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Technological Readiness of Indonesia's Photovoltaic Sector: A Technometric Analysis

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ABSTRACT

Despite Indonesia's vast solar potential (207.8 GWp), its utilization remains far below the 2025 target (0.87 GW), hampered by unmapped industrial capabilities. This study addresses this gap by mapping the technological capabilities of Indonesia's photovoltaic (PV) industry and its supporting sectors using Technometric models. By adopting a quantitative survey methodology involving key industry players (n=3) representing the solar panel, cable, and mounting structure sectors , the study evaluated technoware (T), humanware (H), and infoware (I) components. The main results show that the solar panel industry has "excellent" technology content with a Technology Contribution Coefficient (TCC) of 0.7204 , driven by strong humanware and infoware contributions (both exceeding 70%). In contrast, cable companies, with a TCC of 0.5651 , are categorized as having "good" technology content, indicating a need to improve technoware, which only contributes 47%. Meanwhile, the structure (mounting) company also showed "very good" technological capability with a TCC of 0.7297. The TCC value, which ranges from 0 to 1, measures the contribution of technology in value-added creation, with values of 0.7-0.9 indicating an "excellent" category. The proposed recommendations include prioritizing technoware development through product design computing and test optimization, humanware improvement through innovation training, and infoware strengthening through comprehensive information dissemination. This study provides the first Technometric benchmark for the Indonesian PV sector, offering a clear diagnostic tool for policymakers and industry to enhance competitiveness and achieve sustainable growth targets.

Keyword: *Technology Contribution, Technoware, Photovoltaics, Industrial Capabilities, Production Systems*

ABSTRAK

Meskipun potensi energi surya Indonesia sangat besar (207,8 GWp) , pemanfaatannya masih jauh di bawah target 2025 (0,87 GW), terhambat oleh kemampuan industri yang belum terpetakan. Penelitian ini mengatasi kesenjangan tersebut dengan memetakan kemampuan teknologi industri fotovoltaik (PV) dan sektor pendukungnya di Indonesia menggunakan model Teknometrik. Dengan mengadopsi metodologi survei kuantitatif yang melibatkan pelaku industri utama (n=3) yang mewakili sektor panel surya, kabel, dan struktur (mounting) , studi ini mengevaluasi komponen technoware (T), humanware (H), dan infoware (I). Hasil utama menunjukkan bahwa industri panel surya memiliki kandungan teknologi "sangat baik" dengan Koefisien Kontribusi Teknologi (TCC) sebesar 0,7204 , didorong oleh kontribusi humanware dan infoware yang kuat (keduanya melebihi 70%). Sebaliknya, perusahaan kabel, dengan TCC 0,5651 , dikategorikan memiliki kandungan teknologi "baik", mengindikasikan perlunya peningkatan technoware yang only berkontribusi 47%. Sementara itu, perusahaan struktur (mounting) juga menunjukkan kemampuan teknologi "sangat baik" dengan TCC sebesar 0,7297. Nilai TCC, yang berkisar antara 0 hingga 1, mengukur kontribusi teknologi dalam

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penciptaan nilai tambah, di mana nilai 0,7-0,9 menunjukkan kategori "sangat baik". Rekomendasi yang diusulkan meliputi prioritas pengembangan technoware melalui komputasi desain produk dan optimalisasi pengujian, peningkatan humanware melalui pelatihan inovasi, serta penguatan infoware melalui penyebaran informasi komprehensif. Studi ini menyediakan tolok ukur Teknometrik pertama untuk sektor PV Indonesia, menawarkan alat diagnostik yang jelas bagi pembuat kebijakan dan industri untuk meningkatkan daya saing dan mencapai target pertumbuhan berkelanjutan.

Keyword: Kontribusi Teknologi*, Technoware, Fotovoltaik,* Kemampuan Industri, Sistem Produksi

1. Introduction

Imagine a world where every roof of a house and building is adorned with panels that capture the sun's energy, transforming it into power that powers everyday life; this is Indonesia's vision of a sustainable energy future, a vision that is now within reach thanks to technological innovation and a commitment to renewable energy. Indonesia, as an archipelago straddling the equator, has enormous solar energy potential, making it an ideal candidate to make extensive use of this resource[1]. The potential for solar energy in Indonesia is estimated to reach 207.8 GWp, a fantastic figure that, if utilized optimally, could meet most of the national energy needs [2]. However, the current reality shows that the utilization of solar energy is still far from the existing potential, with a target installed capacity of 0.87 GW in 2025[3].

The use of solar energy in Indonesia faces various challenges, especially the problem of intermittency in energy production [4]. To address these challenges, a comprehensive strategy is needed, including improving supportive regulations and increasing public investment directed at developing solar energy infrastructure [5]. In addition, the development of efficient and affordable energy storage technology is key to overcoming the problem of intermittency and ensuring a stable energy supply. Technology development will continue to drive improvements in meeting the need for electrical energy to support the performance of a technology [6]. Indonesia, which is located in a tropical region, has an average solar irradiation potential of 4.8 kWh/m^2 per day, so the development and utilization of solar energy are very promising [7]. Practical applications of solar energy have been implemented in various sectors, including public street lighting, where the average solar potential is 5.7 kWh/m^2/day [8], electricity provision in remote areas, and solar water heaters [9]. These advances in solar energy technology offer solutions for remote areas that do not have access to conventional electricity grids and contribute to the development of sustainable energy systems.

Solar Power Plants (PLTS) are not just alternative energy sources, but rather a transformative solution that promises energy independence, environmental sustainability, and inclusive economic growth, PLTS can also contribute to national energy security. The installed capacity of power plants, which represents the technical capability of power plants to produce output consistently, is a key performance indicator in the development of technological energy infrastructure. This is in line with the vision of the 2019-2025 Solar Energy Roadmap to achieve the national energy mix target of 23% by 2025, by utilizing solar energy for energy security and increasing domestic industry, as stipulated in Presidential Regulation Number 22 of 2017 concerning the National Energy General Plan. The government has provided support for development, including the utilization of solar energy as determined in the strategic target roadmap with the implementation of solar power plants shown in Figure 1 [10].

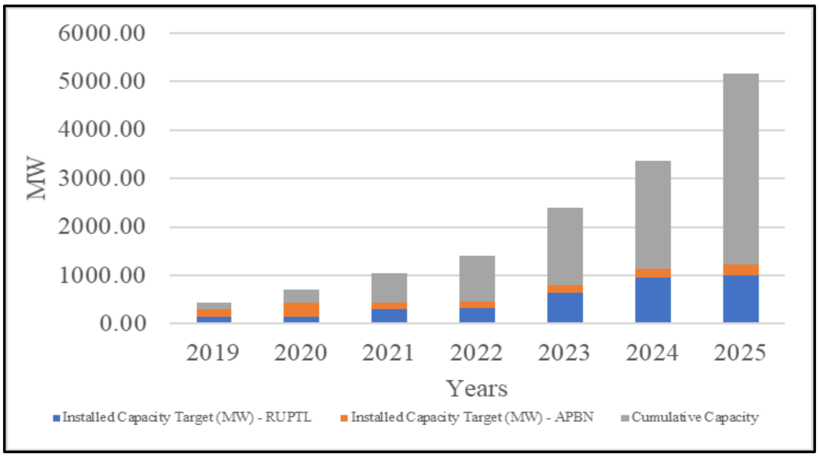

Figure1. National Roadmap for Solar Power Generation

The Directorate General of New, Renewable Energy and Energy Conservation measures performance achievements by comparing realization with targets. Realization compared with the target of the installed capacity of solar power plants causes a difference in value with the target of the national energy policy in Government Regulation Number 79 of 2014, with a difference of 5570 MW [11], because the applicable regulations state that domestically produced raw materials are not available for production needs in companies and the provisions regarding the domestic component content level (TKDN) are 40% so that many companies still choose imported products or raw materials such as solar cells and glass in solar panels [12]. Analysis from observers that the nature of the ambition towards the installed capacity target could worsen the condition of the state electricity company. In fact, there have been many warnings because of the disparity that is too far between the projection and the reality of electricity growth which could lead to a condition of electricity oversupply, where idle capacity but still has to be paid for, which will only become a burden on the state [13].

Recent studies have highlighted the importance of technological development in energy infrastructure as a key performance indicator, especially focusing on installed capacity. Hanan Nugroho & M. Muhyiddin (2021) reported that despite the COVID-19 pandemic, Indonesia experienced an increase in electrification ratio and renewable energy utilization in 2020 [14]. However, there are still challenges from the industrial development side to fulfill the TKDN of Various EBTs, including the domestic solar module industry is not yet competitive, existing regulations do not take into account current industrial and technological developments and the unavailability of the upstream solar module industry [15].

Studies from Institute for Energy Economics and Financial Analysis (IEEFA), explained that the solar panel industry in Indonesia is generally still in the form of assembly. This problem hampers the achievement of targets and implementation of domestic component-level policies that require private electricity developers to use local solar panels [16]. The solar panel industry is faced with conditions that require the use of local solar modules, but inconsistent regulations have caused slow development of solar power plants in Indonesia. The current production capacity of solar panels in Indonesia is not in line with the target installed capacity of solar power plants. The government needs to pay attention to the production capacity of the domestic industry. The domestic solar panel industry can be advanced by implementing domestic component levels [17]. These studies underline the importance of installed capacity as a measure of technical capability in energy generation, in line with the increasing emphasis on developing sustainable and technologically advanced energy infrastructure [18].

While government roadmaps and policies like the Domestic Component Level (TKDN) exist, a significant gap persists between targets and reality. The domestic solar module industry struggles with competitiveness, inconsistent regulations , and an underdeveloped upstream sector. International studies confirm that technological capability is a critical determinant for the successful deployment of renewable energy [19, 21]. However, while technometric models have been applied globally to assess PV industries [20], a specific, component-based diagnostic of Indonesia’s PV sector readiness is lacking. It remains unclear which technological components (Technoware, Humanware, or Infoware) are lagging and where strategic intervention is most needed. This lack of granular data hinders targeted policymaking and industrial upgrading efforts.

Therefore, this study aims to: (1) map the technological readiness of Indonesia's solar panel industry and its key supporting sectors (cables and mounting) using the Technometric (THI) framework; (2) analyze the specific contributions of Technoware, Humanware, and Infoware components; and (3) formulate targeted strategies to accelerate technology adoption and sustainable growth. To achieve these goals, this study will conduct a comprehensive evaluation of raw material procurement, manufacturing processes, and system installation. In addition, an in-depth analysis will be conducted on the impact of current government policies on the growth of the solar panel industry. By conducting this research, it is expected to provide a significant contribution to the development of the solar panel industry in Indonesia, support the achievement of national renewable energy targets, and create a cleaner, more sustainable, and more affordable energy future for all Indonesian people.

2. Method

This research methodology is designed to measure and analyze the level of technological readiness in the solar panel industry and its supporting companies in Indonesia, with a focus on the technoware, humanware, and infoware components that are crucial in the production and installation process of photovoltaic systems [22]. This study adopts a quantitative approach with a survey method as the main instrument in data collection, allowing for in-depth analysis of the perceptions and evaluations of various stakeholders in the related industry. The research objects include companies engaged in the production of solar panels, as well as supporting companies that provide vital components such as cables and mounting structures. The selection of research objects is based on the principles of accessibility and purposive sampling, considering the limitations faced during the pandemic, which limit the number of companies that can be accessed and are willing to participate in the survey [23]. Thus, the research sample was focused on three key companies (n=3) that actively responded and provided material support in solar panel installation: one solar panel manufacturer, one cable supplier, and one mounting structure producer. A purposive sampling strategy was used to identify firms that actively responded to outreach and participated in solar installations. In total, three companies participated in the survey (covering PV panels, cables, and mounting), reflecting the accessible industry sample. While the pandemic limited the sample size, these companies were selected via purposive sampling as representative players in their respective tiers of the PV ecosystem.

In data collection, this study used two main types of questionnaires designed to measure different aspects of a company's technological readiness. The first questionnaire focused on the level of sophistication of the technoware, humanware, and infoware components, using a scale developed by Marlyana et al., which allows determining the lower and upper limits of the level of sophistication that a company has in each technological component [24]. This questionnaire aims to quantitatively measure the extent to which companies have adopted and integrated advanced technologies into their operations, and how human and information resources support the use of these technologies. The second questionnaire measures the state of the art based on a framework that includes weighting of various technology components. This questionnaire is designed to evaluate companies based on assessment criteria relevant to the state-of-the-art conditions of the industry, allowing for the identification of gaps and opportunities for technological improvement. Experts in the solar industry reviewed the questionnaires for face validity, and pilot testing confirmed reliability (Cronbach's $\alpha > 0.70$ for all scales).

The assessment of technology weighting involves two main steps. First, the contribution of each technology component is determined based on the level of sophistication and sophistication of the prevailing technology. Second, the intensity of this contribution is assessed through a questionnaire distributed to business owners, where they are asked to rate the level of importance of each component. The calculation of this intensity uses the pairwise comparison method. By using the values of T, H, I, and β, the Technology Contribution Coefficient (TCC) can be calculated. The TCC value cannot be zero; this means that there is always a contribution from all technology components in every transformation process. The highest TCC value is one. Ultimately, a company's TCC measures how much technology contributes to the output generated from its entire transformation operations. The TCC ranges from 0 to 1, with higher values indicating greater technological contribution to production (0.7–0.9 = "excellent"). Survey data were entered and analyzed using Microsoft Excel for descriptive and inferential statistics. TCC computed based on industry-standard technometric formulas. Specifically, Equation (1) calculates each firm's TCC from T, H, I, and their weights:

$$TCC_{THI} = T^{\beta T} \times H^{\beta H} \times I^{\beta I} \quad \text{......} \quad 1$$

with:

TCC= the numerical value of the level of sophistication of the four components of a normalized production facility relative to the state-of-the-art

β = weight of relative importance level or intensity of contribution of technology components; (∑=1)

The analysis followed established technometric procedures: calculating each component's contribution gap relative to state-of-the-art, applying pairwise comparison to derive β weights, then computing the weighted product in (1).

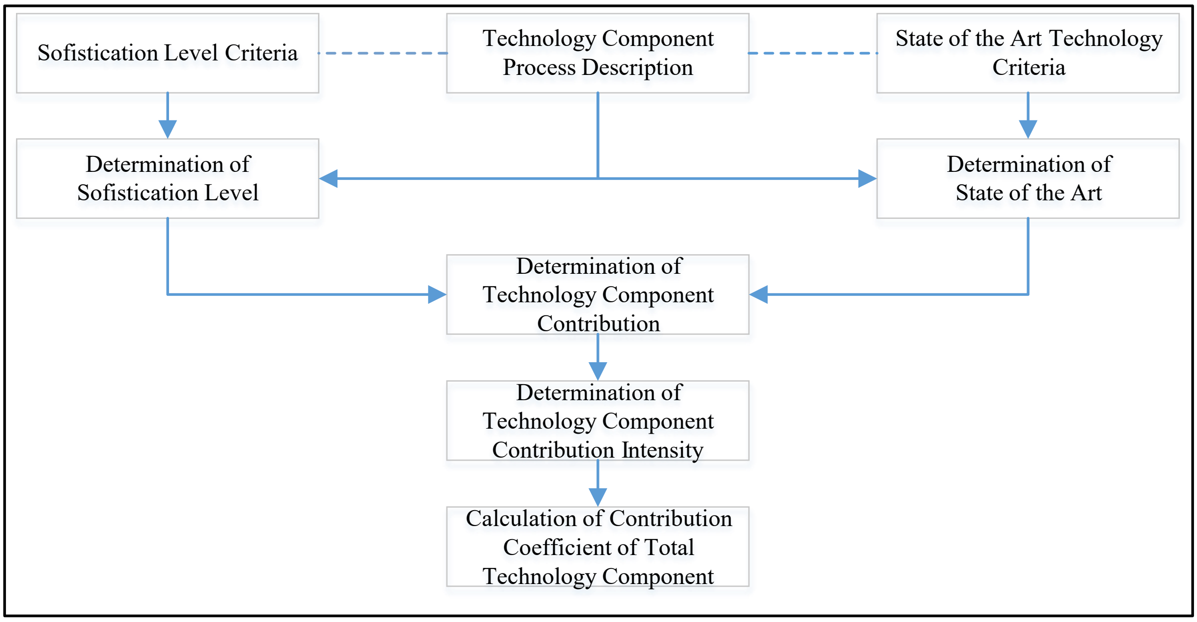

Figure 2. Stages of Assessing the Contribution of Technology Components

This research stage involves a series of systematic steps designed to ensure the validity and reliability of the research results. The initial stage involves identifying the problem, which focuses on the unmapped manufacturing capabilities of the solar panel industry and its supporters in the photovoltaic system. After the data is collected through questionnaires and observations, the next step is to process and analyze the data. Pairwise comparisons were calculated using Microsoft Excel to determine component intensities (β). The questionnaires , based on the established framework by Marlyana et al., were pilot-tested with an industry expert to ensure content validity and clarity of the items, addressing instrument reliability.

This analysis includes descriptive statistical calculations to describe the characteristics of the sample and research variables, as well as inferential analysis to test the relationship between relevant variables, such as the relationship between the level of technological sophistication and the level of sophistication of the company. Interpretation of the results of the analysis is carried out by referring to the relevant theoretical framework and previous empirical studies, to provide an in-depth understanding of the state of technological readiness of the solar panel industry in Indonesia. Thus, this research methodology is designed to make a significant contribution to understanding and improving the competitiveness of the Indonesian solar panel industry through the development and adoption of appropriate technology. Results were interpreted against theoretical benchmarks and prior studies to gauge each sector's readiness.

3. Result and Discussion

Photovoltaic technology has emerged as a viable alternative to meet the increasing energy needs in the Industry 5.0 era [25]. Photovoltaic systems generally consist of four upstream-downstream tiers including the solar panel industry. Solar panels combined with other electrical and mechanical hardware that uses energy from solar radiation to generate electricity are called photovoltaic (PV) systems. Photovoltaic (PV) systems in the scope of solar power plants are composed of materials called Balance of System (BOS). The BOS consists of solar panels, inverters, charger controllers, battery modules, cables, and structures (mounting) can be seen in Figure 3. Figure 3 below illustrates typical PV components (solar panel and overall system).

a.

b.

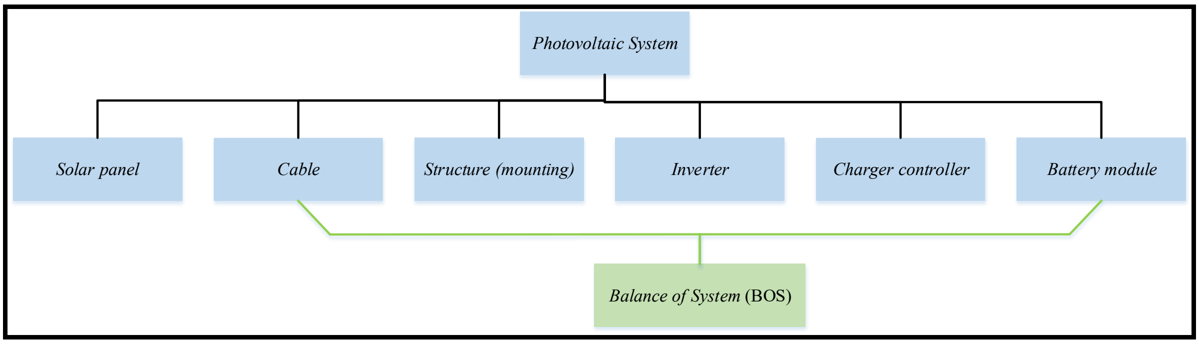

Figure 3.(a) Solar Panel; (b) Photovoltaic System

Technology assessment in the solar power generation industry involves several aspects. This includes evaluating the level of sophistication and modernity of technology, calculating the contribution of each component, and determining the technology contribution coefficient after weighting. The results of this assessment recapitulation will then be presented.

3.1. Sophistication and Modernity Level of Technology Components

The results of the company's sophistication level assessment include components T, H, I. Each assessment consists of upper and lower limit values. With the upper and lower limit values, the position of the technology component is determined based on its state-of-the-art condition. State-of-the-art components will be at the upper limit. Meanwhile, to determine the position of components that are not yet state-of-the-art, a comprehensive technical analysis is needed that involves comparison not only with the facilities being studied, but also with the best transformation facilities.

Table 1. Assessment of the Company Sophistication and Modernity's Level

Component	Mark	Solar Panel	Cable	Structure (*Mounting*)
	L	3	4	2
T	U	7	7	7
	SOTA	0,7904	0,1	0,8166
	L	4	4	2
H	U	8	7	7
	SOTA	0,7692	0,9230	0,8846

Component	Mark	Solar Panel	Cable	Structure (*Mounting*)
	L	4	4	4
I	U	8	6	7
	SOTA	0,76	0,26	0,9

with:
L = Lower Limit Value; U = Upper Limit Value; SOTA = State of the Art

3.2. Contribution, Contribution Intensity, and Technology Contribution Coefficient (TCC)

The contribution of each component is calculated by considering the degree of sophistication and state-of-the-art assessment of technology. The weighting of the intensity of the contribution of technology components is carried out to determine the relative importance of each technology component, namely technoware, humanware, and infoware. A special scale is used to measure this importance, and the calculation is carried out through the pairwise comparison method. TCC shows the scale of technology contribution in creating added value in the industry, with a value between 0 and 1. From this TCC value, we can assess the level of technology of a company. Meanwhile, THI is a normalized numeric value to describe the sophistication of the three components of production facilities.

Table 2. Component Contribution and Technology Contribution Coefficient (TCC)

Component	Mark	Solar Panel	Cable	Structure (*Mounting*)
T	Contribution	0,6846	0,4777	0,6759
	Contribution Intensity	0,623	0,333	0,118
H	Contribution	0,7863	0,7521	0,7136
	Contribution Intensity	0,137	0,333	0,201
I	Contribution	0,7822	0,5022	0,7444
	Contribution Intensity	0,239	0,333	0,681
TCC		0,7204	0,5651	0,7297

3.3. Photovoltaic Industry Capability Mapping

The evaluation results of the contribution of each technology component in a company are visualized using a radar chart. This chart is used to compare the value of the technology contribution coefficient of each component. The radar chart representation of the photovoltaic industry capability in Indonesia is in Figure 4.

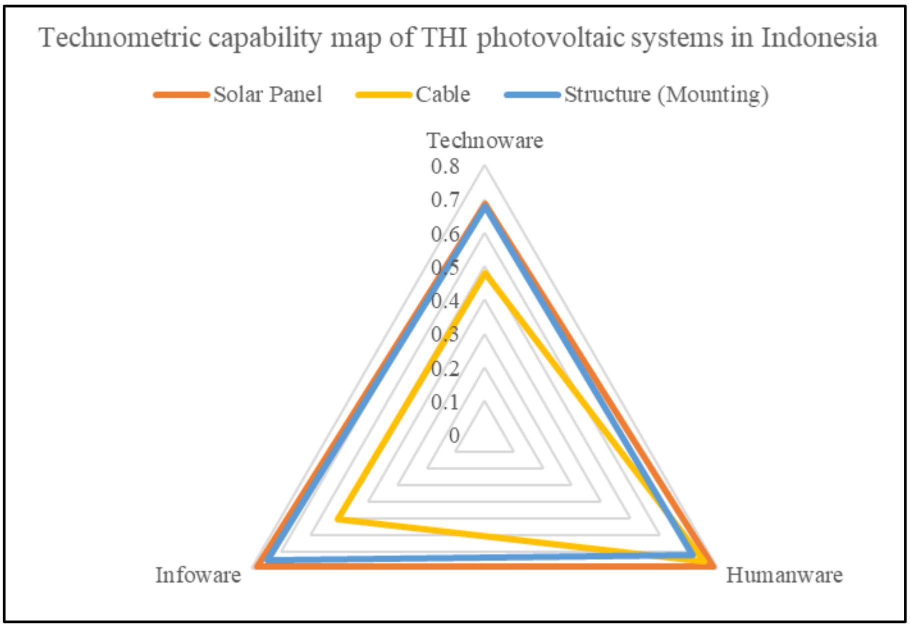

Figure 4. Map of T, H, I Technometric Capabilities of Photovoltaic Systems in Indonesia.

Technological readiness refers to the adaptability of a company or industrial cluster in integrating available technology. The goal is to increase productivity through the use of technology in daily operations and production processes, so that better efficiency is achieved and opportunities for innovation are opened to increase competitiveness. Meanwhile, the level of technology describes the extent to which technological capabilities have been mastered by a company or industrial cluster. Based on the TCC value obtained, it can be described in Table 3.

Table 3. Overview of the Meaning of the TCC Value

Classification	Solar Panel	Cable	Structure (*Mounting*)
Technology Readiness	Very Good	Good	Very Good
Technology Level	Modern	Semi Modern	Modern

Figure 4 presents a radar chart of the computed TCC values for each sector. The survey found a TCC of 0.7204 for solar panel manufacturers, placing them in the “very good” to “excellent” category. This is driven by strong Humanware (education/training, R&D staff) and Infoware (knowledge systems) contributions (each >70%). In practical terms, panel firms have well-trained workforces and good information resources. Technoware (physical tech like equipment) contributed the remaining share, also at a relatively high level. Cable companies showed a TCC of 0.5651, categorized as “good” technology content. Critically, their Technoware contribution was only 47%, highlighting that advanced equipment or in-house technology is comparatively weaker (e.g., cable production still relies on basic machinery). Humanware and Infoware were stronger (>65% each), but overall the lower TCC signals that cables lag behind panel makers. The structure (mounting) sector scored a TCC of 0.7297 (“very good”), with high Humanware/Infoware contributions (>70%). This suggests that mounting manufacturers, often smaller firms, nonetheless maintain good organizational practices and information support, though their Technoware is modest.

These industry-specific results deepen understanding beyond raw figures. For context, other technometric studies in Indonesia have found similar “good” performance for infrastructure sectors. For example, Utomo et al. (2025) reported a TCC of 0.522 (“good”) for the national tsunami warning system [26]. By comparison, our PV panel TCC (0.72) is substantially higher, indicating the panel firms are relatively more advanced. Conversely, the cable sector’s 0.565 is closer to Utomo’s example, confirming it is less advanced. On a global scale, leading PV manufacturing countries (e.g. China, Germany) typically achieve TCCs in the upper “excellent” range (0.8–0.9) through heavy technoware investment (state-of-art machinery and automation). Indonesia’s panel industry approaching 0.72 is promising but suggests room for growth to match international benchmarks. Our findings align with analyses noting that Indonesia has yet to fully attract foreign technology into PV manufacturing [27]. In comparison, neighboring Malaysia and Thailand have integrated more global expertise, achieving higher technology readiness in solar production.

The discussion of these findings reveals critical insights. The solar panel and mounting companies' 'Very Good' status (TCC > 0.72) is driven by high Humanware and Infoware, suggesting strong procedural knowledge and skilled personnel. This aligns with the assembly-focused nature of the industry noted in previous reports. However, the 'Good' status of the cable company (TCC = 0.5651) and its particularly low Technoware contribution (47%) is a significant bottleneck. This low Technoware score suggests outdated machinery, low automation, or a lack of advanced testing equipment, which directly impacts the quality and cost-competitiveness of vital supporting components. This finding is critical because policy often focuses on the main panel , while neglecting the technological gaps in the wider BOS supply chain.

Compared to global benchmarks, where leading PV industries show TCCs approaching 0.90, driven by heavy R&D (Technoware) [20], Indonesia’s reliance on Humanware and Infoware is a vulnerability. It indicates a capability in using technology, but not creating it. This reinforces the challenge of moving from an assembly-based industry to a true manufacturing hub, a challenge exacerbated by local content (TKDN) policies that may not align with current industrial capabilities [28]. The novelty of this study lies in its quantitative, component-level identification of this specific imbalance (T-H-I) within the Indonesian context, providing a more nuanced diagnostic than general policy reports.

3.4. Strategy Recommendations Based on Technology Components

Based on the comparison of the contribution coefficient values of the technology components, it is necessary to make an effort to improve technology in the company. The interaction of existing technology, potential and market needs can support success in meeting the targets set by the government and at the same time prepare the domestic industry to meet market needs. It is hoped that this domestic industry can continue to increase its role in supporting infrastructure development in Indonesia. For this reason, a recommendation was prepared as shown in Table 4 which consists of technology components, recommendation objectives and activities to achieve recommendation objectives for the solar panel industry and supporters.

Table 4. Recommendations for Industrial Capability Policies for Solar Panels and Supporting Facilities Based on Technological Components

Technology Components	Purpose of Recommendation	Recommended Activities
Technoware	Development of production facilities	a. Computerization of product design. b. Optimizing the use of measuring instruments and quality testing. c. Implementation of smart prototypes from the National Industrial Research and Standardization Center. d. Development of efficient power plant design and engineering technology, including mastery of IPR and technology risk management. e. Mastery of production technology through acquisition of advanced test and measurement equipment industry.
Humanware	Workforce skills enhancement	a. Product innovation training. b. Periodic employee performance evaluation. c. Adjusting job descriptions to employee capabilities. d. Machine/equipment maintenance training.
Infoware	Development of corporate information dissemination	a. Provision of up-to-date information on product development. b. Preparation of standard operating procedures (SOP). c. Participation in product exhibitions.

4. Conclusion

This study successfully maps the technological capabilities of the solar panel industry and photovoltaic system support in Indonesia using the Technometric model, revealing significant contributions from technoware (T), humanware (H), and infoware (I) to the Technology Contribution Coefficient (TCC) of each sector. In particular, the solar panel industry shows very good capabilities with a TCC of 0.7204, supported by dominant contributions from humanware and infoware (78%). Meanwhile, cable companies, with a TCC of 0.5651, have good technological content, although the contribution of technoware (47%). Structure companies (mounting) are also classified as very good with a TCC of 0.7297, with contributions from humanware and infoware above 70%.

Based on these findings, it is recommended that companies involved in the photovoltaic ecosystem in Indonesia always be ready to adapt to rapid technological changes, and make increasing technological capabilities a priority program. Specifically, it is recommended to prioritize the development of technoware through product design computation programs and test equipment optimization, improve humanware through innovation training and periodic performance evaluation, and strengthen infoware by providing comprehensive product information and active participation in industry exhibitions, in order to achieve best practices and strengthen overall competitiveness.

In achieving its objective to map technological readiness, this study confirmed the TCC values for three key sectors and identified Technoware as the primary weakness, particularly in the cable industry. However, this study is subject to limitations. The sample size (n=3) was constrained by the pandemic and, while representative, cannot be generalized to the entire national industry. The assessment relies on self-reported data from company management, which may be subject to bias. Future research should expand the sample size to include a wider range of companies, including inverter and battery producers, to create a complete BOS capability map. Further studies could also employ longitudinal analysis to track TCC changes over time in response to policy interventions like the TKDN.

Building on our findings, subsequent research could apply the technometric model to related areas, such as offshore renewable installations or rural solar programs, to benchmark their technology readiness. Incorporating the Orgaware or cyber components of technology (beyond THI) would yield a more holistic view. Experimenting with alternative analysis tools (e.g. analytic hierarchy process in weighting) or mapping supply-chain linkages could also enhance insights. Importantly, repeating this study periodically would allow monitoring of progress as policies (like the new 2026 Solar Roadmap) take effect.

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