Energy

AIMS Energy, 11(3): 540–554.
DOI: 10.3934/energy.2023028
Received: 18 October 2022
Revised: 06 April 2023
Accepted: 19 April 2023
Published: 09 June 2023

http://www.aimspress.com/journal/energy

Research article

Offshore floating photovoltaic system energy returns assessment—A life cycle energy analysis-based perspective

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Abstract: Researchers have long regarded photovoltaics (PV) as a poor energy return (ER) compared to fossil fuels. Although the latter's energy-return-on-investment (EROI), like oil, coal, and gas, are above 25:1 at the primary, they are about 6:1 at the final stage. Following the technology creation, it is essential to investigate whether the solar module technology innovation affects the ER. Much literature delivers the ERs of fossil fuels and PV. However, it does not address the life cycle analysis or life cycle energy analysis (LCEA) assessments. This paper, employing time-series and LCEA analyses, performs an ER evaluation of the 181-MWp global most extensive offshore floating PV (OFPV) in a 30-year life cycle at Changhua Coastal Industrial Park, Taiwan. The results show that the energy payback time (EPBT) is about one year. The EROI is about 29.8, which is superior or complies with the upper limits of previous studies under the same insolation. The approach proposed in this study should help future PV stations' ER analysis and clarify whether the innovation benefits from improving the system's performance. The results also assist in investors' decision-making regarding deploying PV projects in the future.

Keywords: energy return; energy return on investment; life cycle analysis; life cycle energy analysis; offshore floating photovoltaics; energy payback time

1. Introduction

Fossil fuels like oil, coal, and gas will remain the primary energy source until at least 2050. The research indicates they are 5:1 at the primary energy stage [1]. Requiring more embedded energy increases costs and decreases fuel energy-return-on-investment (EROI) ratios. Instead, they should assess the final stage, like exporting power to electricity and petrol.

In 2022, the above fuels were in short supply. Countries, especially European countries, refocus on the energy supply security, necessity, and urgency of clean energy transition policies. However, the epidemic and the Russian-Ukrainian War have increased metal prices and led to the surge of photovoltaic (PV) system costs. It is complex for the country to solve security, affordability, and energy sustainability simultaneously. Thus, it is growing to be an eminent concern, under the premise of the lack of breakthroughs in existing energy technologies, in terms of the energy return (ER) of PV technologies, as declared by much recent research on this topic. Unlike other renewable energy sources, PV technology provides some distinct advantages. It has a long system lifespan and low maintenance expenses. Moreover, it does not require moving and has low initial investment costs [2]. Installing offshore floating PV (OFPV) is feasible after demonstrating convincing successes on onshore water territories in the past few years. When launching the business, it is essential to understand PV deployments' ER since it relates to investment profit.

The energy payback time (EPBT) and EROI are the two most common metrics for ER [2]. The EPBT indicates the crucial period in which a PV system can produce energy equivalent to what it makes. It means a period PV system must manipulate to regain the invested energy throughout its lifetime [3]. EROI refers to the ratio of the energy delivered from a particular energy source to the power consumed to create that output [4]. If the source's EROI is less than or equal to one, it is an "energy sink" and is not a sustainable fountain. To be regarded as viable energy, the EROI ratio between the energy delivered and the energy required to deliver that energy must be not lower than 3:1 [5]. Weißbach et al. compared the EROI of various typical energies according to their efficiency on a consistent mathematical and physical basis with a strict exergy concept. The results indicate that nuclear, hydro, coal, and natural gas power systems are more effective than PV and wind power [6]. Bhandari et al. [2] conducted a systematic review and meta-analysis of the embedded energy, EPBT, and EROI indicators for the crystalline Si and thin-film PV technologies published from 2000 to 2013. They collected 232 references; 11 and 23 were selected for EPBT/EROI and embedded energy analysis, respectively. They also harmonized several parameters to the following values: performance ratio (0.75), system lifetime (30 years), insolation (1700 kWh/m^2•year), module efficiency (Mono-Si: 13.0%; poly-Si: 12.3%; aSi: 6.3%; CdTe: 10.9%; CuInGaSe: 11.5%). The results show that the mean harmonized EPBT varied from 1.0 to 4.1 years. The module types were ranked in the following order from lowest to highest: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), amorphous silicon (a: Si), poly-crystalline silicon (poly-Si), and monocrystalline silicon (mono-Si). The mean harmonized EROI varied from 8.7 to 34.2.

Fukurozaki et al. analyzed the energy requirements for solar module production and system component balance to evaluate Brazil's EPBT and CO_2 emissions of a 1.2 kWp PV rooftop system. Using the life cycle assessment (LCA) methodology, they investigated the monocrystalline unit and considered mass and energy flow over the manufacturing process. Moreover, they calculated the assumed seven different national geographic conditions, cumulative energy demand, energy yield, EPBT, and CO_2 emissions rates from metallurgical silicon growth to power generation. The authors found that the EPBT was 2.47–3.13 years, and the CO_2 emissions rate was 14.54–18.68 gCO_2-eq/kWh for current rooftop mountings [7]. Alsema et al. reviewed and compared many energy analysis studies for thin-film solar cell modules. They began with a short introduction to methodological issues related to PV system energy analysis. Subsequently, they achieved findings from six studies on a-Si modules and three on CdTe modules to present a unified format comparing and clarifying them to observe differences. They found many significant discrepancies, which the choice of materials could explain for the module encapsulation. Moreover, they performed additional analyses to understand these gains better for classifying the significant observed divergences. They delivered the best assessments of the energy required for the primary energy of present-day a-Si and CdTe thin-film modules, which are between 600 and 1500 MJ per m^2 module area, depending on cell and encapsulation type. The EPBT was below two years for a grid-connected module under 1700 kWh/(m^2•year) irradiation. An EPBT below one year seems feasible [8]. Several investigators performed an LCA to identify the greenhouse gas (GHG) footprint, EPBT, and cumulative energy demand of four silicon heterojunction (SHJ) cell designs. They analyzed the environmental impacts for cell processing and entire systems for present and future designs based on in-plane irradiation of 1700 kWh/m^2•year. Current designs show that life-cycle GHG emissions could be 32 gCO_2-eq/kWh for complete SHJ PV systems (module efficiencies of 18.4%), compared with 38 gCO_2-eq/kWh for conventional monocrystalline silicon systems (module efficiency of 16.1%). The EPBT of all SHJ designs is 1.5 years, compared with 1.8 years for the monocrystalline PV system. Increasing cell efficiency, using thin silicon wafers, and replacing silver-based with copper-based metallization could decrease lifetime GHG emissions for systems to 20 gCO_2-eq/kWh for SHJ systems and 25 gCO_2-eq/kWh for the monocrystalline system. In addition, EPBT could drop to 0.9 and 1.2 years, respectively [9].

As an alternative, PV technologies with a lifetime range of 25–40 years are increasing yearly. Kamal et al. proposed a model to assist in reviewing and discussing articles on material compositions, manufacturing, and dismantling processes. In addition, they focus on the goals, critical constraints, and practical strategies of sustainability's environmental, economic, and social pillars within the PV industry and business stages, introducing the possible contributions of industry 4.0 technologies. Consequently, they proposed a research roadmap to help all future studies optimize PV's overall sustainability [10]. Murphy and Hall (2010) [4] reviewed recent empirical findings on five topics, like the EROI for most major fuel types, and provided an EROI history and how they analyze EROI. Ultimately, they listed some areas for improvement in EROI research. Jackson and Jackson developed a model (TranSim) to simulate the economic and financial implications of an energy technology transition involving a reduction in EROI to clarify whether reducing the EROI could result in rising energy prices and decreasing economic growth. They combined the stock-flow consistent approach with an input-output model. The results show an initial increase in output due to increased investment but a subsequent recession and below-trend growth due to higher prices and changes in the functional income distribution. In addition, the capital intensity of green energy production positively correlated with a decrease in EROI [11]. Grant et al. [12] performed an EPBT analysis of all 50 states in the United States of America to estimate changes. They compared how PV unit deployment would change when considering solar intensity to prioritize environmental returns due to discrepancies in the solar potential electricity blend and impact type. Daniela-Abigail et al. [13] examined the disposal of PV waste in the environmentally vulnerable areas of Yucatan, Mexico, from three dimensions: environment, economy, and society, and concluded that implementing sustainable PV waste regulations can shorten the PV system's EPBT. It can also significantly reduce 78% of the toxicity of waste and freshwater ecology and 2% of the levelized cost of electricity with PV recycling compared to those without PV recycling waste.

Some scholars developed a benefit-sharing model and the internal rate of return (IRR) as an investment evaluation metric to examine the primary stakeholders' benefits in waste PV module recycling. The findings show that the IRRs of the installer, waste disposal company, and PV module manufacturer were 7.36%, 4.21%, and 18.62%, respectively, indicating an uneven distribution among stakeholders. In addition, the government revenue from the tax was nearly USD one billion. Thus, the authors proposed three feasible benefit-sharing schemes to mitigate the price impact on the IRR to facilitate investments [14]. Wang et al. investigated and considered various feedstock options, including first-generation feedstock like corn, second-generation feedstock like corn straw and third-generation feedstock like algae, to quantify the trade-off of the EROI of typical biomass conversion systems in China. They unified and compared the system boundaries of previous biomass footprint calculations. The findings showed that the highest EROI (8.06–30.13) converts raw biomass feedstock to solid fuel. The next is biomass power (2.07–16.48), then biogas (1.30–11.05) and biodiesel (1.28–2.23) for the first generation. Among all the biomass conversion ways, for both straw, and wood residues, pyrolysis gasification had the highest EROI. The authors concluded that the eminence of energy efficiency promotion strengthens the economic feasibility of biomass energy business [15]. Zhou and Carbajales-Dale [16] assessed the efficiency and energy inputs based on previous PV system meta-analyses of the EROI under the system's high-cost and low-cost contexts by focusing on the existing wafer, thin-film, and organic technologies. The findings show that highly efficient, low-cost, thin-film technologies have not yet emerged. However, the thin-film process is the optimal ER advancement to date.

Much literature, including the reports by Gagnon et al. [17] and Hall et al. [18], mentions the ERs of fossil fuels and PV. Brockway et al. [1] emphasized that ERs must consider energy consumption in the final stage because many studies only measured these ratios at the primary energy phase [1]. However, they did not address the LCA or LCEA estimates. Thus, they tended to yield favorable results for EPBT and EROI calculations. Practically, conducting empirical research to attain renewable energy's actual ER is still essential. Unlike the previous research on solar energy's ER analysis, this study used time-series and LCEA-based ER estimation to assess the global most extensive OFPV in a 30-year life cycle at Changhua Coastal Industrial Park, Taiwan. It benefits energy consumption and returns under clear boundary conditions in each life-cycle stage. It also helps analyze whether the technology creation benefits from enhancing the system's capability. Moreover, the results serve investors' decision-making regarding funding future PV plans.

2. OFPV deployment

OFPV refers to installing solar modules on a structure floating in offshore waters [19]. The eminent function, occasions, and environment of the OFPV promote its growth [20]. It is increasingly vital and promoted by territories with scarce land but abundant water resources to satisfy a global low-carbon energy trend. To overcome the influence of climate and tide, in addition to the PV unit, OFPV requires a floating stage (usually plastic and galvanized steel or fully plastic units [21]), supporting construction, an anchoring structure, and an underwater cable (Figure 1) [22].

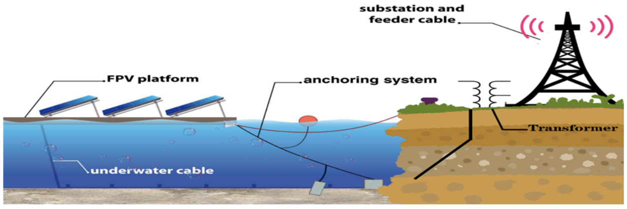

Figure 1. OFPV deployment [22].

The Bureau of Energy of Taiwan [23] announced the "Photovoltaic Two-year Promotion Plan" in 2016 to encourage industries to facilitate clean energy and boost the transition from traditional carbon-based energy to green energy. The OFPV deployment is achievable after the industry demonstrated convincing accomplishments on reservoirs and detention ponds over the past few years.

The 181-MWp OFPV at Changhua Coastal Industrial Park is the most extensive global FPV. It became the first successfully deployed offshore plan. Its cheerful success activates FPV development.

Sahu, Yadav, and Sudhakar (2016) [24] classified PV stations into ground-mounted, roof-top, canal-top, offshore, and floating. The canal-top and floating types commonly use abandoned mines, ponds, reservoirs, and lakes to deploy water-based PV systems (Figure 2). Choi [20] declared that the FPV power generation efficiency is 11% higher than standard ground-based PV because of alleviative module temperature. It enhances its power yield and helps CO_2 emission [25].

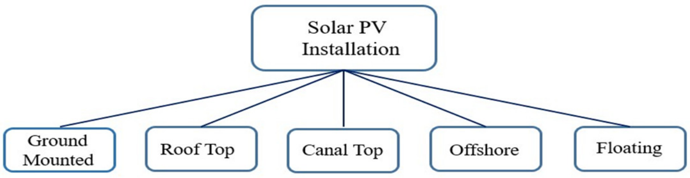

Figure 2. PV system type [24].

3. LCA (Life Cycle Analysis) and Life Cycle Energy Analysis (LCEA)

As described in part of the introductory section of ISO 14040, scientists define Life Cycle Analysis (LCA) as studying the impacts of the environment and potential throughout a design--to-decommissioning. Its research scope includes raw materials acquisition, manufacturing, application, and clearance. Investigators should consider the general environmental impacts on resource use, human health, and ecological consequences (Figure 3) [26].

Constructing an FPV system requires power during the life cycle of manufacturing, creation, and destruction. Considering full energy use over the life of an undertaking, LCA can lessen and determine strategies for energy use. It is an approach that assesses whether all stages (cradle to grave) of a project, product, or service will impact the environment. In the case of finished products, the environmental consequence evaluation is extracting and processing raw materials (cradle) through product manufacturing, distribution, and use, and then recycling or final disposal (grave) of used products [27].

Figure 3. LCA's conceptual illustration [26].

Klöpffer and Grahl [27] pointed out that the LCA assessment's scope includes the influence of material extraction, FPV system construction, and the entire power production. It also consists of system operation during the life cycle and processing measures after the service. Klöpffer [28] further describes that an LCA implementation process should include goals and scope, inventory analysis, impact assessment, and interpretation and follow the ISO 14040 and 14044 standards [24]. He performed a cradle-to-grave life cycle evaluation throughout the entire FPV system life cycle by ecologically and financially simulating and comparing conventional solar plants. Cromratie Clemons et al. [29] conducted an LCA with a 30-year 150 MWp FPV plant lifespan in Thailand. The research results show enormous impacts from approximately 73 kgs of GHG and 110 m^3 of water per MWh.

However, the above research directly links energy use with associated GHG emissions. Since the primary environmental burdens arise from energy consumption, applying the full-scale, multi-impact, conventional LCA is not rational. Therefore, a simplified derivative of LCA, the life cycle energy analysis (LCEA), can be a good alternative.

LCEA is according to the above original four-step LCA methodology, but it focuses on energy and concomitant carbon emissions as the only measure of environmental impacts [30]. Fay et al. claimed that LCEA could not replace conventional LCA [31]. Instead, it presents a more detailed energy analysis for those products and services whose energy consumption resulted from principal environmental impact [32].

As an extension and a common LCA that emphasizes the energy inputs assessment for different stages of the lifespan, the LCEA is a benchmark approach to evaluate the project's energy-saving and environmental benefits. It calculates the total energy required to produce a product. The comprehensive system boundary in the manufacturing process is from importing materials to module disposal after dismantling the system [33]. The Environmental Protection Agency's (EPA) National Risk Management Research Laboratory (NRMRL) further illustrated that as a technique to assess the ecological facets and latent impacts affiliated with a product, process, or service (Figure 4) [34].

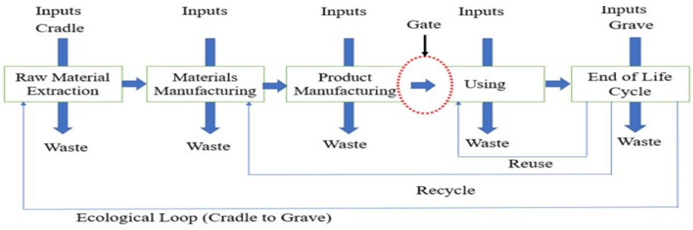

Figure 4. LCA's conceptual stage diagram [34].

4. ER analysis—A case study

4.1. Study area

The Changhua Coastal Industrial Park [35] is the largest industrial zone in the district. It is an outlying island-type industrial zone developed from the new land formed by reclamation and located in the northwest corner of Changhua County. It faces the western Taiwan Strait with multiple industrial productions, research, development, recreation, and sightseeing.

The investor utilized 176 hectares of the sea surface to install more than 570,000 solar modules (181 MWp) and built the world's most broad-scale offshore FPV station at the park (Figure 5). The investor utilized 176 hectares of the sea surface to install more than 570,000 solar modules (181 MWp) and built the world's most broad-scale OFPV station at the park (Figure 5). Unlike other countries' OFPVs, such as Singapore (5 MWp) and the Netherlands (8.5 kWp), the contractors primarily built them near the sea. It is in the intertidal zone, which floats on the water during high tide and on the ground at low tide. It benefits system large-scale construction and maintenance and will not affect shipping safety. The grid-connected system could supply about 41,000 households with electricity since February 2021 [35].

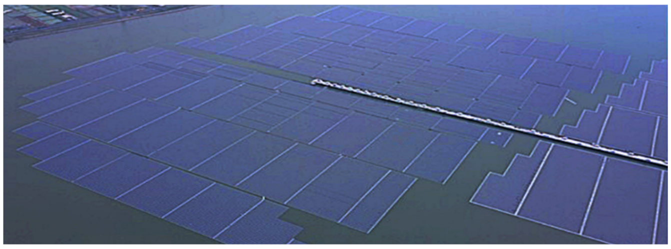

Figure 5. Changhua coastal industrial park's FPV [35].

4.2. Solar module fabrication process and specifications

The module's manufacturing process is as follows:

1. Cell string arrangement: Lay solar cells into cell strings with ribbons.
2. Welding: After laying the cell strings neatly, weld them after connecting them in parallel with the bus bar welding tape.
3. Lamination: Cross-link the encapsulation material by vacuum and high temperature, which can closely bond the glass and protect the cell.
4. Encapsulated aluminum frame: Protect the module frame and strengthen the prevention of moisture infiltration.
5. Mount the junction box: Export the electricity generated by the solar module through the junction box.
6. Classification: Rank the modules according to the power level.
7. Packing: Pack the modules to ensure shipment and transportation quality.

The TAIWAN Plus PV technical specification imposes that installers must use high-efficiency solar modules with a 25-year output warranty for projects recruited by the government in 2019. Figure 6 and Table 1 show the specification, which claims that the PV units comply with the National Standard of the Republic of China (CNS) 15114 and 15115 [36].

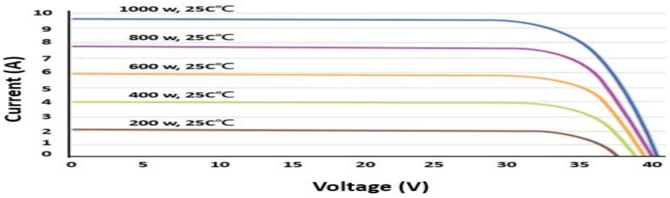

Figure 6. Current-Voltage (I-V Curve) [37].

Table 1. Electrical specifications [37].

P_{max}	>315 W_p
V_{max}	>33.55 V
I_{max}	>9.39 A
V_{oc} (Open Circuit Voltage)	>39.33 V
I_{sc} (Short Circuit Current)	>9.56 A
Efficiency (%)	>19.36
V_{sys} (Maximum System Voltage)	DC1000 V
Maximum Series Current	>15 A

Note: Test Condition: Standard Test Conditions (STC) with an irradiance of 1000 W/m² (AM1.5) and 25 °C [38].

4.3. Research design

This paper used time series and LCEA analyses to conduct the ER assessment of the target OFPV in a 30-year lifespan to examine its EPBT and EROI. The research steps involve the following:

(1) Data collection
(2) Time-series trend and auto-correlogram
(3) LCEA Analysis
(4) EPBT and EROI calculations

4.3.1. Data collection

In this step, the author extracted the recent 15 years of meteorological data, the technical specifications for high-efficiency solar modules [23], and primary standard activity and secondary ones of the organization.

4.3.2. Time-series trend and autocorrelation

Figure 7 shows the 180 monthly time series trend graph, compiled five thousand four hundred seventy-nine data on insolation, sunshine, hours, and radiation amount. Under the condition of significance level α = 5%, the trend sign value (T) performed by the Mann [39]-Kendall [40] trend test is 2, which is slightly more significant than 1.96. It indicates that the trend meets the null hypothesis. Consequently, we may determine that the time series tested steadily upward [41].

Unit: kWh

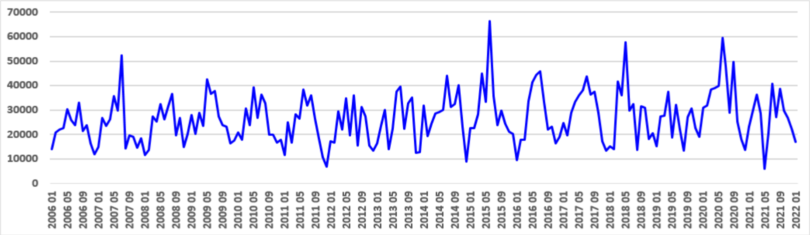

Figure 7. Monthly time series trend graph.

By shifting the data value and calculating the correlation between the original and the lagged values, researchers can plot an auto-correlogram graph to determine whether the data will converge. Figure 8 shows the autocorrelation for the 180-sample data shown in Figure 7. It demonstrates that the autocorrelation gradually converges and approaches zero after 130 lags by transforming and fitting the data. The results of the Mann-Kendall and the autocorrelation tests are consistent, demonstrating the correlation between the original and lagged data [42].

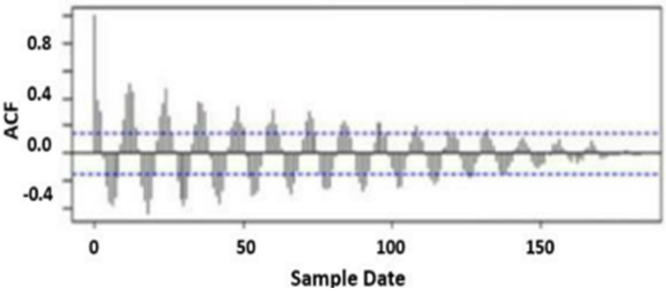

Figure 8. Auto-Correlogram.

4.3.3. LCEA analysis

Although power generation depends on management and climatic factors, including typhoons and earthquakes, the total energy produced is 5,435 GWh of electricity during the 30 years, based on Eq (1) [43].

$$P_p \equiv C_{ic}\ (\text{kWp}) \times G_{efh}\ (\text{h/day}) \times (1+\alpha \times 365.25\ (\text{day/year}) \times 30\ \text{years} \times S_e \times (1-D_r) \times (1-M_{dt}) \quad (1)$$

P_p: 30 years of power production
α: diode ideality factor (based on 11% [20].)
C_{ic}: the solar module installation capacity (kWp)
G_{efh}: practical daily electricity generation hours
S_e: system efficiency (based on 75%) [2]
D_r: decay rate of solar modules (decrease by about 1% annually in 30 years [44].)
M_{dt}: system downtime (Based on 5% [45])

The power consumption almost comes from the activities of product production and various departments, including areas and percentage of occupancy energy used by facilities, that is, the power consumption of production and air conditioning. Energy flow allocation and the materials' emissions follow PCR's computational procedures. The investigated results show that the production power of 12,345 pieces of modules is 2.5 GWh, and the air conditioning power consumption is 71.1 MWh (0.071 GWh), a total of about 2.6 GWh (Table 2) [46]. Consequently, we can attain that the power demand is about 119.7 GWh to produce 574,603 pieces of modules (181 MWp) according to the proportion. Together with the power consumption of the solar cell and its raw material, 62.2 GWh [9], it requires 181.9 GWh to produce 181 MWp solar modules.

In addition, the author assumes the system's operating efficiency to be 75% because he considers the power loss of inverters, transformers, and wiring. Consequently, the power loss will be about 1358.8 GWh during the 30-year operating lifespan.

Table 2. Solar module electricity consumption table [46].

Product Name	315 Wp/h Monocrystalline Silicon Solar
Module (Efficiency)	19.36%
Lifespan	30 years
Product Maximum Output Power(Wp/h)	Administration &Sales; Manufacturing
Product Dimension (mm)	1,640 x 992 x 35mm
Weight (kg)	18.5 ± 5%
Product Quantity(piece)	12,345
Item	Usage (MWh)
Process	2500
Air Conditioning	71.1

4.3.4. EPBT and EROI calculations

When evaluating the feasibility of a new PV project, investors should determine the project's EPBT and EROI.

EPBT is the time required for a power system to generate energy equivalent to its production [2]. Researchers usually utilize years as an EPBT unit. The shorter the payback period, the better energy recovery. Equation (2) [2] shows how to achieve Ppb.

$$P_{pb} = \frac{E_{im}}{Annual(E_{out} - E_{lc})} \tag{2}$$

$P_{\mathbf{pb}}$ represents the energy payback period, $E_{\mathbf{im}}$ to the energy required to provide that energy (embedded energy), $E_{\mathbf{out}}$ to the annual energy production, and $E_{\mathbf{lc}}$ to the energy consumed during the FPV life cycle.

By Eq (2), we can achieve the $P_{\mathbf{pb}}$ (including solar cell and cell raw material [9]) about 1.38 years (local insolation: 1278 kW/m^2•year), which complies with the upper limit of previous studies.

EROI is a practical investment assessment index in energy economics and ecological energetics. It expresses the ratio between net energy produced by the system (E_{out}-E_{lc}) during the lifecycle and the power required to provide that output ($E_{\mathbf{im}}$) [2]. Equation 3 [2] shows the balance between the available energy resources provided by a specific number of energy sources.

$$E_{\mathbf{roi}} = \frac{E_{out} - E_{\boldsymbol{lc}}}{E_{im}} \tag{3}$$

When EROI > 1, the total energy output is greater than the input energy, indicating that the energy is efficient. The higher the EROI value, the higher the efficiency of energy output. The difference between the total energy output and energy input energy must be more dominant than one since net energy is equivalent to EROI-1 [2]. By Eq (3) [2], EROI is about 22.4 (local insolation: 1278 kW/m^2•year), which is in line with the better result of the previous research.

Table 3 shows the study's results of EPBT and EROI. Figure 9 illustrates the comparison results between this study and Bhandari et al. (2015) under different photoelectric conversion efficiencies of monocrystalline modules.

Table 3. EPBT and EROI calculation results.

Product Name	Monocrystalline Silicon Solar Module	
P_{max} (Wp/h)	315	
Efficiency (%)	>19.36	
Item	EPBT	EROI
Insolation (kW/m^2.y)	about 1.38 years	
1278 (Local):	about one year	22.4
1700 (Benchmark):		29.8

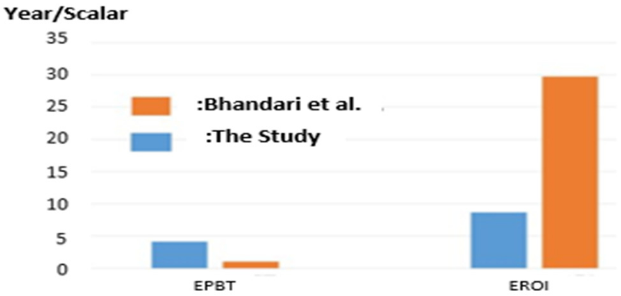

Figure 9. EPBT and EROI comparison.

The solar radiation of the case is 1278 kW/m^2•year, far less than the benchmark, 1700 kW/m^2•year sunshine conditions of Bhandari et al. (2015), Alsema and Frankl (1998) and Louwen et al. (2015), the study results recalculated and shown in Figure 9 are under the same conditions. Consequently, it reduces the EPBT from 1.38 to 1 year and increases the EROI from 22.4 to 29.8.

5. Discussion

With the continuous PV technical advancement, such as SHJ, Passivated Emitter and Rear Cells (PERC), high-efficiency N-type, and perovskite solar cells, the use of thin silicon wafers and replacement of silver-based with copper-based metallization, it is essential to re-investigate the PV system ER to provide stakeholders with decision-making.

As mentioned above, Brockway et al. [1] addressed that fossil fuels' EROIs are above 25:1 at the primary energy stage and around 6:1 at the final stage. It implies that the fuels' EROI may be much closer to those of renewable energies than previously expected. Bhandari et al. [2] concluded that the mean harmonized EPBT and EROI varied from 1.0 to 4.1 years and 8.7 to 34.2 for the various PV technologies. Weißbach et al. [6] indicated that nuclear, hydro, coal, and natural gas power systems are more effective than PV and wind. Fukurozaki et al. [8] found that the EPBT is 2.47–3.13 years for current rooftop mountings from metallurgical silicon growth to power generation.

The complete LCEA of a PV power generation project is highly complex. It must involve the primary energy requirements of the cell raw material and the system components' production, such as module aluminum frames, cables, inverters, and transformers. In addition, it is indispensable to consider the lifespan energy requirements of the transportation, installation, and disposal phase. Thus, whether the PV system's ER analysis can achieve sufficient reliability and validity depends on whether the boundary settings of the LCEA process are distinct and subsequent vertical integration. Indeed, there are many factors affect the research results, like project scale, system efficiencies including transformer and inverter efficiency, copper wire diameter and wiring length, solar module conversion efficiency, equipment installation location (radiation), onshore or offshore installation pattern, framework's lifespan, and weak-light effects.

Compared with fuels, the public has always believed that ER indicators of PV are inferior to fuel energies. However, under the PV technology creation, it is imperative to re-examine it for the parties concerned.

6. Conclusions

This paper has employed the time series and LCEA analyses to conduct a case study to explore the PV's ER indicators and investigate whether the PV technology creation involves energy recovery indicators by comparing previous studies, like Bhandari et al. [3]. They concluded that the EPBT is 4.1 years and the EROI is 8.7 under the condition that the efficiency of the monocrystal module is 13%. They are inferior to this study's EPBT (about one year) and EROI (about 29.8).

The researcher concludes that LCEA's boundary setting and PV technology innovation significantly impact EPBT and EROI. Regarding OFPV deployment, when defining LCEA boundaries more specifically, researchers will discover that PV's ER is not inferior to fuel energies. It echoes the conclusions of Brockway et al., Bhandari et al., and Alsema et al.

Due to the LCEA's scope of the study, the author does not consider the system's transport and final disposal stage. Nevertheless, the energy depletion in the delivery and removal stage seems insignificant (less than 1% of the LCEA cut-off rule) compared to the system's life cycle. Indeed, as the solar cell's fabrication is in the manufacturer's overseas factory, the survey range is limited to modules. However, to present the LCEA consequences more accurately, the investigator added previous findings in the study [9]. In his future work, he intends to implement the ER investigation of the whole production chain in vertical segments.

The researcher also suggests enhancing the research to strengthen the integrity of LCEA assessments to increase the validity of PV's ER. The approach presented in this paper may benefit the related studies of the ER more practically and help investors' decision-making for future funding in OFPV or other PV schemes.

Use of AI tools declaration

The author declares he has not used Artificial Intelligent (AI) tools in the creation of this article.

Conflict of interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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