary materials for each sub-technology. Required MG-Si for Al-BSF Si PV (Fig. 4B) will decrease from 43,000 metric tons in 2021 to 3,000 metric tons in 2030 due to replacing Al-BSF Si PV with other Si PV technologies. The solar glass will also decrease from 585,000 metric tons in 2021 to 71,000 metric tons in 2031.

PERC Si PV (Fig. 4B) will need the highest amount of materials among Si PV technologies. PERC technology was 83% of the Si PV market and is expected to shrink to 72% in 2031 [22]. About 346,000 metric tons of MG-Si and 6.1 million metric tons of solar glass were needed in 2021 for manufacturing PERC Si PV laminate which will decrease to 177,000 metric tons of MG-Si and 5.3 million tons of solar glass. HJC Si PV (Fig. 4C) was 6% of the Si PV market in 2021 and is likely to be 18% of the Si PV market in 2031 [22]. MG-Si demand will increase from 30,000 metric tons in 2021 to about 55,000 metric tons in 2031. A similar trend was projected for solar glass, where the demand increased from 0.56 million metric tons in 2021 to 1.78 million metric tons in 2031. The last technology in the Si PV market is perovskite/silicon tandem which is expected to be a part of mass production after 2023 [22]. MG-Si demand for manufacturing perovskite/silicon tandem will increase about 2.5 times in the next couple of years. Approximately 4,000 and 14,000 metric tons of MG-Si will be required in 2023 and 2031, respectively.

B. Resource availability

Fig. 5 shows available silica sand and MG-Si resources in 2020. Industrial-grade silica sand is the primary material for producing solar glass and MG-Si. Some countries such as the US, the Netherlands, and Spain had the highest amount of available silica sand resources in 2020 (Fig. 5A). MG-Si is the other key material for the Si PV market, which is mainly produced in China. Other leading MG-Si producers were Russia, Norway, and the US in 2020 (Fig. 5B). The primary stockpiles' users are the aluminum and chemical industry for MG-Si and the concrete, roads, and construction industry for silica sand, while the PV industry consumed a small percentage of MG-Si and silica sand [15]. However, PV deployment growth may increase the dependency of Si PV producers on MG-Si and high-quality silica sand resources. This may result in competition between various stakeholders to supply material demand for Si PV manufacturing which may affect the environment due to the possibility of excessive mining or using illegal silica sand.

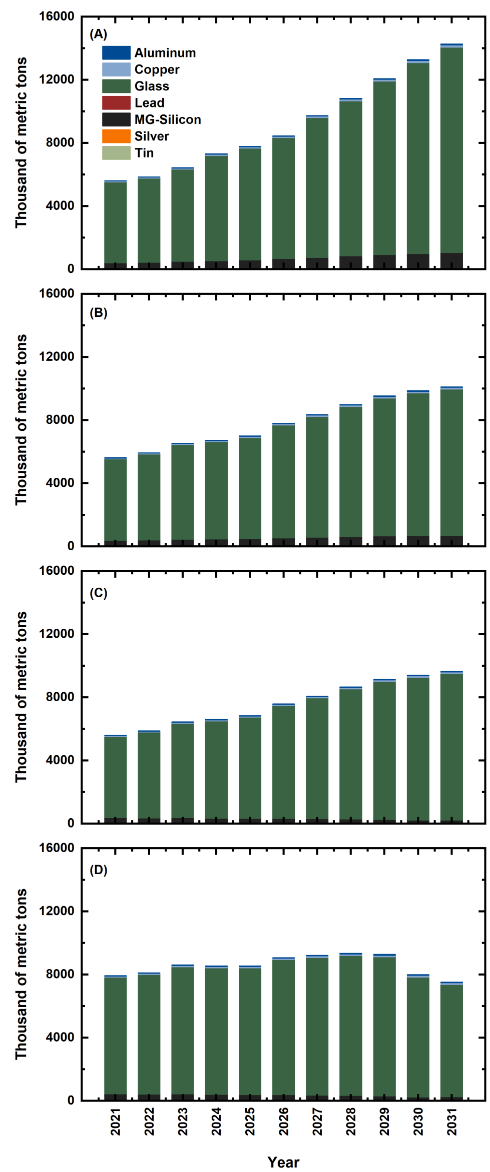

Fig. 3. Material requirements for manufacturing Si PV to meet the electricity demands from 2021 to 2031 for various scenarios. (A) Baseline , (B) S_1, (C) S_2, and (D) S_3.

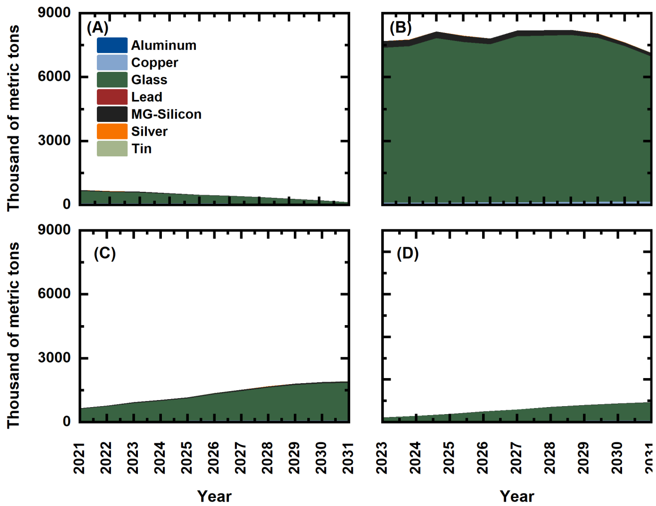

Fig. 4. Material requirements for manufacturing Si PV technologies to meet the electricity demands from 2021 to 2031. (A) Al-BSF Si PV, (B) PERC Si PV, (C) HJT Si PV, and (D) Si/Perovskite tandem.

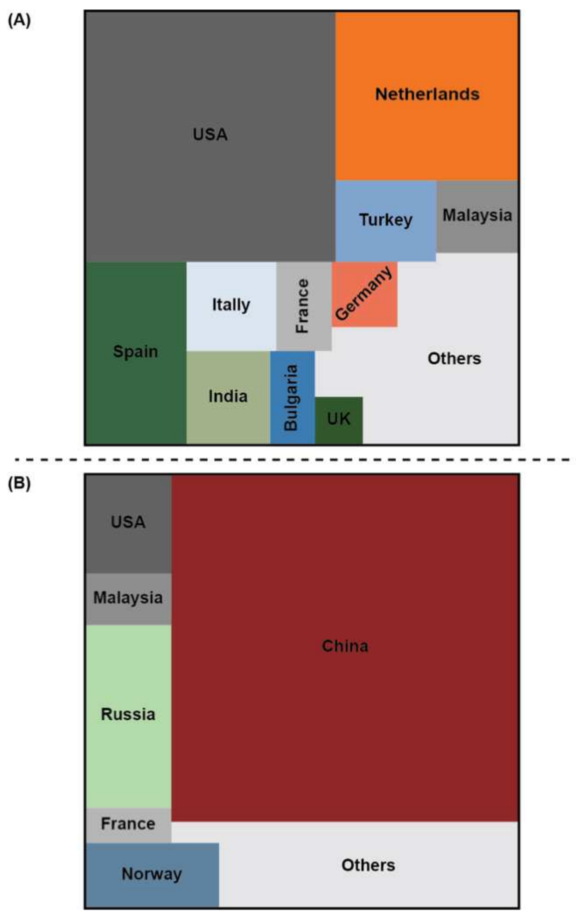

Fig. 5. Available industrial-grade silica sand (A) and MG-Si (B) in 2020.

IV. Conclusion and Future Work

The material shortage is a potential issue for PV deployment. This study showed the importance of considering PV technology improvements in material projections. We evaluated Si PV material demand for different scenarios to cover typical assumptions that were considered by previous studies for material requirement estimations. The baseline was representative of previous studies where conducted analysis only based on historical data and ignored PV technology changes. The first and second scenarios were based on assumptions used by previous studies, where they focused only on efficiency and market share and ignored sub-technology deployment and manufacturing improvements. In the 3rd scenario, we projected material requirements considering improvements in the efficiency and market share of c- and mc-Si PV sub-technologies, glass thickness, and Si wafer thickness in the next decade. The estimated required materials in S_3 were 22% to 78% lower than the baseline and 23% to 66% lower than 1st and 2nd scenarios. MG-Si and solar glass have the highest demand for Si PV laminate manufacturing. About 74 million metric tons of solar glass and 3 million metric tons of metallurgical grade silicon will be required in the next decade for Si PV laminate manufacturing.

The availability of silica sand resources for MG-Si and solar glass production may cause some challenges for Si PV producers, which could result in excessive mining that may increase the socioenvironmental impacts of Si PV. There is also a possibility of using silica sand from illegal mines due to accessibility to enough resources. It is essential to consider third-party certifications to monitor the Si PV supply chain to ensure Si PV materials will be provided from legal mines without severe impacts on the environment.

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References

[1] International Renewable Energy Agency (IRENA), "Future of Solar Photovoltaics," 2019.

[2] W. Luo, Y. S. Khoo, A. Kumar, J. S. C. Low, Y. Li, Y. S. Tan, Y. Wang, A. G. Aberle, and S. Ramakrishna, "A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multi-crystalline silicon technologies," Sol. Energy Mater. Sol. Cells, vol. 174, no. September 2017, pp. 157–162, Jan. 2018.

[3] "Annual Energy Outlook 2019 with projections to 2050," 2019.

[4] A. Valero, A. Valero, G. Calvo, and A. Ortego, "Material bottlenecks in the future development of green technologies," Renew. Sustain. Energy Rev., vol. 93, no. March 2017, pp. 178–200, Oct. 2018.

[5] A. Elshkaki and T. E. Graedel, "Dynamic analysis of the global metals flows and stocks in electricity generation technologies," J. Clean. Prod., vol. 59, pp. 260–273, 2013.

[6] P. H. Brunner and H. Rechberger, Handbook of material flow analysis: for environmental, resource, and waste engineers. CRC Press, 2016.

[7] A. Adriaanse, S. Bringezu, A. Hammond, Y. Moriguchi, E. Rodenburg, D. Rogich, and H. Schütz, "Resource flows: the material basis of industrial economies," Harvard, 1997.

[8] M. K. Hubbert, "Energy resources: a report to the Committee on Natural Resources of the National Academy of Sciences," United States, 1962.

[9] C. Brian, Hubbert Peak Theory - Oil: A Cultural and Geographic Encyclopedia of Black Gold. Santa Barbara, CA, USA.: ABC-CLIO, 2014.

[10] C. S. Tao, J. Jiang, and M. Tao, "Natural resource limitations to terawatt-scale solar cells," Sol. Energy Mater. Sol. Cells, vol. 95, no. 12, pp. 3176–3180, 2011.

[11] A. Zuser and H. Rechberger, "Considerations of resource availability in technology development strategies: The case study of photovoltaics," Resour. Conserv. Recycl., vol. 56, no. 1, pp. 56–65, 2011.

[12] S. Davidsson and M. Höök, "Material requirements and availability for multi-terawatt deployment of photovoltaics," Energy Policy, vol. 108, no. June, pp. 574–582, 2017.

[13] "United Nations Comtrade annual reports, International Trade Statistics Database, https://comtrade.un.org."

[14] "U.S. Geological Survey (USGS) MINERAL COMMODITY SUMMARIES, https://www.usgs.gov/centers/nmic/mineral-commodity-summaries."

[15] "U.S. Geological Survey (USGS) MINERAL COMMODITY SUMMARIES 2019," Reston, Virginia, 2020.

[16] G. Dingemans and W. M. M. Kessels, "Status and prospects of Al 2 O 3 -based surface passivation schemes for silicon solar cells," J. Vac. Sci. Technol. A Vacuum, Surfaces, Film., vol. 30, no. 4, p. 040802, Jul. 2012.

[17] S. Guo, T. M. Walsh, and M. Peters, "Vertically mounted bifacial photovoltaic modules: A global analysis," Energy, vol. 61, pp. 447–454, Nov. 2013.

[18] W. Chen, R. Liu, Q. Zeng, and L. Zhou, "Low cost multicrystalline bifacial PERC solar cells – Fabrication and thermal improvement," Sol. Energy, vol. 184, no. February, pp. 508–514, May 2019.

[19] A. Louwen, W. van Sark, R. Schropp, and A. Faaij, "A cost roadmap for silicon heterojunction solar cells," Sol. Energy Mater. Sol. Cells, vol. 147, pp. 295–314, Apr. 2016.

[20] S. E. Sofia, H. Wang, A. Bruno, J. L. Cruz-Campa, T. Buonassisi, and I. M. Peters, "Roadmap for cost-effective, commercially-viable perovskite silicon tandems for the current and future PV market," Sustain. Energy Fuels, vol. 4, no. 2, pp. 852–862, 2020.

[21] R. Frischknecht, P. Stolz, L. Krebs, M. J. de Wild-Scholten, and P. Sinha, Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems (IEA PVPS), Task 12: PV Sustainability. 2020.

[22] ITRPV, "International Technology Roadmap for Photovoltaic," 2020.

[23] "2020 Photovoltaics Report_Fraunhofer Institute for Solar Energy Systems, ISE," 2020.

[24] A. Elshkaki and T. E. Graedel, "Dynamic analysis of the global metals flows and stocks in electricity generation technologies," J. Clean. Prod., vol. 59, pp. 260–273, Nov. 2013.

[25] G. Masson, I. Kaizuka, E. Bosch, A. Detollenaere, G. Neubourg, J. van Wetter, and J. Lindahl, IEA PVPS report - Trends in Photovoltaic Applications 2020. 2020.