國立臺灣大學工學院土木工程系

博士論文

Graduate Institute of Civil Engineering

College of Engineering

National Taiwan University

Doctoral Dissertation

浮力式光伏電源可靠性和能量回饋的整合分析方法

A Holistic Analysis Approach for Power Reliabilityand Energy Return of Floating Photovoltaic Deployment

陳 慶 豐

Ching-Feng Chen

指導教授: 游景雲教授

Advisor: Gene Jiing-Yun You, Ph.D.

中華民國 113 年 1 月

January 2024

doi:10.6342/NTU202400056

國立臺灣大學博士學位論文
口試委員會審定書

國立臺灣大學博士學位論文

口試委員會審定書

浮力式光伏電源可靠性和能量回饋的整合分析方法

A Hollistic Analysis Approach for Power Reliability and Energy Return of Floating Photovoltaic Deployment

本論文係陳慶豐君（學號：D08521038）在國立臺灣大學工學院土木工程系完成之博士學位論文，於民國113年1月 24 日承下列考試委員審查通過及口試及格，特此證明。

口試委員：

（簽名）

（指導教授）

系主任、所長 （簽名）

國立臺灣大學圖書館 National Taiwan University Library

doi:10.6342/NTU202400056

誌 謝

本人在所就讀期間，承蒙游景雲指導教授於學業方面的指導，特別是在論文寫作期間的悉心指正與勉勵，才能如期地完成論文。也感謝指導暨口試委員們能在百忙之中撥冗對論文的方向及研究內容惠予指點令論文的內容更為完善。在此，也要感謝我在臺灣大學的授課教授們對我熱心地解惑，引導我進入學術的殿堂。最後感謝我家人的支持，若沒有他們的支持，本人也無法順利地完成學業。

陳慶豐 謹誌於臺灣大學 113 年 1 月

doi:10.6342/NTU202400056

摘 要

隨著傳統火力發電排放溫室氣體（GHG）對環境的嚴重影響，近年來發展可再生能源引起了全球的關注。太陽能是最廣泛使用的可持續能源之一。與其他綠色能源替代方案相比，它具有豐富、可用性、可擴展性、多功能性、環境影響小以及低運營成本等明顯優勢。然而，它也存在一些限制，包括間歇性、低能量密度和土地限制。

為了應對太陽能發電的缺點，台灣能源局於 2016 年 9 月 8 日推出了“兩年太陽能發展計劃”，以推動太陽能產業的發展，特別是浮力式光伏（FPV）系統。可再生能源系統電力供應的可靠性、其能量回饋（ER）以及其經濟影響之間的相互關係對於理解可持續能源解決方案至關重要。

強大而可靠的電源供應提高了可再生能源系統的吸引力，而良好的 ER 可確保其可持續性。經濟考量，包括初始投資成本、運營費用和比較經濟分析等因素，則會進一步地影響到決策過程及可再生能源技術的廣泛應用。這種複雜的相互作用突出了需要以一種綜合方法，整合其可靠性、ER 和經濟評估，據以推動對可持續能源解決方案的理解和實施。

雖然先前的研究已成功地發展了光伏（PV）系統效率、可靠性和安全性的模型分析。然而，它卻尚未引入一種更簡潔的指標來評估 FPV 電站的電源供應可靠性。此外，儘管現有的文獻已廣泛地討論了 FPV 的環境影響、生產所耗用的能源和系統安裝，但進一步地探索 FPV 電源供應的可靠性顯有必要。因它除可以擴大該領域的知識基礎外並可幫助投資者做出有利的決策。

以 Agongdian Reservoir FPV 電站的成功的商業運營模式作為案例研究（案例研究 1），由於與天氣條件、設備故障、老化和太陽能系統中固有的電網併網相關問題的不確定性，評估其電源供應的可靠性顯得十分重要。在這項研究中，作者結合了統計和超越機率的分析方法，以 Agongdian Reservoir FPV 作為案例研究，探討了 FPV 的可靠性分析。結果表明，本研究所採用的方法可以提供當地的電力局

doi:10.6342/NTU202400056

電源供應的平衡指標。它有助於負載分配措施的實施或增加每日系統的發電量以提高 PV 系統的可靠性。

太陽能長期以來一直被認為它的 ER 比傳統化石燃料低。儘管後者在初級階段的能源投資回報率（EROI）超過 25:1，但在最終階段會降至約 6:1（Brockway 等人，2019）。鑑於多年來太陽能技術的創新，調查它的 ER 是否因技術的創新而增長變得越來越重要。因為這項研究對於電力公司和決定投資 FPV 項目的投資者而言，是一項重要的考量因素。此外，考慮地理位置和陽光條件等因素，評估 ER 變得不可或缺，特別是對於國際投資者而言。

在陸地 FPV 系統（如 Agongdian 水庫）成功運營之後，台灣彰化工業區的一項容量為 181MWp 的世界上最大的離岸 FPV（OFPV）項目於 2021 年 11 月完成並投入使用。在本論文中提出的另一個案例研究（案例研究 2）中，作者從生命周期能量分析（LCEA）的角度分析了該 OFPV 項目的能量回饋。結果表明，本 OFPV 項目的實施可以在 30 年的生命周期內減少約 2079.7 百萬噸二氧化碳排放，EPBT 為 0.97 年，EROI 在 1700 kWh/m²•year 光強條件下約為 31。這些數值超過或接近先前研究的上限。

最終的案例研究（案例研究 3）整合了經濟比較分析的方法。它分析了台灣 Agongdian 和日本 Yamaura 水庫 FPV 具有相同系統安裝容量的投資方案。研究結果顯示，國際投資人投資日本更為有利，因為它的淨現值（NPV）在 5%折現率下達到 7269.8。內部收益率（IRR）和成本效益比（BCR）分別為 10.1%和 1.71，回本點約為 48.5%。我們可以確定兩地不同的電費價格是影響 FPV 投資盈利的關鍵因素。

另一方面、涵蓋十五年的有限樣本數據表明，更廣泛的時間尺度取樣可以提高調查的效果。未來的研究應該著眼於研究 FPV 系統在水體上的最佳安裝比例，考量水質和經濟最大化等變數。此外，晴天和多雲天氣間太陽能發電的波動強化了天氣因素在確定太陽能是否可作為可再生能源的可靠性和一致性方面的重要性。研

doi:10.6342/NTU202400056

究人員和利益相關者有必要經常分析這些變化以提高太陽能系統在不同天氣條件下的可預測性和效率，這是同儕們未來研究時應留意的問題。

全面的 LCEA 可確保吾人全面性地瞭解產品的可持續性。它有助於決策者更明智地決策，以改進生產過程或尋找替代方案。案例研究 2 受制於製造商所生產的產品種類單一性，在作者進行調查時難以垂直整合產品上下游的所有的生產階段。此外，該研究的範圍也未包括系統的運輸和最終的拆除處理階段。作者在此指出，這些階段的能耗，雖然並未超過本研究中所設定的 LCEA 的 1%截止規則，但如能改進，將有利於提高 PV ER 評估的準確性，因為它們可能會影響到吾人對其潛在的能效和環境的影響產生了觀點上的偏差。未來的研究應探討產品的整個垂直整合的生產鏈，以令 LCEA 的評估更為準確。此外、鑑於作者所獲得的有限但堪用的財務訊息，作者建議同儕們應儘可能地獲取更多的數據以進行綜合分析。在本研究中作者並沒有考慮到如極端天氣等不確定因素，未來進一步地研究它們對系統的影響有其必要性。

綜上，在本論文中所呈現的三個案例研究，協同地拓寬了可再生能源的知識領域，它們提供了 FPV 領域實證上的見解，形塑了此一領域的未來，令其向更清潔和更高效的能源系統轉變。在本文中，不論是 FPV 的電源供應可靠性分析，或基於 LCEA 的 OFPV 的 ER 評估，或是 Agongdian 和 Yamakura 水庫的 FPV 的經濟比較分析都為可再生能源領域做出了顯見的貢獻。它們的每項研究都涉及了浮力式光伏系統的重要議題，為決策者及利益相關人士提供做出明智的決策和戰略規劃所需要的見解。

關鍵詞：溫室氣體，光伏，電力供應可靠性，能量回饋，能源投資回報率，成本效益比，CO_2 排放

doi:10.6342/NTU202400056

國立臺灣大學

Abstract

In recent years, the global spotlight has increasingly focused on developing renewable energy sources due to the severe environmental repercussions of **greenhouse gas (GHG)** emissions from traditional thermal power generation. Among these, solar energy is one of the most extensively utilized sustainable options. Its advantages have been widely recognized, including abundance, availability, scalability, versatility, minimal environmental impact, and comparatively low operational costs when contrasted with other green energy alternatives. Solar energy also poses limitations, including intermittency, low energy density, and land constraints.

Addressing the disadvantages of solar power generation, the Taiwan Bureau of Energy introduced the "Two-Year Photovoltaic Promotion Plan" on September 8, 2016, to advance the solar energy industry's development, particularly in **Floating Photovoltaic (FPV)** systems. The interrelationship between the reliability of a renewable energy system's power supply, its **energy return (ER)**, and its **economic implications** is crucial to understanding sustainable energy solutions.

A robust and reliable power supply enhances the attractiveness of renewable energy systems. In contrast, a favorable ER ensures its sustainability. The economic considerations, encompassing factors such as initial investment costs, operational expenses, and comparative economic analyses, further guide the decision-making process

doi:10.6342/NTU202400056

and impact the broader adoption of renewable energy technologies. This intricate interplay underscores the need for a comprehensive approach that integrates reliability, ER, and economic assessments to advance the understanding and implementation of sustainable energy solutions.

Previous research has effectively constructed models to analyze the efficiency, reliability, and safety of **photovoltaic (PV)** systems. However, a straightforward indicator for assessing the power supply reliability of **floating PV (FPV)** deployments has yet to be introduced. Moreover, while existing literature extensively covers the environmental impacts, energy production, and system installation of FPV, there persists a necessity for further investigation into the reliability of FPV power supply. Such exploration will enrich the knowledge base in this domain and facilitate investors in making informed decisions.

Considering the successful commercial operation of **the Agongdian Reservoir FPV station** as a case study **(Case Study 1)**, the assessment of its power supply reliability assumes paramount importance. This necessity arises from the uncertainties associated with weather conditions, equipment malfunctions, aging, and grid integration issues within solar power systems. In this study, the author employs a combination of statistical and Exceedance Probabilistic analysis methods to delve into the reliability analysis of FPV, utilizing the Agongdian Reservoir FPV as a focal point. The findings reveal that the

doi:10.6342/NTU202400056

methodologies employed offer a well-rounded indicator of local power supply, thereby facilitating the implementation of load-shedding measures or the augmentation of daily system generation to bolster the reliability of PV systems.

For many years, people have perceived solar energy to yield a lower **Energy Return (ER)** than traditional fossil fuels. While the latter boasts an **Energy Return on Investment (EROI)** exceeding 25:1 in its primary stages, it dwindles to approximately 6:1 in its final stages (Brockway et al., 2019). Given the ongoing innovation in solar energy technology, investigating whether its ER has grown due to technological advancements has become increasingly pertinent. This research is paramount for power companies and investors deciding on FPV projects. Moreover, considering factors such as geographical location and sunlight conditions, assessing ER becomes indispensable, especially for international investors.

Following the successful operation of onshore FPV systems (such as the Agongdian Reservoir), the world's largest **Offshore FPV (OFPV)** project with a capacity of 181MWp in Taiwan's Changhua Industrial Zone was completed and commissioned in November 2021. In another case study **(Case Study 2)** proposed in this paper, the author analyzes the energy feedback of this OFPV project from the perspective of **Lifecycle Energy Analysis (LCEA)**. The results indicate that the implementation of this OFPV project can reduce approximately 2079.7 million tons of carbon dioxide emissions over a

doi:10.6342/NTU202400056

30-year lifecycle, with an **Energy Payback Time (EPBT)** of 0.97 years and an EROI of approximately 31 under light intensity conditions of 1700 kWh/m²•year. These values surpass or approach the upper limits of previous studies.

The final case study **(Case Study 3)** adopts a comprehensive approach to comparing and analyzing the investment schemes of Taiwan's Agongdian Reservoir FPV and Japan's Yamaura Dam, both with the same system installation capacity. The findings indicate that the investment in Japan is more advantageous, yielding a **Net Present Value (NPV)** of 7269.8 at a discount rate of 5%. The **Benefit-Cost Ratio (BCR)** and **Internal Rate of Return (IRR)** stand at 1.71 and 10.1%, respectively, with a break-even point of approximately 48.5%. Critical factors influencing the profitability of FPV investments include disparities in electricity bill prices between the two locations.

However, the limited sample data spanning fifteen years suggests that extending the time-scale sampling could enhance the effectiveness of the investigation. Future research endeavors may study the optimal installation ratio for FPV systems on water bodies, considering variables such as water quality and economic maximization. Moreover, fluctuations in solar power generation between sunny and cloudy conditions underscore the significance of weather patterns and atmospheric factors in determining the reliability and consistency of solar energy as a renewable power source. Researchers and industry stakeholders often analyze these variations to improve the predictability and efficiency of

doi:10.6342/NTU202400056

solar energy systems in diverse weather conditions, representing an issue that future research should address. Moreover, the fluctuations in solar power generation between sunny and cloudy conditions underscore the significance of weather patterns and atmospheric factors in determining the reliability and consistency of solar energy as a renewable power source. Researchers and industry stakeholders often analyze these variations to improve the predictability and efficiency of solar energy systems in diverse weather conditions, representing an issue that future research should notice.

A comprehensive LCEA ensures a thorough comprehension of the sustainability of a product, enabling more informed decision-making regarding improvements or alternatives in the production process. However, Case Study 2, constrained by an investigation of the manufacturer's products produced, needs vertical integration across various production stages. Additionally, the study's scope excludes the system's final transportation and disposal stages. The author observes that considering the energy consumption of these stages, though deemed insignificant and not estimated in this study per the 1% cutoff rule, could enhance the accuracy of PV ER assessment if addressed. Their exclusion contributes to a limited and potentially skewed understanding of the system's energy efficiency and environmental impact. Future research should explore the entire production chain in vertical segments for a more precise LCEA assessment.

Acknowledging limitations in the availability of financial information, the author

doi:10.6342/NTU202400056

recommends acquiring more data for a comprehensive analysis. It emphasizes the need to account for uncertain factors such as extreme weather, prompting further research on their impact on the system and advancements in solar technology.

In summary, the case studies presented in this dissertation collectively advance knowledge in renewable energy, offering practical insights to shape the future renewable energy potential and drive the transition towards cleaner and more efficient energy systems. The research on power supply reliability analysis of FPV, ER assessment of OFPV based on LCEA perspectives, and comparative economic analysis of FPVs at the Agongdian Reservoir and Yamakura Dam make valuable contributions to the renewable energy domain. Each study addresses critical aspects of floating photovoltaic systems, providing insights crucial for informed decision-making and strategic planning in the renewable energy sector.

Keywords: greenhouse gas, photovoltaic, power supply reliability, energy return, energy return on investment, benefit-cost ratio, CO_2 emission

doi:10.6342/NTU202400056

Index

doi:10.6342/NTU202400056

doi:10.6342/NTU202400056

Figures

doi:10.6342/NTU202400056

Tables

doi:10.6342/NTU202400056

List of Abbreviations (In alphabetical order)

Academic Terms	Abbreviation	Academic Terms	Abbreviation
Analytic Hierarchy Process	AHP	Energy Payback Time	EPBT
Analytic Network Process	ANP	Energy Return on Investment	EROI
Benefit-Cost Ratio	BCR	Feed-in-tariff	FIT
Building Attached Photovoltaic	BAPV	Floating Photovoltaic	FPV
Building Information Modeling	BIM	Greenhouse Gas	GHG
Building Integrated Photovoltaic	BIPV	Hybrid Mini-grid System	HMS
Carbon Border Adjustment Mechanism	CBAM	Inconsistency Index	InCI
Carbon Capture and Sequestration	CCS	Internal Rate of Return	IRR
Carbon Pricing	CP	kilotons	kt
Cadmium Telluride	CdTe	Load Following	LF
Copper Indium Gallium Diselenide	CIGS	Maximum Power Point Tracking	MPPT
Cost-Benefit Analysis	CBA	Natural Gas Combined Cycle	CNS
CO_2 Dioxide Equivalent	CO_2e	National Standard of the Republic of China	CNS
Cost of Energy	COE	Net Present Value	NPV
Consistency ratio	CR	Offshore Floating Photovoltaic	OFPV
Cumulative Distribution Function	CDF	Probability Density Function	PDF
Electricity Carbon Emission Coefficient	ECEC	Single Diode Model	SDM
Emissions Trading Systems	ETS	Standard Test Conditions	STC

doi:10.6342/NTU202400056

Chapter 1 Introduction

1.1 Definitions, Sources, and Characteristics of Primary and Secondary Energies

All energies on Earth come initially from the sun. Through natural energy chains, the energy is in other forms of energy, kinetic or stored. The vital distinguishing characteristic of primary and secondary energies is the process/activity by humans to use the power in the source. Separating new energy entering the primary system and the energy transformed within the secondary system is crucial to prevent double counting. Øvergaard (Øvergaard, 2008) elaborated that a clear and internationally agreed primary and secondary energy definition affects the energy flow's measuring and recording of the energy balance. **Figure 1** illustrates the definitions of primary and secondary energies.

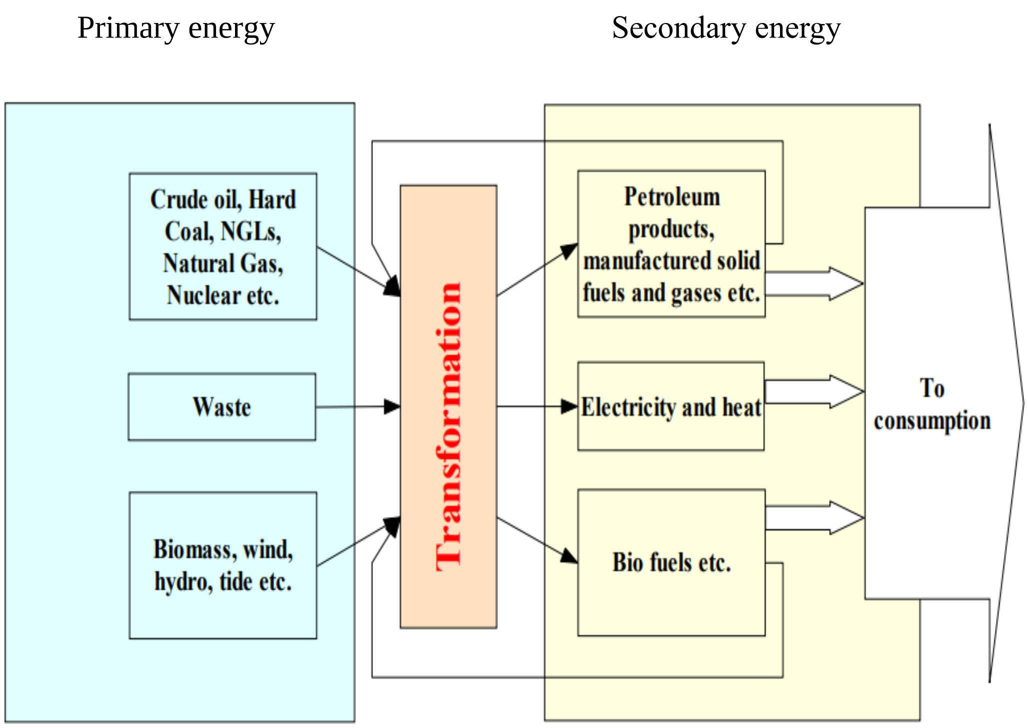


Figure 1: Primary and Secondary Energy Definitions (Øvergaard, 2008)

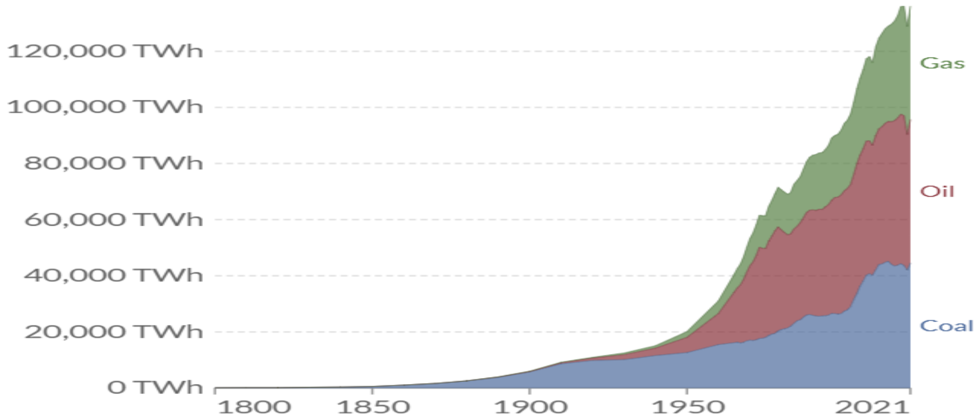
doi:10.6342/NTU202400056

1.2 Conventional, Low-Carbon, Clean, and Renewable Energies

1.2.1 Conventional Energy

According to the maturity of application technology, physicians classify energy into conventional and new (renewable) energies. Conventional energies, like fossil fuels - coal, oil, and gas, taking hundreds of millions of years to form, refer to those energy sources that have been produced and widely used on a large scale and have relatively mature technologies (Cantoni, 2018). However, they will remain primary energy sources used until 2050 as the goods carbon embodied in the product, like plastics, and in sectors where low-emissions technology options are measly (IEA, 2021).

Figure 2 (Smil, 2017; Ritchie et al., 2022) shows the global fossil fuel consumption between 1800 and 2021. When burned to produce energy, they cause harmful greenhouse gas (GHG) emissions, like carbon dioxide (CO_2).



Source: Our World in Data based on Smil (2017) and BP Statistical Review of World Energy

Figure 2: Evolution of Global Fossil Fuel Consumption from 1800 to 2021 (Ritchie et al., 2022)

doi:10.6342/NTU202400056

1.2.2 Low-Carbon Energy

Low-carbon energy includes nuclear and renewable energies. It introduces clean coal technology, fossil fuel plus the installation of CO_2 capture and storage device–equipment of **Carbon Capture and Sequestration (CCS)** (Dindi et al., 2022), and Natural Gas Combined Cycle (NGCC) (Cheng et al., 2022) power generation. They are measures taken to contribute to low-carbon energy development.

1.2.3 Clean and Renewable Energies

IEA's Renewable Energy Working Party defines **renewable energy** as energy derived from natural processes that are constantly replenished (Vakulchuk et al., 2020). Unlike finite fossil fuels, which contribute to environmental pollution and climate change, it has a low **carbon footprint** and minimal negative environmental impact. Nearly 90% of the power yield will come from renewable energies. Solar and wind energies will account for about 70%; most of the rest will be from nuclear. (IEA, 2021).

1.3 Common Renewable Energy Sources

Solar, wind, geothermal, hydropower, ocean, and bioenergies are familiar and constant supplemental sources (UN, 2023). Global electricity demand in 2050 will be around 8% smaller than today in the net zero pathway. However, renewable energy serves an economy that is more than twice as big. Integrating more efficient energy use, behavioral changes, and resource efficiency balances energy service requirements. It

doi:10.6342/NTU202400056

contributes to the healthy development of the world economy (IEA, 2021).

1.3.1 Solar Energy

Solar energy is the most ample of all energy resources (Paridaa et al., 2011). It harnesses the energy from sunlight using **concentrating solar power (CSP)** and **photovoltaic (PV)** systems (Ghirardi et al., 2021). The former uses lenses or mirrors to concentrate sunlight to produce heat. Then, using heat generates electricity. The latter directly converts sunlight into electricity. These technologies help convert sunlight into heat or electricity through mirrors or solar modules, concentrating solar radiation and delivering natural lighting, heat, cooling, and electricity for various applications. **Table 1** shows its advantages and disadvantages.

Table 1: Advantages and Disadvantages of Solar Energy

Pros	Cons
1. Sustainable 2. Clean energy source 3. Reduce or eliminate energy costs 4. Governments offer rebates or tax credits	1. High upfront costs 2. It requires significant and constant sunlight.

1.3.2 Wind Energy

Wind energy drives moving air to generate kinetic energy by using large wind turbines located on land (onshore) or sea or freshwater (offshore) (Fang & Abd Rahim, 2022). Beiter et al. (2021) claimed that people have used it for millennia, and on-land

doi:10.6342/NTU202400056

and offshore wind energy technologies have advanced over the past years to optimize electricity yield. Installers often construct wind farms with multiple turbines in areas with strong and consistent wind patterns. Despite the vast potential in most regions, enabling significant wind energy deployment, many sites worldwide have substantial wind speeds, and the affable sites for producing wind power are sometimes remote (Timilsina et al., 2013). **Table 2** shows the advantages and disadvantages of wind energy. Its potential will exceed global power production and increase 11-fold (IEA, 2021). Especially offshore wind power offers enormous capacity.

Table 2: Advantages and Disadvantages of Wind Energy

Pros	Cons
1. Cost-effective 2. Clean energy source 3. The largest source of renewable energy in the USA 4. Sustainable	1. Located in remote, rural areas (away from cities) 2. It creates noise and visually impacts the landscape. 3. It impacts local wildlife (like birds).

1.3.3 Geothermal Energy

Geothermal energy is an approachable thermal power. Drilling deep wells and extracting hot water or steam from extensive areas with geothermal reservoirs or active volcanoes generate energy stored beneath the Earth's surface (Wang et al., 2018). **Table 3** shows its advantages and disadvantages.

doi:10.6342/NTU202400056

Table 3: Advantages and Disadvantages of Geothermal Energy

Pros	Cons
1. Low carbon footprint	1. Location-specific
2. Renewable	2. Risks trigger earthquakes.
3. Sustainable	3. It is expensive to tap.
4. It does not require fuel.	

1.3.4 Hydropower Energy

Hydropower energy is one of the most abundant renewable energy sources in the electricity sector (Ming et al., 2017), which utilizes the falling or flowing water force to drive turbines and produce electricity. Building dams across rivers or using the natural water flow in tides or rivers are common manners (Pal & Khan, 2021). **Table 4** shows its advantages and disadvantages.

Table 4: Advantages and Disadvantages of Hydropower Energy

Pros	Cons
1. Low carbon emissions	1. It negatively impacts people and the environment.
2. Renewable	
3. Provides flood control	2. It is expensive to build dams/turbines.
4. Low-cost energy	3. It affects the ocean's ecosystem.

1.3.5 Ocean Energy

Ocean energy (Marine energy or Ocean power) includes tidal, wave, ocean currents, ocean temperature difference, and seawater salinity difference energies. Although there are the above manners in which the ocean can produce energy, the highlights are waves

doi:10.6342/NTU202400056

and tides (Westwood, 2004). **Table 5** shows the advantages and disadvantages of ocean energy (Rahman et al., 2022).

Table 5: Advantages and Disadvantages of Ocean Energy

Pros	Cons
1. Renewable 2. Clean energy source 3. Predictable energy production 4. Large energy potential	1. Impact local wildlife. 2. It only benefits coastal cities and towns. 3. It affects the ocean's ecosystem.

1.3.6 Bioenergy

Bioenergy originates from various organic materials, called biomass, like wood, charcoal, dung, and other manures for crops for liquid biofuels (Mohammed et al., 2013). Most biomass is utilized in rural areas for cooking, lighting, and space heating by poorer populations in developing countries (Mboumboue & Njomo, 2016). Modern biomass systems involve dedicated crops or trees, residues from agriculture and forestry, and various organic waste streams (Toklu, 2017). **Table 6** shows its advantages and disadvantages.

Table 6 Advantages and Disadvantages of Bioenergy

Pros	Cons
1. Renewable 2. Clear landfills 3. Come from many sources	1. It generates some pollution, although it is limited. 2. Biofuels require agricultural land (taking food away from tables).

doi:10.6342/NTU202400056

1.4 Alternatives to Traditional Energy Resources

Traditional energies and fossil fuels such as coal, oil, and natural gas have enjoyed widespread utilization for centuries due to their abundance and accessibility. Nevertheless, their standing is a subject of continuous debates and transformations within the global energy landscape. It is primarily attributed to the emission of **greenhouse gases (GHGs)**, notably carbon dioxide (CO_2), into the atmosphere during combustion, contributing significantly to climate change and global warming.

Many countries and organizations are transitioning to renewable power sources like solar, wind, hydropower, and geothermal (Osman, 2023). This shift aims to reduce GHG emissions and mitigate climate change (Huang and Zhai, 2021). The technologies have experienced significant advancements and cost reductions, making them increasingly competitive with fossil fuels. They have been driven by government incentives, public demand, and falling prices of wind turbines and solar modules (Tran & Smith, 2021).

Despite the global acceleration and the progress in renewable energy, reducing fossil fuel use and its environmental impacts comprise **power supply reliability**, **energy return (ER)** improvements, **carbon pricing (CP)**, and stricter measures and emissions regulations (Mercure et al., 2018) require continuous efforts (Paltsev et al., 2021).

1.5 Photovoltaic (PV), Floating PV (FPV) and offshore FPV (OFPV) Systems

1.5.1 Fundamentals of PV Effect

doi:10.6342/NTU202400056

The PV effect elucidates generating the voltage and current between semiconductors and between metals and semiconductors upon light or electromagnetic radiation. The discovery of this phenomenon dates back to 1839. We can attribute it to the pioneering work of the French physicist Alexandre Edmond Becquerel (Zaidi, 2018). Derived from the PV effect, scientists designed a PV system that directly converted sunlight into electrical power through solar cells. In practical applications, solar power is the predominant source of incident light energy. Significantly, the PV effect demonstrates a profound connection with the photoelectric effect.

In the photoelectric effect framework, a material absorbs photon energy, releasing free electrons to migrate to the surface. Following the establishment of a PN junction within the solar cell under the influence of a self-generated electric field, the excited electrons and electron-deficient holes travel in opposite directions, creating positive and negative poles. The internal heterogeneity of the material engenders this dynamic (Li et al., 2018).

1.5.2 Solar Cell Materials, Solar Panels, and Solar Arrays

The solar cell materials used for power generation mainly include **monocrystalline, polycrystalline, amorphous silicon, Copper Indium Gallium Diselenide (CIGS), and Cadmium Telluride (CdTe)** (Solaclad, 2023). **Solar panels** (Zarmai et al., 2015) are also called **PV panels** (Fouad et al., 2017) or **solar modules** (Park & Zhu, 2020). A single

doi:10.6342/NTU202400056

module interconnects many solar cells, whose most common size comprises 60. A solar array includes multiple interconnected modules. Using several solar arrays together with an inverter, energy storage battery pack (usually used in the case of off-grid), and interconnection lines can form a PV system and generate energy achieved by such interconnection in residential, commercial, and even factories (Shubbak, 2019; Motech, 2023; Tang et al., 2023). **Figures 3** and **4** show two engineers installing them on the roof and solar array at sunset.

Image Courtesy :iStock

Figure 3: Installation of Solar Panels on a Rooftop by Engineers

Image Courtesy :iStock

Figure 3: Installation of Solar Array during Sunset

doi:10.6342/NTU202400056

1.5.3 Principal Components of the FPV System

(1) Solar Module Manufacturing Process

The panel production sequence is as follows:

a. Cell string arrangement and welding: Organize solar cells into cell strings and weld them together using ribbons.

b. Parallel Connection of Cell Strings: After arranging the cell strings neatly, establish parallel connections using bus bar welding tape.

c. Lamination: Utilize vacuum and high temperature to cross-link the encapsulation material, fostering a close bond between the glass and the cell for enhanced cell protection.

d. Encapsulated Aluminum Frame: Integrate an encapsulated aluminum frame to shield the module body and fortify resistance against moisture infiltration.

e. Junction Box Installation: Channel the electricity generated by the solar module through the junction box for output.f. Classification: Classify them according to the power level.

f. Packing: Pack the solar modules to ensure the quality of shipment and transportation.

Arrange the cell strings neatly, and connect the cell strings in parallel with the bus bar welding tape.

(2) Inverter

To meet the FPV system performance requirements, contractors must select an inverter

doi:10.6342/NTU202400056

with a built-in maximum power point tracking (MPPT) algorithmic technique (De Brito, 2011; Azli et al., 2008). Moreover, it must pass the salt spray test (IEC 60068-2- 52 severity 5) to test its reliability in a salt mist environment (Lai et al., 2022). MPPT helps track the best linear relationship between voltage and current and generates the maximum power of the solar module. In addition, this technique also helps solar modules improve their photoelectric effect sensitivity under the minimum irradiation conditions to produce the maximum photovoltaic current. As the performance of MPPT will affect the fill factor by approximately 4% when the temperature rises, the power generation of the solar system will vary due to changes in climatic conditions and regional characteristics (Azli et al., 2008).

1.5.4 FPV and Offshore FPV (OFPV) Systems

In contrast to alternative renewable energy sources, the PV system presents notable advantages, with an extended system lifespan and minimal maintenance costs. It obviates mechanical movement and incurs low initial investment expenses (Bhandari et al., 2015). The feasibility of FPV and OFPV has become evident, underscored by compelling successes on onshore water territories in recent years. **Figure 5** illustrates the specific design of solar panels intended for floating on the water's surface, with potential deployment locations encompassing lakes, reservoirs, ponds, and even oceans. In contrast to traditional mounting on rooftops or the ground, the FPV deployment process entails a series of critical components and considerations, outlined as follows:

doi:10.6342/NTU202400056

(1) **Floats or Buoyant Structures:** Floating solar panels require a stable platform to remain afloat. Floats or buoyant structures, usually made of materials like high-density polyethylene (HDPE) or other plastic composites, provide buoyancy and support for the solar panels. Designed with durability, resistance to corrosion, and the capacity to withstand environmental elements such as waves and wind, manufacturers showcase the robust design characteristics of these floats.

(2) **Solar Panels:** The PV panels used in floating solar installations are similar to those used in traditional solar energy systems. These panels consist of multiple solar cells converting sunlight into electricity through the PV effect. Crystalline silicon or thin-film solar cells commonly constitute the composition of the panels. They are mounted on the floats, facing upward to capture maximum sunlight.

(3) **Mooring System:** A mooring system anchors the floating solar array in place. This system uses cables, ropes, or chains connected to weights or anchors at the bottom of the water body to prevent the solar panels from drifting away or being carried by strong currents or winds. The mooring system ensures stability and keeps the floating solar array in position.

(4) Electrical system: The electricity generated by floating solar panels needs to be efficiently collected, converted, and transmitted to the grid or storage systems. An electrical system consists of cables, junction boxes, and inverters to connect the solar panels and convert the direct current (DC) produced by the panels into alternating current (AC) suitable for use in households and industries or for feeding into the grid.

doi:10.6342/NTU202400056

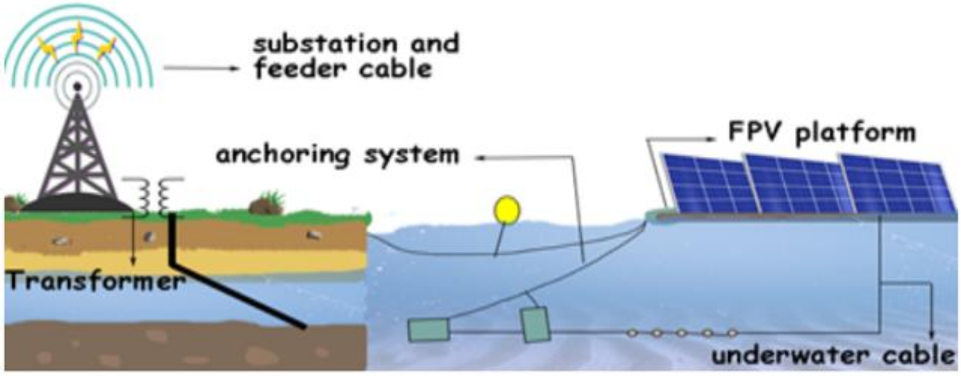


Figure 4: Conceptual Diagram of FPV Deployment

1.6 Case Studies

The decision to employ case studies is grounded in their proven efficacy as a research methodology (Yin, 2014). This approach facilitates a profound examination of specific phenomena, allowing researchers to delve into the contextual intricacies. Moreover, case studies provide practical insights directly applicable to real-world situations, offering practitioners valuable learnings to inform decision-making and enhance practices (FitzPatrick, 2019). Conducting an in-depth examination of a phenomenon within its natural context and concurrently considering multiple variables, case studies facilitate a nuanced exploration of uncommon occurrences, providing insights that may be challenging to attain through alternative research approaches. The comprehensive analysis and contextual perspective in case studies contribute significantly to a profound comprehension of the intricate interplay between various factors (Malhotra & Grover, 1998). The deliberate incorporation of case studies in this dissertation is a strategic choice to address research questions, investigate problems thoroughly, and present clear and well-substantiated solutions.

doi:10.6342/NTU202400056

Chapter 2. Literature Review

This section primarily investigates the implication and application of the ANP, the reliability analysis of PV and FPV systems, **Exceedance Probability**, and the analysis of ER and financial indicators in the case studies to identify research gaps and contribute to the renewable energy field.

2.1 Implication and Impacting Factors of Power Supply Stability

A system's **power supply reliability** refers to operational stability without incidents under particular conditions within a specified time when a solar power system converts sunlight into PV modules to generate electricity (Hayat et al., 2019). Enhancing reliability, system design, installation quality, regular maintenance, and consideration of backup options is crucial during its planning and implementation ((Tan et al., 2021; Olatomiwa et al., 2022). It consistently provides electricity based on sunlight (insolation) availability. It is subject to natural factors like weather conditions (El Hammoumi et al., 2022). The following are factors that affect the power supply reliability:

(1) Insolation availability: A PV system's power output is directly proportional to the sunlight received. The geographical location and installation site, seasonal variations, and climatic conditions greatly influence the system's reliability. For example, areas with ample sunshine and minimal cloud cover tend to have higher power supply reliability (Fakour et al., 2023).

doi:10.6342/NTU202400056

(2) System design and installation: A system's design and installation are critical in ensuring reliable power supply. Factors like the solar module's orientation and tilt angle, shading analysis, and proper sizing of components, such as panels, inverters, and batteries, impact the system's overall performance and reliability. A well-designed and professionally installed PV system can maximize power generation and minimize potential issues (Behura et al., 2021).

(3) System monitoring and maintenance: Regular monitoring and maintenance of a PV system are critical to ensure its long-term reliability. It includes inspecting and cleaning the solar panels, checking for any damage or shading issues, and verifying the proper functioning of components like inverters and batteries. Timely maintenance helps identify and address performance degradation or faults, ensuring the system operates optimally and reliably (Keisang et al., 2021).

(4) Battery storage: As the solar farm directly feeds the electricity it generates into the grid, some PV systems incorporate battery storage to store excess electricity generated during high sunlight availability. The stored energy can be utilized during cloudy or nighttime conditions, enhancing the system's reliability. Battery technology and capacity, along with efficient charge and discharge management, influence the reliability of the system's power supply during non-sunlight hours (Tan et al., 2021). As the installation capacity of the cases in this study is above 10 MWp, The installers must store the

doi:10.6342/NTU202400056

electricity generated by the system in batteries if they adopt the off-grid approach.

(5) Grid connection: Grid power supply reliability refers to consistent and uninterrupted electricity delivery to consumers (Benysek & Pasko, 2012). A reliable power supply improves the quality of life for individuals and communities. Numerous critical services and public safety rely on a continuous power supply (Sarker & Lester, 2019). Electricity powers various aspects of daily life, including lighting, heating, cooling, refrigeration, communication, entertainment, and access to the Internet (Tushar et al., 2021). Power failures lead to significant financial losses, disruption of operations, and decreased productivity (Heffron et al., 2020). It is paramount for economic productivity as power outages lead to considerable financial losses, disruptions in manufacturing processes, data loss in information technology sectors, and halted productivity (Akpeji et al., 2020).

2.2 Reliability of PV and FPV systems

2.2.1 FPV

Conventional **PV** systems are usually installed on the ground. Installing the solar modules requires considerable land. Countries like Taiwan, with high-density urban or island areas, must find sufficient space for PV's large-scale deployment (Yue and Huang, 2011; Van de Ven et al., 2021). Implementing FPV systems on water bodies is one of the solutions. FPV technology is an innovative method. It offers several advantages by utilizing water bodies, reducing evaporation, and mitigating the impact of water scarcity

doi:10.6342/NTU202400056

(Gadzanku et al., 2021; Kumar et al., 2021). It provides opportunities for combined land-water use, promotes biodiversity, and contributes shade that benefits aquatic ecosystems.

Profiting from the water's natural cooling effect helps dissipate heat and improve overall system efficiency. The reflections from the water surface enhance the sunlight reaching the solar cells, increasing electricity generation (Gorjian et al., 2021), thereby less affecting the environment compared with conventional solar farms, like land disturbance and habitat fragmentation (Bax et al., 2022), and exploiting the energy-water nexus that addresses energy and water demand (Farrar et al., 2022). It is a growing area with interest within the renewable energy sector, offering a promising alternative for solar power generation and expanding potential energy production (Pouran et al., 2022). The Bureau of Energy of Taiwan issued the “Photovoltaic Two-year Promotion Plan” on September 8, 2016 (Taiwan Bureau of Energy, 2016) to facilitate investors’ funding to renewable energies. Taiwan initially developed FPV systems benefiting from this plan.

2.2.2 Single-Diode Model (SDM)

The model depicted in **Figure 6** (Gray, 2011) portrays the PV cell as a constant function representing operating conditions and electrical parameters. It comprises a current source, diode, shunt, and series resistor connected to the load.

doi:10.6342/NTU202400056

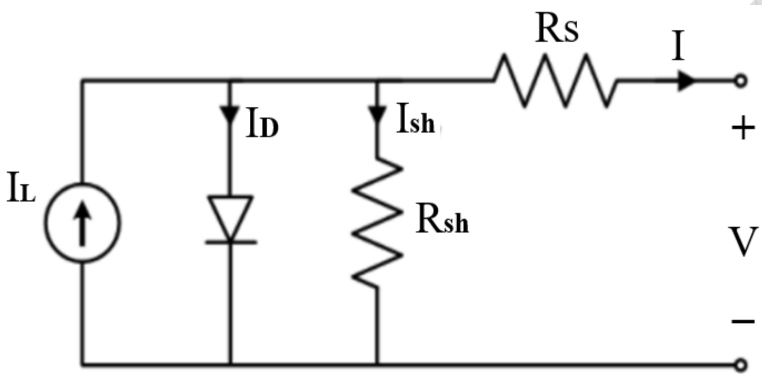


Figure 5: Equivalent Circuit Representation of PV Cell (i.e., SDM)

Equations (1) to (6) define the load current (I_L) for the SDM as outlined by Di Piazza et al. (2017):

$$I_L = I_{pc} - I_D - I_{sh} \quad (1)$$

I_{pc} denotes the photoelectric current, ID refers to the diode current, and Ish signifies the current flowing through the shunt resistor.

Equation (2) elucidates the current through the diode.

$$I_D = I_{rsc} \text{ x } \exp\left(\frac{V+I_L R_S}{\alpha V_{jv}}\right) \quad (2)$$

I_{rsc} denotes the reverse saturation current, V represents the cell output voltage, R_S signifies the series resistance, α indicates the diode ideality factor, and V_{jv} denotes the diode junction voltage.

Equation (3) defines V_{jv}.

$$V_{jv} = \frac{N_{sc} KT}{I} \quad (3)$$

N_{sc} indicates the number of cells in series, T denotes the module temperature in Kelvin, K represents the Boltzmann constant (1.380649×10^{-23} J/K), and I signifies the

doi:10.6342/NTU202400056

electron charge (1.602×10^{-19} Coulomb).

$$V_{jv} = \frac{N_{sc}K(T-12)}{I} \quad (4)$$

Equation 5 shows the current through the shunt resistance (I_{sr}).

$$I_{sh} = \frac{V+I_L R_s}{R_{sh}} \quad (5)$$

By substituting equations (2) to (5) into equation (1), we can derive the output current in the SDM as equation (6):

$$I_L = I_{pc} - I_{rsc}[\exp(\frac{V_0+I_L R_s}{\alpha V_{jv}})-1] - \frac{V+I_L R_s}{R_{sh}} \quad (6)$$

In equation (6), I_L, I_{rsc}, R_s, α, and R_{sh} are unknown. Manufacturers must use STC to assess these parameters.

2.2.3 Reliability of the On-grid System

As outlined earlier, the case studies in this dissertation pertain to on-grid systems with capacities exceeding 10 MWp. These systems entail fewer components than off-grid systems since the grid typically does not store energy (Crow, 1990). They integrate the energy generated and are connected to the power network, feeding power directly into the grid near the local power plant (Kececioglu, 1991; Fu et al., 2013). System failures can impact interconnected systems' operation and disrupt users' power supply, underscoring the importance of conducting a thorough reliability analysis of the power system parallel to the grid (IEC, 1995). Establishing an acceptable system maintenance plan for power supply reliability is crucial for minimizing power outages. Furthermore, operators

doi:10.6342/NTU202400056

dispatch these systems under a load-following **(LF)** strategy. They are more optimal than off-grid systems in terms of net present value **(NPV)** and cost of energy **(COE)** (Nesamalar et al., 2021).

2.2.4 Performance and Power Generation Comparison of PV and FPV systems

Kougias et al. (2016) presented integrating PV systems in water infrastructure to offer pros for renewable energy sources' growth and a methodology to identify developing favorable canals and dams. The study analyzed the Mediterranean islands' potential to contribute significantly to irrigation water savings. Yadav et al. (2016) analyzed and compared the performance and power generation efficiency of the FPV and land-based PV systems with an installed capacity of 250 Wp under the tested insolation between 125W/m^2 and 945W/m^2. They analyzed the Current (I) - Voltage (V) curves and power (P) -Voltage (V) curves of the results. The FPV has shown more considerable generation efficiency and higher total power gain than traditional deployment.

In comparing operating environments on a roof and water to analyze different FPV systems' performance and share several issues encountered, Liu et al. (2018) presented extensive and high-quality field measurement data. They compared operating environments on water and a rooftop, analyzed the performance of different FPV systems, and shared some issues encountered. They summarized that FPV has several performance pros and suggested that establishing best practices is dispensible to prevent new pitfalls

doi:10.6342/NTU202400056

and issues associated with deploying PV on water.

Kamuyu et al. (2018) claimed that the FPV market status has emerged since it utilizes the system's excellent ambient environment near the water surface, according to remarkable FPV module reliability studies. It showed a degradation rate below 0.5% p.a. when using novel assembling stuff. They collected and analyzed data over five-minute intervals from a PV system over a year using MATLAB to derive predictable environmental variables' equation coefficients and perform PV module temperature analysis. They compared the theoretical prediction to realize field PV module operation temperature. They found that the associated model errors ranged from 2% to 4% based on the number of equation coefficients used. Results show that FPV systems generate 10% more power than other LPVs.

Ranjbaran et al. (2019) analyzed and studied different FPV systems as power generation systems. They compared the ground-mounted and FPV deployments and denoted the gaps in the examined subjects. They conferred the most favorable schemes of FPV array interconnection and reconfiguration. They investigated multilevel DC-DC converters for grid integration of FPV panels.

Taye et al. (2020) compared an FPV system with a land-based PV station for Debre Mariam Island to increase efficiency and save land. They modeled it to satisfy the daily energy load demand of Debre Mariam Island community electric loads. Results indicated

doi:10.6342/NTU202400056

that the wind speed and temperature significantly contribute to panel efficiency drops and low power output in land PV installations. The FPV generated 294.8 kWh of power output compared to 289.9 kWh generated by land PV station installation. The FPV system increases the power output by 4.9 kWh compared with land-based PV.

Kumar et al. (2021) presented how the FPV's specific design and structure influence its output power generation, durability, and investment cost. They analyzed and updated solar systems' performance and degradation to model PV modules' performance and temperature underwater, such as altering active cooling techniques and evaporation rates in FPV systems. They explored how FPVs' performance and reliability under the water body's harsh conditions challenge their cost-effective power generation for the economic feasibility and environmental effects from an electrical perspective. They concluded that predicting PV systems' performance at a specific location requires prior to meeting the system's desired energy demand and secure investment.

Elminshawy et al. (2021) claimed that FPV's lower working temperature and efficiency are better than an LPV system. They experimented by constructing a system to examine its performance under natural windy conditions and explained the reason for such dominance. The findings showed that it strengthened FPV's superiority through an innovative partially floating system for more energy harvest. The underwater portion allows reliable temperature management for the PV system via mutual heat transfer with

doi:10.6342/NTU202400056

the ambient water. Consequently, it raises electricity production. Hammoumi et al. (2021) designed and built a small-scale FPV for research and demonstration purposes, attempting to analyze and compare its electrical and thermal performance with land-based PV under Moroccan operating conditions. The test result shows that the FPV produces the highest energy when installed at the optimal tilt angle.

Dörenkämper et al.(2021) conducted an estimated specific yield comparison between conventional and FPV systems by thoroughly studying the water cooling effect. They confirmed that FPV systems could outperform conventional PV systems regarding energy yield due to the effect across different climatic conditions by a PVsyst model with inputs of the heat loss coefficients based on field tests located in two different climate zones: the Netherlands, a temperate maritime climate, and Singapore, a tropical climate. The comparison results show that the gain in energy yield from the FPV stations' cooling effect compared to the reference PV deployments is up to 3% in the Netherlands and 6% in Singapore.

Luo et al. (2021) analyzed the performance stability of FPV systems located in the Tengeh Reservoir in Singapore with a tropical rainforest climate from one of the sizable FPV testbeds worldwide using three commonly used statistics to compute seasonal and trend decomposition and performance loss rates. They compared two monitored PV strings mounting crystalline silicon units from a nearby rooftop reference structure.

doi:10.6342/NTU202400056

Overall, there is no remarkable difference between the rooftop and the FPV installations in the testbed regarding performance stability during the first three years of operation.

Kjeldstad et al. (2021) analyzed weather data and production from one year of operation for an open FPV system with a small water area installed on a water body in Kilinochchi, Sri Lanka. They compared it to a land-based PV system erected on the shore of the lake. They found that the technology has had a stable overall performance over one year. The amphibious operation period did not impact the continued system's performance. Based on the production and weather data, calculations of the system's heat loss coefficient value (U-value) grant a median U-value of 33 W/m^2K, slightly better than the default PVsyst value of 29 W/m^2K for freestanding land-based PV systems.

Micheli (2022) reviewed and gathered the literature on FPV's thermal behavior, outlining the models and discussing the currently available experimental findings. He found that different FPV configurations can experience different thermal behaviors, sometimes better than LPV. He suggested that considering their various cooling mechanisms helps distinguish air- and water-cooled FPV systems. Initial comparative analyses help identify designs and conditions. It benefits from heat transfer in FPV compared to LPV. Kumar et al. (2023) declared that the FPV's pioneering concept values land in urban areas and provides a cooling effect that keeps solar panels cooler than land-based systems. An FPV system's high power output relies on using the right technology

doi:10.6342/NTU202400056

and a comprehensive design, construction, and consideration of environmental factors like evaporation. The last factor influences its reliability, operations, durability, and output power generation. The module technology type and local climate conditions impact the system's performance and reliability.

2.2.5 Modeling and Optimization Methods of Reliability

In previous research, Meydbray et al. (2008) adopted a dynamic programming technique to solve the optimization problem, system sizing, and control optimization (Meydbray et al., 2008; Mahmoudimehr & Shabani, 2018). They combined a genetic algorithm and designed objective functions, like investment cost and loss of power supply probability, as design variables. Additionally, they developed a long-term stochastic optimization method that simultaneously considers the streamflow and PV power output uncertainty to obtain operational decisions. Katsigiannis et al. (2010) introduced an approach for the modeling and reliability assessment of small isolated energy systems. It includes PV, wind turbines, and diesel generators. They implemented four scenarios to describe the power system's performance under different conditions and compared each developed scenario. Nine reliability and performance indexes have been calculated and compared. Aihara et al. (2012) proposed a genetic algorithm and tabu search-based method to improve benefits generation and system reliability. They evaluated the impact and enhanced the power supply reliability by arranging an effective operating pattern and

doi:10.6342/NTU202400056

integrating the PV system into a pumped-storage hydropower plant.

Yang et al. (2018) used PVsyst software to simulate the total energy generated and put the simulation results into the field grid-connected. The failure of PV members from the ground shows that some manufacturers' reliability analysis of the PV module is insufficient. Due to the more severe use conditions of the later developed FPV than those of ground systems, it is more likely that the structure will fail before the end of its life cycle and affect the power supply stability. Consequently, developing an elaborated approach to analyze and estimate the system's near-term and long-term power supply reliability creates a balance indicator for planning and assessing the grid's potential power supply and demand risks.

Kamuyu et al. (2018) collected and analyzed data over five-minute intervals from a PV station over a year. They used MATLAB software to derive equation coefficients of predictable environmental variables and the module temperature operation models after comparing the theoretical prediction to solar modules' actual field operation temperature. They found that the corresponding model errors range between 2% and 4% depending on the number of equation coefficients incorporated. The validation results of their other studies show that FPV systems produce 10% more energy than land-based systems. They concluded that PV module temperature analysis is another critical area governing the efficiency performance of solar cells and modules.

doi:10.6342/NTU202400056

Mazzeo et al. (2018) presented a dynamic and power supply reliability analysis of a renewable hybrid trigeneration system. It includes a PV generator, a wind micro-generator, and an energy storage battery (electric renewable hybrid system ERHS) to furnish electric office devices, and employed the dynamic simulation results to investigate the dynamic interaction between the ERHS with the three electric loads in different characteristic weeks and determine the system's energy reliability in the absence and presence of a battery storage system. Lu et al. (2019) proposed a reward-penalty mechanism (RPM) for accelerating the development of zero-energy communities without considering the reliability effect. The findings show that the proposed RPM works efficiently under ideal conditions. Simultaneously, the community costs and buildings significantly increased when considering the PV system reliability effect. Esan et al. (2019) presented a novel approach to evaluating the power supply reliability of a hybrid mini-grid system (HMS) according to the optimal design result from the HOMER software. They performed a typical case study in a Nigerian rural area – Lade II, in Kwara State, where the power requirement for the commercial and residential loads was 2.5MWh/day and 171kWh/day, respectively. The results show the HMS's reliability and depict a highly economical and feasible hybrid energy system.

Lee et al. (2020) reviewed the associated benefits of hybrid FPV-hydropower system operation and a novel geospatial approach to assess the global technical potential of these

doi:10.6342/NTU202400056

systems employing publicly available, global datasets to support decision-making. They identified significant global potential for FPV hybridized with hydropower ranging from 3.0 to 7.6 TWh (4,251 to 10,616 TWh annual generation) based on the assumptions made. Pereira (2020) designed a 3MWp FPV system compared with other evolved PV technologies. He analyzed it using the PVSyst simulation software interface and actual climatic data from NASA. Results proved that the designed system generates more power compared to other methods' negative impact on the environment as it only utilizes water surfaces to install the system.

Sulaeman et al. (2021) assessed increasing system adequacy benefits. They elaborated that alternative power sources are required to meet future energy needs. Even though solar energy in Brazil accounts for a small percentage of its total integrated generation, large-scale deployment is one of the promising solutions for offsetting dams' underlying underproduction. They evaluated the system adequacy with the dams' current production and the required FPV system capacities to support their short production, the correlation between system load, PV output, and the social and environmental concerns associated with dam expansion in the Amazon basin. The results show that the investment toward installing FPV systems on the dams' reservoirs remarkably minimizes load reduction, improves the entire system's reliability, and potentially increases flexibility in the operation to manage energy generated by hydropower plants during peak

doi:10.6342/NTU202400056

requirements.

Kaymak and Sahin (2021) installed three different FPVs based on examining Büyükçekmece Lake in Istanbul. They assessed the difficulties and critical faults that can arise with such systems. They found that, compared to previously installed systems with their new 30 kWp FPV designs, the semi-flexible fitting elements were sustainable and robust even with the severe wave and wind conditions on the Lake for the study period between July 2018 and April 2020. It also revealed that the most well-known float and frequently used designs for FPVs are not sufficiently robust for severe environmental conditions.

Claus and López (2023) presented a comprehensive methodology for evaluating FPV structures, focusing on wind and wave impact from hydrodynamic and structural perspectives. They considered various environmental actions, configurations, and mooring line chain sections. They provided practical data on loads and motion time series for subsequent structural analysis. They observed, compared, and found the hinged configuration to the rigid one, a remarkable reduction in maximum yaw motions of 32% to 76%, depending on the employed mooring chain section. The structural analysis highlights the significance of wave characteristics, mooring system configuration, and system flexibility. They emphasized the need to consider environmental conditions, structural aspects, and energy efficiency in optimizing FPV configurations.

doi:10.6342/NTU202400056

2.3 Exceedance Probability

The **Exceedance Probability** refers to the likelihood that **a specific value or level of drought will occur based on historical data**. Researchers have widely used it as an assumed risk indicator in climate change research, hydrology, engineering, finance, river discharge or precipitation, and environmental science (Hayhoe et al., 2004; Meydbray et al., 2008). In hydrology, they use it to predict extreme events like floods, earthquakes, and hurricanes (Lambert et al., 1994; Kunreuther, 2002; Hayhoe et al., 2004; Meydbray et al., 2008). For example, if we achieve the Exceedance Probability of a river discharge of 1,000 cubic meters per second, a 10% Exceedance Probability would mean a 10% chance that the discharge will equal or exceed 1,000 cubic meters per second in a given period.

In finance, applying the Exceedance Probability to evaluate risks associated with investment portfolios is applicable. For instance, a 5% Exceedance Probability for a certain level of financial loss indicates that the losses will be greater than or equal to that level 5% of the time (Zhang & Huang, 2006). Mathematically, it is often expressed as a percentage and can be represented by a **probability density function (PDF)** or a **cumulative distribution function (CDF)**, depending on the specific context and the nature of the analyzed data. It provides valuable information for risk assessment,

doi:10.6342/NTU202400056

decision-making, and the design of structures and systems that need to account for extreme events (Maritato & Uryasev, 2023).

After studying a hypothetical trend case superimposed on a random stationary variable, Porporato and Ridolfi (1998) highlighted its strong influence on possible non-stationarities. They analytically developed a general outline using the Gumbel distribution, focusing on its quick increase over time in the presence of weak rising trends. Under its unnoticed sensitive underestimation, they applied the work to hydrological rainfall and river flow series.

Piechota et al. (2001) presented a methodology to forecast seasonal streamflow using the Exceedance Probability to extend a previously developed categorical streamflow forecast model to five Australian catchments. They used persistence (i.e., the previous season's streamflow) and El Niño-Southern Oscillation indicators to perform linear discriminant analysis. The prediction continuously benefits the water resource systems' design and operation. It demonstrates that researchers can use Exceedance Probability in prediction. Mason et al. (2007) proposed a procedure in the forecast ensembles scenario. It extends the binned probability histogram. They treated individual ensemble members as quantile estimates of the forecast distribution. They calculated the conditional Exceedance Probability that the observed precipitation, for example, exceeds the amount forecast.

doi:10.6342/NTU202400056

Liu et al. (2013) considered the combined Exceedance Probability of multiple hazards. They took China's Yangtze River Delta region as an example to calculate their Exceedance Probability distribution to human life using the life loss data of natural hazard disasters between 1950 and 2010. Using a geographical information system, they mapped multi-hazard risks to human life at different mortality rates and loss at risk-return periods to achieve the Exceedance Probability. Results show that Hangzhou and Ningbo are at a relatively high risk from multiple natural hazards, and Shanghai is at a relatively low risk.

Haigh et al. (2014) estimated for the first time present-day extreme water level exceedance probabilities around the whole coastline of Australia. They configured a high-resolution depth-averaged hydrodynamic model for the Australian continental shelf region. They successfully validated the model output by comparing it to measurements from 30 tide gauge sites. They fitted extreme value distributions to the derived time series of annual maxima and the several most immense water levels each year at each numeric coastal grid point to estimate exceedance probabilities. It provides a reliable estimate of water level probabilities around southern Australia.

Nathan et al. (2016) elaborated on applying two considerable independent manners to examine such extreme rainfall frequencies. One manner is based on stochastic storm transposition, combining an extreme storm's "arrival" and "transposition" probabilities employing the total probability theorem. The second approach combines point rainfall

doi:10.6342/NTU202400056

frequency curves with regression assessments of local and transposed areal rainfalls according to "stochastic storm regression." They generated rainfall maxima and stochastically sampled independent variates and achieved the required exceedance probabilities using the same theorem. These two methods are applied to two enormous catchments with areas of 15,280 km2 and 3550 km2 located in inland southern Australia, providing similar frequency estimates of extreme areal rainfalls for these two study catchments.

Some scholars claimed that the global instrumental record of tropical cyclone intensity is generally unsuitable for global trend analysis as it is heterogeneous in space and time (Kossin et al., 2020). They mentioned that the previously created homogenized data records according to satellite data for the period 1982–2009 were not statistically significant at the 95% confidence level. They are shorter than the time required for a statistically significant positive global TC intensity trend to appear. Thus, they extended the homogenized global TC intensity record to the 39 years 1979–2017 and identified statistically significant advances at the 95% confidence level. Results showed that increases and trends in the Exceedance Probability are consistent with expectations based on theoretical understanding and trends identified in numerical simulations in warming contexts.

Mackay and Haselsteiner (2021) investigated the relationship between the marginal

doi:10.6342/NTU202400056

Exceedance Probability of each variable’s maximum value along an environmental and the total probability outside the contour. Findings reveal that the marginal ratios to total exceedance probabilities for direct sampling contours are similar to those for the inverse first-order reliability method. However, the marginal Exceedance Probability of each variable’s maximum value along the highest density contour is not a fixed relationship to the contour Exceedance Probability. It depends on the shape of the joint density function.

2.4 Lifecycle Energy Analysis (LCEA) and Energy Return (ER)

2.4.1 LCEA

LCEA is an essential tool to assess and understand a product’s energy implications, system, or process throughout its lifespan. Its broader approach is often called **Life Cycle Assessment (LCA)**. Academic circles often use LCEA to assess the total energy consumption. It encompasses energy and a more comprehensive set of environmental impacts (Morales et al., 2015). It provides a comprehensive perspective on energy consumption. It aids in pinpointing areas where energy efficiency can be enhanced and helps identify the stages or processes within a product's lifecycle that consume the most energy (Cabeza et al., 2014; Najjar et al., 2022).

Additionally, it quantifies and evaluates the energy inputs and outputs associated with various stages from the cradle to the grave, including extraction of raw materials, manufacturing, transportation, use, and end-of-life disposal or recycling, often declared

doi:10.6342/NTU202400056

in energy units like megajoules or kilowatt-hours (Menzies et al., 2007; Venkatraj & Dixit, 2021; Loveday et al., 2022). The evaluated information allows decision-makers to prioritize efforts and resources for energy optimization and reduction. Focusing on these energy hotspots makes achieving substantial energy savings and minimizing environmental impacts possible (Ingrao et al., 2014). Thus, the solar system must remain operational and productive in its lifecycle. During the solar module's lifespan, generally 25 to 30 years, it should generate electricity (Biswas, 2021).

By considering the entire product's lifecycle, the LCEA helps avoid environmental impacts from one stage to another. For instance, a commodity may be energy-efficient during its use phase. However, the overall environmental consequences may still be significant if the manufacturing process is energy-intensive (Cabeza, 2014). Specifically, a product's lifecycle typically includes the following stages:

(1) Raw Material Extraction and Processing: It involves the energy required to extract and process raw materials before manufacturing products.

(2) Production: The energy consumed during product fabrication includes processing, assembly, and packaging.

(3) Transportation: Transporting raw materials to the manufacturing site, the finished product to distribution centers, and the product to the end-user all need energy.

doi:10.6342/NTU202400056

(4) Use: The energy consumed during the product's use can vary depending on the product type. For example, household appliances, vehicles, and electronic devices have different energy use patterns during operational phases.

(5) End-of-life: Energy is associated with the product's disposal, recycling, or treatment at the end of its life (Bongaerts & Drebenstedt, 2023).

In addition to energy consumption, researchers can extend LCEA to include other environmental factors, like GHGs, water usage, and other resource consumption metrics. LCEA is a valuable tool for businesses, policymakers, and researchers seeking to understand and mitigate the environmental footprint of products and processes (Salehi et al., 2021).

2.4.2 ER

A solar system's ER refers to the power produced by the setup compared to the capability invested in its construction, installation, and maintenance over its lifetime. The **energy payback time (EPBT)** and the **energy return on investment (EROI)** are often expressed (Chen, 2023). A higher ER signifies that the system has generated more energy than was consumed in its lifecycle, indicating a more efficient and sustainable energy source (Celik et al., 2018). As PV technology has become more efficient and advanced, the ER tends to improve, reducing the EPBT and increasing the EROI and the system's overall sustainability (Pamponet et al., 2022). The system's ER varies depending on solar

doi:10.6342/NTU202400056

technology, geographical location, system design, efficiency, and maintenance practices (Omar, 2021). When evaluating a system's ER, investigators must consider the following factors:

(1) Manufacturing: The energy needed to manufacture solar panels includes raw materials extraction and processing. Its investment includes producing system components like inverters, cabling, and support structures (Eskew et al., 2018). The power required to manufacture solar panels includes raw materials extraction and processing. Its investment involves producing system components like inverters, cabling, and support structures (Eskew et al., 2018).

(2) Installation: The energy expended during the solar panels' installation comprises any associated infrastructure, such as mounting systems, electrical connections, and grid integration. That is the labor, equipment, and transportation required to set up the system (Li et al., 2019).

(3) Operation and maintenance: The capability to operate and maintain the solar energy system over its lifetime involves cleaning, monitoring, and repairing the system and any energy losses due to system inefficiencies or degradation (Biswas, 2021).

(4) System lifetime: Various factors can influence the lifetime of an FPV system, such as materials and components, maintenance, environmental conditions, technology advancements, and regulatory and policy environment (Ahmed et al., 2023).

doi:10.6342/NTU202400056

The two primary metrics for assessing ER are the EPBT and EROI (Bhandari et al., 2015). The EPBT delineates the critical period during which a photovoltaic (PV) system can generate energy equivalent to its production, emphasizing the necessity for efficient energy management throughout its lifespan (Gessert, 2012). On the other hand, the EROI represents the ratio of energy delivered from a specific energy source to the power consumed in its production (Murphy & Hall, 2010).

In a comprehensive review, Alsema et al. (1998) scrutinized multiple energy analysis studies focusing on thin-film solar cell modules. The analysis initiated an exploration of methodological issues in PV system energy analysis. Findings from studies on a-Si and CdTe modules were presented cohesively, revealing substantial disparities in material choices, especially in module encapsulation. The study meticulously evaluated the energy requirements for contemporary a-Si and CdTe thin-film modules, ranging from 600 to 1500 MJ per m^2 module area. Notably, the EPBT for a grid-connected module, under 1700 kWh/ (m^2•year) irradiation, demonstrated feasibility below two years, suggesting potential for an EPBT below one year.

Murphy and Hall (2010) thoroughly reviewed empirical findings on EROI for significant fuel types, providing a historical perspective and analytical methodology while highlighting areas for improvement in EROI research. Fukurozaki et al. (2013) analyzed the energy requirements and CO_2 emissions of a 1.2 kWp PV rooftop system

doi:10.6342/NTU202400056

in Brazil, utilizing the LCA methodology. The EPBT ranged from 2.47 to 3.13 years, with CO_2 emissions rates between 14.54 and 18.68 gCO_2-eq/kWh for current rooftop installations. Atlason and Unnthorsson (2014) asserted that an EROI less than or equal to one designates an "energy sink" and is unsustainable, advocating for an EROI ratio not lower than 3:1 for viability.

Numerous researchers conducted LCAs to assess the greenhouse gas footprint, EPBT, and cumulative energy demand of silicon heterojunction (SHJ) cell designs. Current designs exhibited lower life-cycle GHG emissions and EPBT than conventional monocrystalline silicon systems. Improvements in cell efficiency, the use of thin silicon wafers, and the substitution of silver-based with copper-based metallization demonstrated potential reductions in lifetime GHG emissions and EPBT for both SHJ and monocrystalline systems (Louwen et al., 2015).

Bhandari et al. (2015) systematically reviewed and comprehensively analyzed the embedded energy, EPBT, and EROI indicators for the thin-film PV and crystalline silicon technologies issued between 2000 and 2013. They referred to 232 articles and selected 23 and 11 for embedded energy and EPBT/EROI analyses. They assorted some parameters to the following values: insolation (1700 kWh/m**2**•year), performance ratio (0.75), system lifetime (30 years), module efficiency (aSi: 6.3%; CdTe: 10.9%; CuInGaSe: 11.5%Mono-Si: 13.0%; poly-Si: 12.3%;). The findings show that the mean

doi:10.6342/NTU202400056

harmonized EPBT varied from 1.0 to 4.1 years. Additionally, they ranked module types according to the order from highest to lowest: monocrystalline silicon (mono-Si), poly-crystalline silicon (poly-Si), amorphous silicon (a: Si), copper indium gallium diselenide (CIGS), and cadmium telluride (CdTe). The mean assorted EROI varied from 8.7 to 34.2. Zhou and Carbajales-Dale (2018) examined energy inputs and efficiency based on previous PV system EROI meta-analyses under the system's low-cost and high-cost contexts by centering the existing wafer, thin-film, and organic technologies. The results reveal that low-cost and highly efficient thin-film techniques have not yet arisen. Nevertheless, the thin-film process is the optimal ER advancement to date.

They referred to 232 articles and selected 23 and 11 for embedded energy and EPBT/EROI analyses. They assorted some parameters to the following values: insolation (1700 kWh/m^2•year), performance ratio (0.75), system lifetime (30 years), module efficiency (aSi: 6.3%; CdTe: 10.9%; CuInGaSe: 11.5%Mono-Si: 13.0%; poly-Si: 12.3%;). The findings show that the mean harmonized EPBT varied from 1.0 to 4.1 years. Additionally, they ranked module types according to the order from highest to lowest: monocrystalline silicon (mono-Si), poly-crystalline silicon (poly-Si), amorphous silicon (a: Si), copper indium gallium diselenide (CIGS), and cadmium telluride (CdTe). The mean assorted EROI varied from 8.7 to 34.2. Zhou and Carbajales-Dale (2018) examined energy inputs and efficiency based on previous PV system EROI meta-analyses under the system's

doi:10.6342/NTU202400056

low-cost and high-cost contexts by centering the existing wafer, thin-film, and organic technologies. The results reveal that low-cost and highly efficient thin-film techniques have not yet arisen. Nevertheless, the thin-film process is the optimal ER advancement to date.

The research conducted by Jackson and Jackson in 2021 presented the TranSim model, designed to simulate the economic and financial consequences associated with an energy technology transition. This transition involved a reduction in EROI to ascertain whether such a reduction could lead to increased energy prices and a subsequent decline in economic growth. The model integrated a stock-flow consistent approach with an input-output model. In a separate study, Wang et al. (2021) delved into the investigation of various feedstock options, encompassing first-generation feedstock like corn, second-generation feedstock like corn straw, and third-generation feedstock like algae. They aimed to quantify the trade-offs in EROI associated with typical biomass conversion systems in China. The researchers unified and compared system boundaries employed in prior biomass footprint calculations. The findings illuminated that the conversion of raw biomass feedstock to solid fuel yielded the highest EROI (ranging from 8.06 to 30.13), followed by biomass power (2.07–16.48), biogas (1.30–11.05), and biodiesel (1.28–2.23) for the first generation. Notably, regardless of the biomass type (straw or wood residues), pyrolysis gasification exhibited the highest EROI. The conclusion was that emphasizing the enhancement of energy efficiency strengthens the economic viability of the biomass energy sector.

doi:10.6342/NTU202400056

In the evolving landscape of PV technologies, which exhibit lifetimes ranging from 25 to 40 years and are consistently advancing, Kamal et al. (2022) have proposed a model to facilitate the critical examination of articles on material compositions, manufacturing processes, and dismantling procedures. Their focus extends to elucidating the objectives, pivotal constraints, and pragmatic strategies of the environmental, economic, and social dimensions of sustainability within the PV industry. Furthermore, they explore the potential contributions of Industry 4.0 technologies. Consequently, they present a comprehensive research roadmap to guide forthcoming studies in optimizing the overall sustainability of PV systems.

In a separate study, Tina and Scavo (2022) estimated and compared ER performance metrics and simulated data annually for a mounted LPV/FPV system featuring two-axis tracking and either mono or bifacial modules. The analysis concerning the Anapo Dam in Sicily (Italy) and the Aar Dam in the Lahn-Dill district (Germany) provides insights into the energy output variations based on geographical locations. Addressing the environmental implications of PV waste, Daniela-Abigail et al. (2022) examined the environmentally vulnerable areas of Yucatan, Mexico, considering three dimensions: environment, economy, and society. Their findings advocate for implementing sustainable regulations governing PV waste, asserting the potential to reduce PV systems' EPBT.

doi:10.6342/NTU202400056

2.5 Analytic Network Process (ANP)

Saaty (2004) claimed that the ANP is a measurement multicriteria theory employed to originate absolute numbers of relative priority scales from individual judgments. These indicate the relative influence of one of two metrics over the other by pairwisely comparing the process on a third metric in the system regarding an underlying control criterion. The ANP synthesizes the dependence outcome and feedback within and between metrics clusters through its supermatrix. The ***A*****nalytic Hierarchy Process (AHP)** is a specific ANP case. It has independent hypotheses on upper levels from lower levels and the metrics independence in a level. The ANP is an essential tool in helping us determine an issue.

Ergu et al. (2014) presented a maximum eigenvalue threshold as the ANP consistency index in a decision analysis and risk assessment. The threshold is mathematically equivalent to the **consistency ratio (CR)**. To reduce consistency test times, they introduced a block diagonal matrix to perform consistency tests simultaneously for all comparison matrices. An induced bias block diagonal comparison matrix can also identify and adjust the inconsistent elements. They reveal the effectiveness and simplicity of the consistency test method by their proposed maximum eigenvalue threshold, inconsistency identification, and adjustment method shown by two illustrative examples of emergent situations. Cakmak and Cakmak (2014) analyzed the

doi:10.6342/NTU202400056

leading causes of disputes in the construction industry. To reach this aim, they undertook a literature review to identify the common construction disputes. They classified the disputes from a cross-section of the literature into main categories. They determined the leading causes of construction disputes. Finally, they performed an analysis using the ANP to determine their relative importance.

Lin et al. (2015) applied the ANP to supplier selection at a Taiwanese Electronics Company. Results show that using ANP helps to arrest the imprecision in human judgment. With ANP’s assistance, they take a company's holistic view in the decision-making process and develop a framework to enable its general application, environmental protection, and economic development. Hashemi et al. (2015) used economic and environmental criteria to propose a comprehensive green supplier selection model. They used ANP to deal with the interdependencies between the criteria. They modified the traditional Grey relational analysis (GRA) to better address the uncertainties inherent in supplier selections, weigh the criteria, and rank the suppliers. The proposed approach allows decision-makers to attain the assessment process.

Aragonés-Beltrán et al. (2017) presented a method to measure stakeholders’ influences within a project from the project manager’s perspective. They calculated the index with the ANP by breaking down its influence into criteria, assessing different aspects that define an index that measures each stakeholder’s influence concerning the

doi:10.6342/NTU202400056

rest of the project team. Results reveal that the most influential stakeholders are the signaling systems provider and the contractor, accounting for 40% of the total influence. These findings have helped the project manager be aware of the two most influential stakeholders and set future stakeholder management guidelines. Kadoić et al. (2018) reviewed possible method upgrades that might decrease the original ANP complexity. They explored this by structuring the problem as a weighted graph and using the compatibility concept between interdependent matrices in the ANP. Chen et al. (2019) used bibliometric techniques to overview the ANP research status and development characteristics to help researchers in future research directions. They concluded ANP's past and present hotspots and determined future research trends. They performed the bibliometric analysis from 1485 ANP-related publications. Investigators retrieved them from the Web of Science. Results indicate that Expert Systems with Applications was the most productive journal publishing articles (118) in ANP research.

2.6 Cost-Benefit Analysis (CBA)

Mouter et al. (2013) systematically overviewed the attitudes of critical actors in the Dutch CBA practice in the decision-making process for spatial infrastructure plans. They scrutinized the extent to which there is agreement among these Dutch actors regarding the role of the CBA in the decision-making process. This study's most important conclusion is that in Dutch CBA practice, there is agreement that CBA must

doi:10.6342/NTU202400056

play a role in the appraisal process of spatial infrastructure projects. The FPV can compete with LPV in Spain regarding the electricity cost and profit in a lifespan when affirming the prospective lower operating temperatures. The maximum acceptable capital expenditure also varies with the location (Atlason & Unnthorsson, 2014). Annema et al. (2015) proposed what is a helpful transport policy appraisal tool from a politician's perspective. They interviewed twenty-one Dutch transport politicians' views on CBA. Results show that they use CBA in a non-decisive manner and find the aggregate outcome (the composite result) of CBAs pretentious. They seem especially interested in appraisal tools that clearly show the critical political trade-offs of a transport policy.

Asplund and Eliasson (2016) proposed a question of how robust the policy conclusions of CBA are related to uncertainties. They used simulations based on actual data on national infrastructure plans in Sweden and Norway. They studied how total realized benefits change and investment selection when making decisions based on CBA evaluation vulnerable to different uncertainty types. Their findings showed that realized profits of the investment option are considerably insensitive to all studied uncertainty types, even for high levels of uncertainty. Manning et al. (2016) summarized the significant steps used in CBA. They included a discussion of incremental cost-comparison analysis, the optimal choice of program, and incremental cost analysis. They identified and described nine steps, such as

doi:10.6342/NTU202400056

specifying alternatives, deciding whose costs and benefits to include, and performing the production of sensitivity analysis. Carolus (2018) investigated the possible prerequisites, limitations, and advantages of applying CBA in what may be considered an alternative, “bottom-up” approach. They suggested an approach begins with the underlying environmental problem and then assesses the benefits and costs of solutions and strategies as identified by directly affected and local stakeholders.

Regarding two river catchments in Sweden and Latvia for the empirical case study, they used the bottom-up CBA approach to assess plans for local conditions. However, they are also likely more acceptable to local society and shed additional light on possible distributional effects. By benefitting from and supporting participatory environmental planning, bottom-up CBA aligns with the growing trend of embedding stakeholder participation within decision-making and environmental policy.

Two scholars provided an up-to-date overview of recent literature regarding CBA's application and development on Transport Policy and Planning. They elaborated on CBA's history and its foundations in welfare economics. They reviewed the literature on recent developments and debates on the method and the literature to practice the CBA. They described research challenges associated with CBA to respond to future research (Koopmans & Mouter, 2020). Micheli (2021) assessed the maximum capital budget, the Levelized Cost of Energy, and the **NPV** of latent **in-land photovoltaic (LPV)** and FPV

doi:10.6342/NTU202400056

deployments in Spain. He concluded that FPV installers should optimally make the PV systems profitable as stations. Biancardo et al. (2023) performed a CBA correctly and designed sustainable infrastructures. In the case of infrastructures, it is imperative to demonstrate the impacts of their construction most efficiently and show them to all the involved stakeholders. The findings demonstrate the utilization of this framework in the context of a Building Information Modeling (BIM)-centered design methodology applied to the ongoing construction of the Napoli-Bari High-Speed Rail corridor.

2.7 Comparative Economic Analysis and Carbon Pricing (CP)

2.7.1 Comparative Economic Analysis

A **comparative economic analysis** is a method used to evaluate and compare different schemes or projects based on their economic aspects. It involves assessing each scheme's costs, benefits, and financial implications to determine their relative economic viability and potential return on investment (Wu, 2021). By systematically analyzing different schemes' costs, benefits, financial indicators, and risks, decision-makers can make informed choices and help consider the financial implications of different options (Cookson et al., 2017). They provide valuable insights into each option's economic feasibility and potential returns, helping prioritize schemes that offer the most favorable economic outcome (Jouny et al., 2018). The following factors are indispensable for performing comparative economic analysis.

doi:10.6342/NTU202400056

(1) Benefits: The analysis examines each scheme's potential tangible and intangible benefits. Tangible benefits include revenue generation, cost savings, increased productivity, and improved efficiency. Intangible benefits involve environmental impact, social welfare, or stakeholders' satisfaction. These benefits are usually assessed in monetary terms wherever possible to facilitate comparison (Joseph et al., 2015).

(2) Costs: The analysis identifies and quantifies all costs associated with each scheme under consideration. It includes capital costs (like initial investments and equipment expenses), operating costs (like maintenance, labor, and energy), and other relevant expenses. Considering short-term and long-term costs throughout the scheme's life cycle is critical (Li et al., 2020).

(3) Financial indicators: In comparative economic analysis, researchers frequently utilize diverse financial indicators to assess the economic viability of each scheme. The set of conventional metrics comprises **the net present value (NPV)**, **internal rate of return (IRR)**, **benefit-cost ratio (BCR)**, and payback period. These metrics offer a quantitative gauge of the economic allure of each scheme, facilitating their ranking according to financial performance (Khamharnphol et al., 2023).

(4) Sensitivity analysis: Performing each scheme's metrics sensitivity analysis, i.e., the variation of financial indicators, such as costs, benefits, or interest rates, helps decision-

doi:10.6342/NTU202400056

makers better understand the risks, uncertainties associated, and crucial changes in critical variables or assumptions with each option (Kropf et al., 2022).

(5) Risk assessment: It helps decision-makers understand each scheme's potential vulnerabilities and uncertainties and guides them in developing risk mitigation strategies. The analysis must consider risk factors associated with each scheme. It includes evaluating potential risks affecting costs, benefits, or overall financial performance (Thorne et al., 2018).

2.7.2 CP

CP is a policy approach to reduce GHG, specifically carbon dioxide (CO_2) emissions. It involves the emissions of industries and activities that produce GHG (Nippa et al., 2021). It is often considered a flexible and market-based approach, which provides economic incentives for emission reductions and allows market forces to determine the most cost-effective solutions to addressing climate change.

Additionally, the fundamental idea behind CP is to create economic incentives for individuals, businesses, and governments to mitigate their carbon footprint and transition to cleaner, more sustainable alternatives (Nippa et al., 2021). It can generate revenue reinvested in sustainable development, climate adaptation, or supporting disadvantaged communities affected by the transition to a low-carbon economy. Usually, it imposes a carbon tax or an

doi:10.6342/NTU202400056

emission trading system (ETS), a requirement to purchase credits to make up for excess discharges (Nippa et al., 2021; Rontard & Hernández, 2022).

A **carbon tax** is a direct levy imposed on the carbon emissions content associated with fossil fuels. Typically, the government applies this tax to fuel producers or importers, contingent upon the anticipated CO_2 emissions generated. By increasing the cost of carbon-intensive activities, such as burning coal or using gasoline, carbon taxes encourage individuals and businesses to seek out lower-carbon alternatives.

ETS, known as cap-and-trade systems, implements and meets specific mitigation targets limiting the remaining carbon budget subsidies (Stavins, 2022). It establishes a cap or limit on the total GHG allowance emissions released by covered industries or entities within a specific jurisdiction. The tolerated emissions, representing the right to emit a particular GHG estimate, are distributed among these organizations. If a maker emits less than its allocated capacities, it can sell the excess to other entities needing additional amounts. It creates a market for trading emissions permits, enabling organizations to buy or sell allowances based on their emissions needs. The overall emissions cap declines over time, reducing the total emissions allowed. Scientists consider it efficient, covering 21.7% of global GHG emissions in 2021 (Hagmann et al., 2019). Rogelj et al. (2018) and Ritchie et al. (2022) declared that an approbated pricing level should be $100–5500 in 2030 to contribute to climate change (Hurwitz et al., 2020).

doi:10.6342/NTU202400056

The underlying principle of the carbon tax and ETS is to internalize the social cost of carbon emissions (Zhou, 2022). By assigning a price to carbon, these mechanisms reflect the environmental and societal damages caused by GHG emissions. The elevated expenses linked to carbon emissions incentivize businesses and individuals to embrace cleaner technologies, enhance energy efficiency, allocate resources to renewable energy sources, and investigate alternative low-carbon practices (Li & Yao, 2020). Notably, CP is just a tool in a broader set of policies and actions needed to tackle climate change effectively. It is often implemented alongside regulations, subsidies, research and development initiatives, and international cooperation to achieve substantial emissions reductions and mitigate the impacts of climate change (Blanchard et al., 2023).

doi:10.6342/NTU202400056

Chapter 3 Research Framework

After a thorough review of the existing literature, the author crafted the framework for this dissertation, aiming to address significant gaps and challenges in the field of solar power, particularly in the context of FPV systems, as shown below.

Though solar power is one of the primary alternatives to conventional energy, we cannot use it as a base load power source to provide stable energy due to its vulnerability to climate. **Existing research has established models to analyze PV systems' efficiency, reliability, and safety. However, it has not yet presented a more straightforward indicator for assessing FPV power supply.** This dissertation proposes a synthesis methodology based on the **Exceedance Probability** and **Weibull Function** (Bailey & Dell, 1973) approaches to analyze the power supply reliability by conducting a case study of Agongdian's FPV system. The study results should benefit the FPV development in the areas with small lands but available water bodies and lacking power.

Considering the grid's resilience and investment feasibility, clarifying that the solar business is still a low-return energy industry after the creation of PV technology and determining the optimal scheme for transnational investors is crucial. Much literature did not deliver estimates of the **LCA** or **LCEA analyses.** Consequently, they facilitate **EPBT** and **EROI analysis** outcomes. Unlike the previous research on solar energy's ER assessment, this dissertation used time-series and LCEA-based ER estimation

doi:10.6342/NTU202400056

to evaluate the 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 clarify whether the technique innovation benefits from improving the system's capability compared to the traditional skill.

Additionally, several studies have elaborated on FPV's advantages and disadvantages (Ranjbaran et al., 2019). Most focus on contrasting the conversion efficiency and cost with **LPV** systems, improving water quality, and mitigating water evaporation. Academic circles need more literature using comparative economic analysis to determine an optimal scheme and the potential benefits of carbon trading on FPV funding to help investors make decisions. This dissertation compares the financial gains of FPVs of Japan's Yamakura Dam and Taiwan's Agongdian Reservoir using time series, ANP, and financial indicators analyses to determine which scheme is optimal. The methodology presented in this paper provides comprehensive views. It should help stakeholders comprehend advantages and determine a favorable funding decision.

Chapter 1 aims to link the subsections closely, guiding the reader through systematically exploring energy definitions, types, renewable sources, alternatives, and specific solar technologies with real-world applications.

In this chapter, the introduction seamlessly connects a series of subsections to provide a comprehensive overview of the energy landscape, emphasizing the need for alternatives

doi:10.6342/NTU202400056

to traditional energy resources. The progression begins with **Subsection 1.1**, Energy Profile, delving into the Definitions, Sources, and Characteristics of Primary and Secondary Energies. It establishes a foundational understanding of the primary elements shaping the energy sector. In the same chapter, **Subsection 1.2** explores the spectrum of energy options, encompassing Conventional, Low-carbon, Clean, and Renewable Energies. This section aims to categorize and distinguish between different energy types, setting the stage for a nuanced discussion. The narrative then unfolds in **Subsection 1.3**, Common Renewable Energy Sources, delving deeper into the specifics of renewable energy. This section elucidates widely adopted and environmentally sustainable sources, offering insights into the renewable energy landscape.

Building on this foundation, **Subsection 1.4** explores Alternatives to Traditional Energy Resources. Here, the focus shifts to innovative approaches and substitutes, providing a nuanced understanding of diversification within the energy domain. Within the broader context of renewable energy, **Subsection 1.5** narrows the scope to PV, FPV, and OFPV systems and the significance of case studies. This subsection introduces specific solar energy technologies and incorporates practical applications through case studies, fostering a deeper comprehension of the discussed systems. Additionally, **Subsection 1.6** explains the rationality of case studies as research.

doi:10.6342/NTU202400056

Chapter 2 explores multiple facets of electricity supply, renewable energy systems, reliability, energy return (ER), and economic analysis in an academic and active context.

Commencing with **Subsection 2.1,** Power supply reliability, discusses ensuring consistent and dependable power availability. It sets the stage for a nuanced exploration of reliability considerations. Expanding on the groundwork in the preceding subsection, **Subsection 2.2** delves into the Reliability of PV and FPV systems. It focuses on the specific reliability challenges and solutions pertinent to PV and FPV (including OFPV) systems, offering a specialized examination within the broader context of power supply. Additionally, **Subsection 2.3 Exceedance Probability** extends the exploration by introducing the concept of probability in the context of energy systems. This subsection links reliability discussions and probabilistic considerations, fostering a more quantitative understanding of energy system performance.

Expanding the scope, **Subsection 2.4** LCEA and ER bring an assessable lens to the analysis. This subsection evaluates the energy efficiency of systems throughout their lifecycles. It introduces the concept of ER, enhancing energy technologies' economic and environmental perspectives. Segueing into decision-making methodologies, **Subsection 2.5** ANP introduces a structured approach to decision analysis, connecting reliability and lifecycle considerations to decision-making frameworks. It offers a systematic method to evaluate and prioritize factors influencing energy systems.

doi:10.6342/NTU202400056

The subsequent **Subsection, 2.6** CBA, integrates economic considerations into the discourse, providing a robust framework for evaluating the economic feasibility of energy projects. This subsection forms a crucial link between quantitative analysis and economic assessments. **Subsection 2.7**, Comparative Economic Analysis and CP broadens the discussion to encompass broader economic implications and policy considerations. This final subsection synthesizes the economic aspects discussed throughout the chapter, tying together the various threads of power supply reliability, system reliability, probabilistic considerations, lifecycle analysis, decision-making methodologies, and economic assessments.

Chapter 3, ”Research Framework,“ provides a foundation for exploring complex aspects of renewable energy, reliability, economic analysis, and case studies. It organizes various chapters and subsections within the dissertation. It sets the stage for exploring the intricate facets of renewable energy, reliability, economic analysis, and case studies.

Chapter 4, titled “Case Study 1: Power Supply Reliability Analysis on FPV,” delineates methodologies, presents empirical findings, and discusses the power supply reliability analysis conducted on the Agongdian Reservoir FPV system. This chapter ensures a comprehensive and academic exploration of the subject matter, emphasizing the intricacies of power supply reliability analysis through the Exceedance Probability approach within the context of the first case study.

doi:10.6342/NTU202400056

The case study of **Chapter 5** challenges conventional beliefs that Photovoltaics (PV) exhibit lower ER than fossil fuels, especially in the final stage. It explores the influence of solar module technology innovation on ER through extensive LCEA assessments. The research uses time series and LCEA analyses to evaluate the ER of the 181 MWp OFPV system at Changhua Coastal Industrial Park over a 30-year lifecycle.

Chapter 6, "Case Study 3: Determine the Optimal Scheme for FPV," employs a robust analytical approach, integrating time series forecasting, ANP, and financial analyses to determine the more favorable FPV commerce investment between Taiwan's Agongdian Reservoir and Japan's Yamakura Dam. While existing literature explores various aspects of FPV, a critical gap exists in the comparative economic analysis for optimal schemes, which is crucial for investor decision-making. In the context of global economic challenges, post-epidemic events, geopolitical conflicts, and financial uncertainties, the study identifies critical metrics influencing FPV deployment scales.

This dissertation systematically assesses the power supply reliability of FPV, conducts empirical analyses on the ER of OFPV, and integrates FPV economic analysis and case studies. **Chapter 7** synthesizes the accumulated findings and contributions from the preceding six chapters within the dissertation framework. It critically reviews the limitations encountered during the research and delineates future research directions suggested by peers for further investigation.

doi:10.6342/NTU202400056

Chapter 4 Case Study 1: Power Supply Reliability Analysis on FPV

4.1 Study Area: Agongdian Reservoir FPV System

The Agongdian Reservoir FPV system (depicted in Figure 7) stands out as one of the largest commercial installations among existing projects, significantly contributing to the advancement of FPV technology in Taiwan (Water Resources Agency, 2023). This research designates it as a case study to examine the reliability of FPV power supply and demand.

(a) On-Site Photograph (b) Image Courtesy: Water Resouces Agency

Figure 6: FPV Installation at Agongdian Reservoir

4.2 Specifications of Solar Modules Used in Agongdian Reservoir's FPV System

The TAIWAN Plus PV technical specification mandates the utilization of high-efficiency solar modules with a 25-year output warranty for government-recruited projects since 2019. Table 7 and Figure 8 present the

doi:10.6342/NTU202400056

specifications, asserting compliance with the National Standards of the Republic of China (CNS) 15114 and 15115 (Bureau of Standards and Inspection, 2016).

Table 7: Electrical Specifications (Source: Motech, 2023)

P_{max}	>315W_p
V_{max}	>33.55V
I_{max}	>9.39A
V_{oc}(Open Circuit Voltage	>39.33V
I_{sc} (Short Circuit Current)	>9.56A
Efficiency (%)	>19.36
V_{sys}(Maximum System Voltage)	DC1000V
Maximum Series Current	>15A

Note: Standard Test Conditions (STC) with a temperature of 25°C and an irradiance of 1000 W/m² (AM1.5) (Huffman & Antelme, 2009)

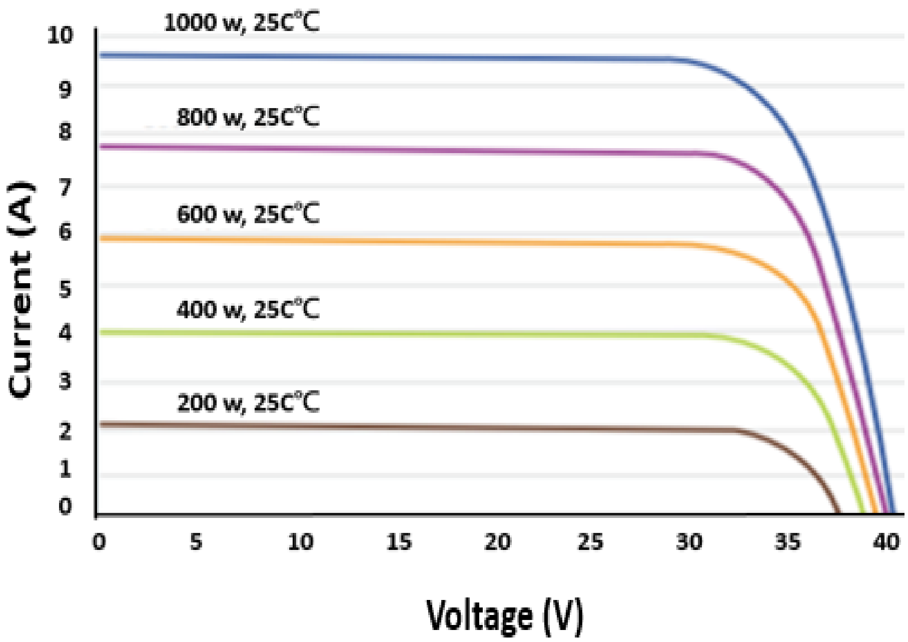


Figure 7: Current-Voltage Characteristics (I-V Curve) (Motech, 2023)

doi:10.6342/NTU202400056

4.3 Methologies

4.3.1 Time Series Analysis

Time series analysis employs the theory of random processes and mathematical statistics to forecast future values based on historical data. Typically, sequential, random data pertains to time, involving statistical examination such as autocorrelation analysis (Mills, 2019). In time series analysis, instances where a deterministic trend dictates that the process's realizations depend on a fixed function of time, like a high-order polynomial equation (7).

$$y_t = \beta_0+\beta_1 t+\beta_2 t^2+\beta_3 t^3 \quad (7),$$

where y_t is dependent on t. By introducing a stationary component to the trend, we can modify it as equation (8), given by

$$y_t = \beta_0+\beta_1 t+\beta_2 t^2+\beta_3 t^3+\varepsilon t \quad (8)$$

The process is said to be trend-stationary. Long-run forecasts will converge to the trend. In the simplest case, we have $y_t = \beta_0 + \beta_1 t$, a linear trend, which described as equation (9).

$$\Delta y_t = \beta_0, \text{ or } \Delta y_t = \beta_0+\varepsilon t \text{ (incorporating noise).} \quad (9)$$

A dataset comprising 5,479 observations on insolation, sunshine hours, radiation amount, and principal component specifications was gathered and compiled (Central

doi:10.6342/NTU202400056

Weather Bureau, 2023). Additionally, the author conducted a comparison and analysis of the installation settings at Agongdian Reservoir and Yamakura Reservoir alongside the "Technical Specifications for High-Efficiency Solar Modules" issued by the Bureau of Standards, Metrology, and Inspection in 2019 as part of the system reliability analysis (Bureau of Energy, 2023; Japan Dam Foundation, 2023).

4.3.2 Power Supply Reliability Analysis of FPV systems based on Exceedance Probability Approach

In analyzing power supply reliability, the exceedance probability approach establishes a robust framework for evaluating power supply dispatch. This method sets multiple thresholds for actual demand based on extensive long-term meteorological data specific to local power plants. The strategic directions for implementing this approach are outlined as follows:

(1) Integration of the Mann-Kendall and Auto-Correlogram Tests

It involves synthesizing statistical methods, specifically the **Mann-Kendall** and **auto-correlogram** tests. This integration is instrumental in comprehensively analyzing an FPV system, allowing for a pre-examination of the correlation between preceding and lagging meteorological data. Such an approach enhances the predictive capability of the system, providing valuable insights into its performance.

doi:10.6342/NTU202400056

(2) Developing a Practical Approach to Electricity System Assessment

The strategy aims to create a practical methodology for assessing the FPV system's ability to meet near-future electricity demands effectively. This endeavor entails establishing robust procedures to evaluate the system's electricity generation capacity vis-à-vis anticipated user demand. The focus is on devising a method that harmonizes real-world scenarios and facilitates informed decision-making regarding power supply reliability

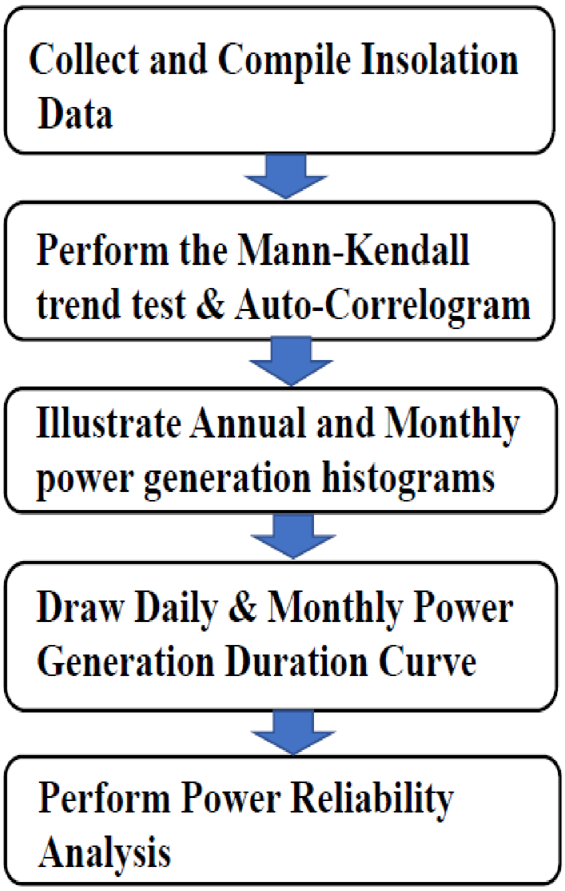


Figure 8: Flowchart of Power Supply Reliability Analysis for Agongdian Reservoir FPV

doi:10.6342/NTU202400056

Based on these tactics, the research devised the following steps, outlined in **Figure 9**, to apply the exceedance probability method for analyzing the reliability of the power supply and demand capacity of the FPV system. **The measures encompass data collection, determination of the time series trend, and illustration of the auto-correlogram.** The author calculated annual and monthly power generation and plotted curves for daily and monthly power generation duration. Then, he analyzed the reliability of the power supply and demand capacity. **The second step** involves assessing whether the collected data will continue to increase or decrease over time. **Steps 3 to 4** encompass illustrating the auto-correlogram, computing annual and monthly power generation, and plotting daily and monthly power generation duration curves. **The final step** involves analyzing the power supply and demand reliability of the FPV system in the Agongdian reservoir.

4.4 Results

4.4.1 Collection of Time Series Data

In the study, the researcher chose sunshine duration instead of terrestrial solar radiation from the Central Weather Bureau’s report on climate change in Taiwan over the past century (1994) to elucidate Taiwan’s insolation variation. The Bureau uses sunshine hours, considering the total radiation amount in the area (global insolation) exceeding 120 w/m² (Chang et al., 2016) as significant. For instance, if the total sky radiation surpasses

doi:10.6342/NTU202400056

120 w/m² for 30 minutes within an hour, then the number of sunshine hours in that hour is considered 0.5. Consequently, these hours represent only the duration when the radiation amount surpasses the threshold. Although this value does not precisely reflect the amount of sunshine, it signifies the light intensity condition necessary for solar module electricity generation (Reich et al., 2009).

Additionally, based on the Central Weather Bureau’s average solar radiation data in the Kaohsiung area from 2007 to 2011, which was 1484.4 kWh/m2 (Central Weather Bureau, 2023), the daily effective power generation hours are estimated at 4.07 hours, equivalent to the 4 hours discussed in this dissertation. In this case study, the author collected and compiled five thousand four hundred seventy-nine data on insolation, sunshine hours, radiation amount, and the specifications of principal components (Central Weather Bureau, 2023). He also investigated the “Technical Specifications for High-Efficiency Solar Modules” issued by the Bureau of Standards, Metrology, and Inspection in 2019 for the system reliability analysis. (Bureau of Energy, 2023; Japan Dam Foundation, 2023).

Using the Mann-Kendall trend test, the researcher transformed and fitted the 180-monthly time-series power generation data from January 2006 to December 2020. **Figure 10** shows the test result (Mann, 1945; Kendall, 1975). **Figure 11** illustrates the auto-correlogram for the 180-sample data. By shifting the data value and calculating the

doi:10.6342/NTU202400056

correlation between the original and the lag values, the researcher generated an auto-correlogram graph to ascertain data convergence. The results indicate that the autocorrelation function between the original and the lag values gradually decreases, and the autocorrelation gradually converges and approaches zero after 130 lags. It indicates a correlation between the two sets of data (Box et al., 1994). The alignment of the test results of the Mann-Kendall and the auto-correlogram, along with $T_{\alpha/2} > 1.96$ (where T indicates the trend sign value; $T_{\alpha/2} = 2$ under the condition of significance level α=5%), demonstrates a correlation between the original and lagging data, indicating that the trend meets the null hypothesis. Consequently, the author concluded that the time series steadily grows (Salas, 1993).

Unit: kWh

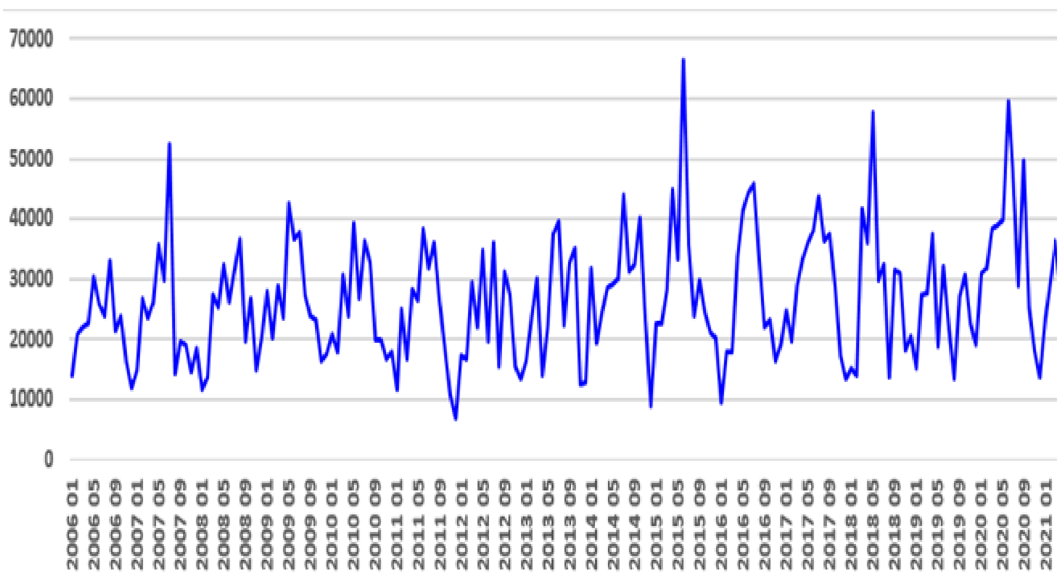


Figure 10: Trend Analysis of 180 Monthly Power Generation Data

doi:10.6342/NTU202400056

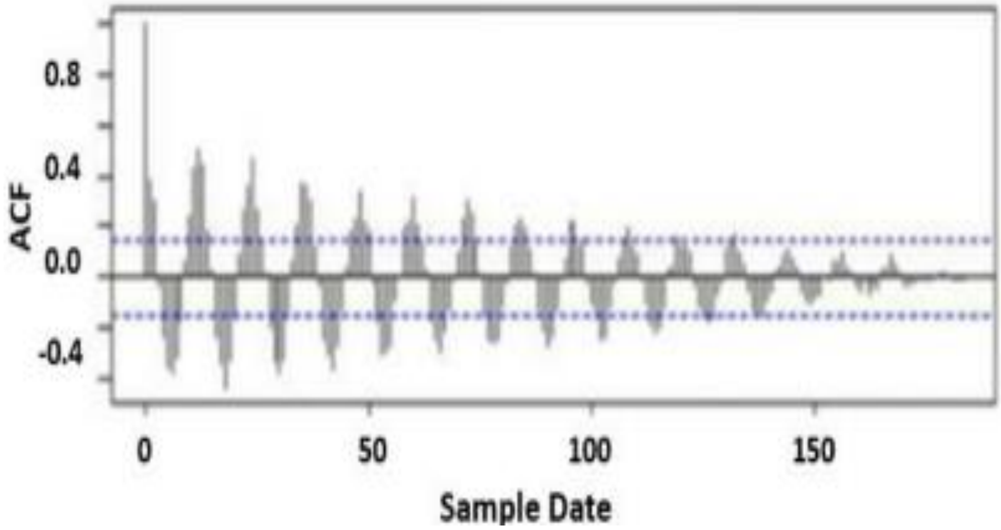


Figure 11: Auto-Correlogram Analysis of 180 Monthly Power Generation Data

4.4.2 Analysis of Annual and Monthly Power Generation with Power Generation Duration Curves

Unit: kWh

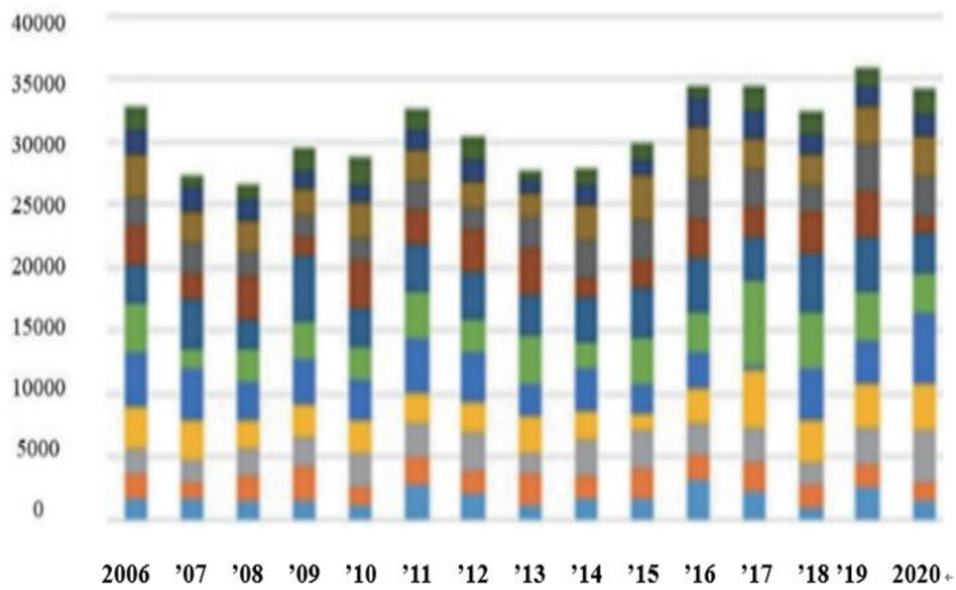


Figure 12: Annual Electricity Generation from 2006 to 2020

Note: There are twelve colors, with blue indicating the lower end and green indicating the higher end, representing the annual power generation from January to December.

doi:10.6342/NTU202400056

Unit: kWh

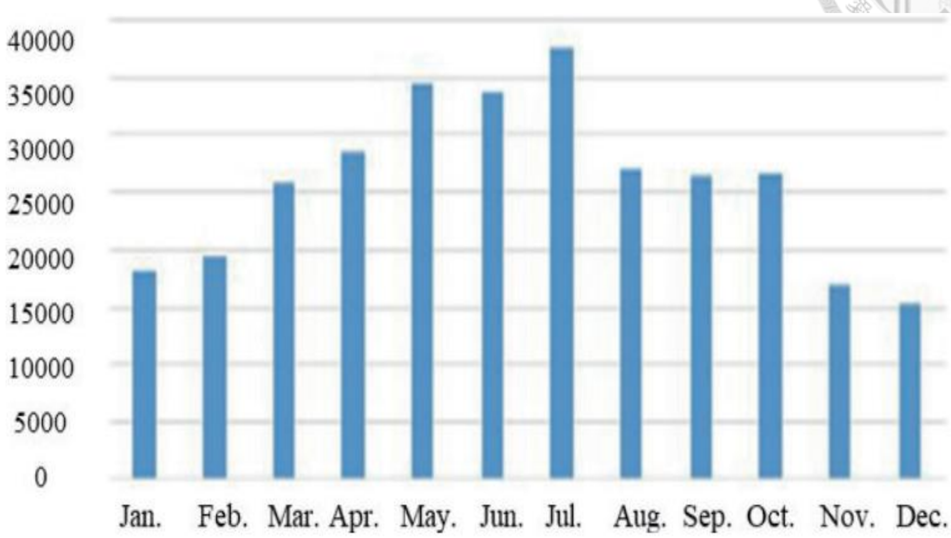


Figure 9 Average Monthly Electricity Generation Amount from ’06 to ’20

Figures 12 and 13 show annual and monthly power generation histograms from January 2006 to December 2020, respectively. They illustrate that consistent annual power generation results vary with climate conditions. The average power generation in summer is prominently higher than in winter. It is the highest from May to July, while significantly lower than in summer from November to February (Singh, 2013).

To understand whether the power generation will exceed or fall below the specific power consumption value in a period, we can obtain it by calculating and sorting all the daily power generation data through equations (10) and (11) from January 1, 2006, to December 31, 2020. The Weibull method expressed in equation (12) helps sort and descend the monthly power generation data in order (**Table 8)**. Then, we can achieve the total number of samples N_{ts}, the number of rankings m_r, and the value of **Excess**

doi:10.6342/NTU202400056

Probability P_{ex}% with **the Weibull function**. Consequently, we can illustrate the daily and monthly duration curves based on the calculation results.

$$G_{effh}\,(h/day) = MJ/d \div 3.6\ MJ/kW \cdot m^2 \div [1kW/(hrs/d \cdot m^2)] \quad (10)$$

$$Y_{die} \equiv G_{effh}\,(h/day) \times 1000\ W/m^2 \div 1000\ W/kW \times C_{eff} \times S_{eff} \times (1-D_{ar}) \times (1-M_{dt})\ (kW/m^2) \quad (11)$$

Where Y_{die} represents the daily incident energy. G_{effh} means effective daily electricity generation hours (4 hours in southern Taiwan). C_{eff} denotes solar module photoelectric conversion efficiency. S_{eff} is system efficiency. D_{ar} represents the annual decay rate (1% based on annual average) (Staeble and Wronski, 1977). M_{dt} means the proportion of downtime for system shutdown and maintenance (5% based on sound management).

$$P_{ex} = m_r \div (N_{ts} + 1) \quad (12)$$

Table 8: Monthly Power Generation Exceedance Probability Statistics

Unit: kWh

Ex. Pro.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct...	Nov.	Dec.
0.1	29,523	25,627	34,995	39,575	48,973	53,278	48,383	36,530	34,605	37,056	22,045	20,381
0.2	24,333	23,460	29,925	33,575	42,441	38,598	44,052	35,409	32,213	32,,765	19,603	19,990
0.3	21,108	21,182	29,065	33,265	41,087	38,224	40,946	33,073	31,313	29,336	18,391	18,719
0.4	16,924	20,153	28,682	30,236	37,913	37,129	38,960	32,255	28,379	27,176	17,136	18,319
0.5	16,184	19,527	27,239	28,313	35,751	30,201	36,431	30,413	25,588	24,359	16,490	17,664
0.6	15,603	18,498	23,911	25,670	33,430	29,766	35,794	25,214	23,869	23,932	16,377	13,445
0.7	14,,644	17,520	21,504	23,834	30,120	26,710	32,350	21,729	21,823	23,321	15,358	12,609
0.8	12,100	14,588	18,271	22,717	26,898	25,878	31,691	16,128	20,215	20,539	14,682	10,198

doi:10.6342/NTU202400056

0.9	10,734	13,700	16,867	18,823	14,784	18,050	28,428	14,059	19,592	18,864	11,728	8,056

Figure 14 shows the difference in the daily power generation to illustrate the duration curve. In contrast, **Figure 15** provides a variety of potential monthly power ratios, explains the potential power generation of the PV system under different climatic conditions, and illustrates the Exceedance Probability distribution curve based on the possible power generation data.

As seen above, researchers can use the exceedance probability as a risk indicator (Meydbray et al., 2008; Piechota et al., 2001). When the daily power generation is lower than the specific value, the local power plant must dispatch insufficient electricity to meet users' demands. Therefore, this indicator can help power companies consider adopting curtailment measures or increasing the power generation to provide the power consumption required by the users. These two figures allow power companies to view more macroscopically how to dispatch power supply between FPV and self-owned power plants to meet the power needs of users (Lin et al., 2012). Indeed, as the daily climatic conditions change, a shorter-term duration curve will be more helpful to power scheduling.

doi:10.6342/NTU202400056

Unit: kWh

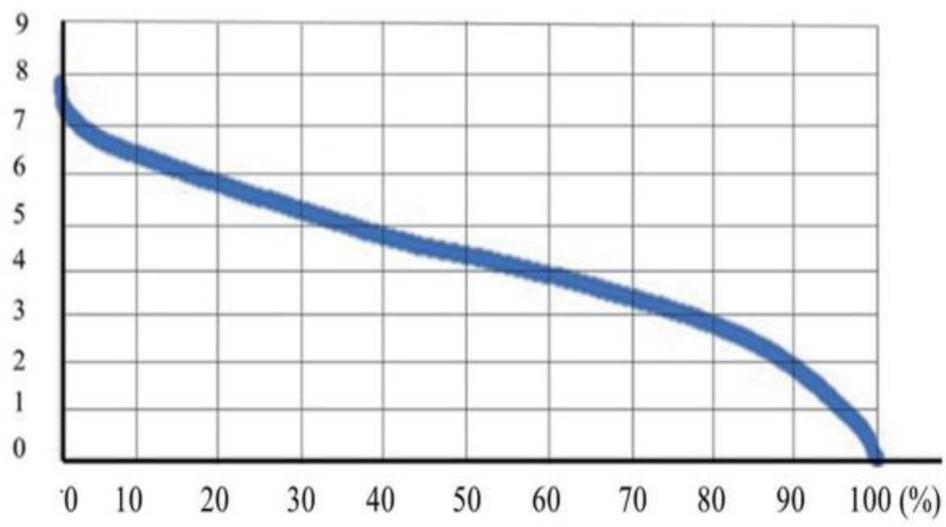


Figure 14: Duration Curve of Daily Electricity Generation

Unit: kWh

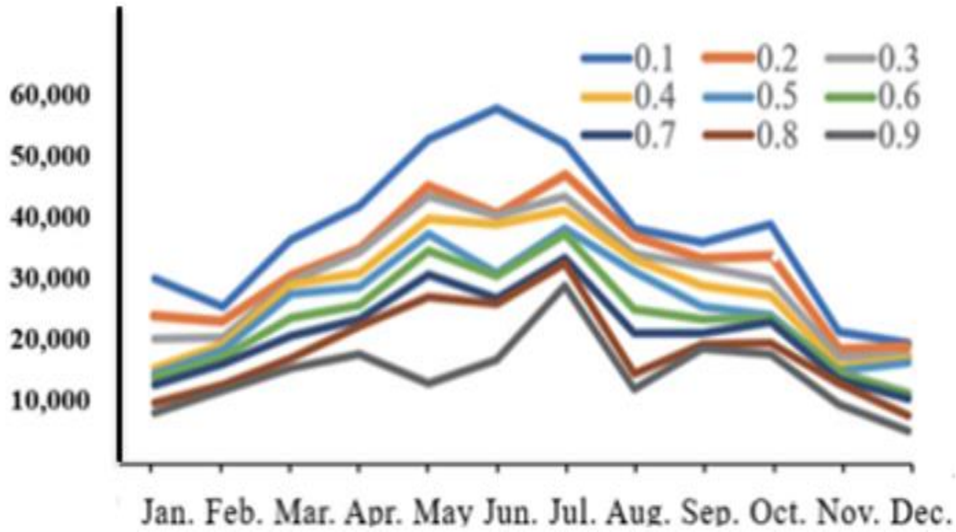


Figure 15: Duration Curve for Monthly Electricity Generation

4.4.3 Conducting an Analysis of Power Supply Reliability

Using the total household population in Gangshan District allows for the estimation of electricity consumption. Assuming that each household consumes 12

doi:10.6342/NTU202400056

kWh of electricity daily, the collective daily electricity consumption amounts to 421.74 MWh. Subsequently, the installed capacity of solar modules will be 185 MWp, as determined by Equation (13) (Bureau of Energy, 2022; Staeble & Wronski, 1977).

$$C_{ins} = D_{dp} \div P_{eg} \div S_{eff} \div (1-D_{ar}) \div (1-M_{dt}) \quad (13)$$

Where C_{ins} represents the installation capacity of solar modules, D_{dp} signifies the daily power demand, P_{eg} denotes the daily effective power generation hours (Bureau of Energy, 2022), *S*eff represents the efficiency of the FPV system, typically calculated as 75% (Aihara et al., 2012), *D*ar represents the decay rate of solar modules, conservatively estimated at 20% (Staeble & Wronski, 1977), and *M*dt is the system shutdown and maintenance time, influenced by management and climatic factors such as typhoons and cloudy days, calculated as 5%. Assuming E represents the power supply and e represents the power demand, E must be greater than or equal to e to meet the user's power consumption. Therefore, the probability of occurrence is $P(E \geq e)$ or $1-P(E<e)$.

Consequently, replacing the demand with the probability distribution of a specific day yields a predetermined Exceedance Probability value. This value serves as a power supply and demand balance index to aid local power companies in transmitting electricity (Ang & Tang, 1984).

doi:10.6342/NTU202400056

4.5 Discussion

The analysis reveals a robust system performance ratio of 75%, achieved by utilizing 185MWp solar modules distributed across 1.59 km^2, approximately 5% of the reservoir catchment area (Southern Water Resources Bureau, 2022). This deployment injects 740 MWh of energy into the grid daily, satisfying around 2.11% of Taiwan's peak power demand. Moreover, it effectively meets the daytime electricity needs of Gangshang's thirty-five thousand one hundred forty-five households (TPC, 2022).

Taiwan's reservoir infrastructure, comprising 96 reservoirs, including 18 significant ones, showcases a diverse range of catchment areas, from 2.88 km^2 to 763.4 km^2, totaling 3749.44 km^2. Notably, the Agongdian Reservoir encompasses an area of 31.87 km^2, accounting for 0.85% of the total. Proposing the installation of FPV stations across these 18 reservoirs, employing the same solar module installation ratio, would yield a collective installed capacity of 2.18 GWp. This initiative would generate 7.26 GWh of power daily, considering the varied sunshine conditions of each reservoir, representing 20.74% of Taiwan's current daily peak power consumption of 35 GWh (Taiwan Power Company, 2022).

Furthermore, this strategy presents significant environmental benefits, including a reduction of approximately 226 kt of CO_2 emissions over a 20-year service life (Sultan et

doi:10.6342/NTU202400056

al., 2021), annual savings of 8.6 kt of water (Santafé et al., 2014), and the enhancement of water quality by inhibiting algae growth post-FPV system installation.

In response to the GHG Emission Reduction Management Act enacted on July 1, 2015, Kaohsiung and Pingtung emerged as Taiwan's pioneering cities enforcing total GHG control. They project this regulatory action to reduce approximately 1,920 kt of CO_2 emissions over 20 years (Sultan et al., 2021), aligning with the Kyoto Protocol's objectives and stabilizing atmospheric GHG levels amidst climate change.

Moreover, 47 countries implement domestic carbon trading platforms, indicating that green energy power generation systems with zero CO_2 emissions, such as FPV, benefit significantly from carbon rights trading (Shivam et al., 2021). Despite FPV's track record of no water pollution incidents in recent years, ongoing monitoring of water quality post-system installation remains imperative.

4.6 Summaries

This case study introduces a synthesis method to enhance an FPV system's reliability analysis, thereby fostering its operational dependability. The outcomes of this study have yielded significant contributions by:

(1) Investigate the correlation between previous and lagging data.

(2) Assess the presence of an upward trend and consistency in the series data (Mann, 1945; Kendall, 1975; Box et al., 1994).

doi:10.6342/NTU202400056

(3) Evaluate the reliability of the power supply to derive the monthly power generation duration curve.

(4) Provide local power companies with a balanced indicator to guide decisions regarding power curtailment measures or adjustments to system power generation on days where it deviates from this indicator value.

Moreover, the proposed methodologies offer potential utility in expanding FPV systems to regions lacking adequate power but possessing water bodies. However, given the limited sample data spanning only fifteen years in this study, including longer time scale samples for analysis would enhance the effectiveness of investigations. An essential avenue for future research is examining the optimal setting ratio for FPV system installation on water bodies to ensure minimal impact on water quality while maximizing economic benefits.

doi:10.6342/NTU202400056

Chapter 5 Case Study 2: ER Assessment on OFPV based on LCEA Perspectives

5.1 Study Area: Changhua Coastal Industrial Park's OFPV

The Changhua Coastal Industrial Park, as documented by the Water Resources Agency in 2023, stands as the most remarkable industrial zone within the district. Situated in the northwest corner of Changhua County, this industrial zone adopts an outlying island-type configuration stemming from land reclamation efforts. It positions along the western Taiwan Strait. It accommodates diverse industrial activities, research and development endeavors, recreational facilities, and tourist attractions. Spanning an expanse of reclaimed land, the investor has leveraged 176 hectares of the sea surface to accommodate over 570,000 solar modules, totaling 181 MWp in installed capacity. This initiative has established the world's most expansive OFPV station (**Figure 16**).

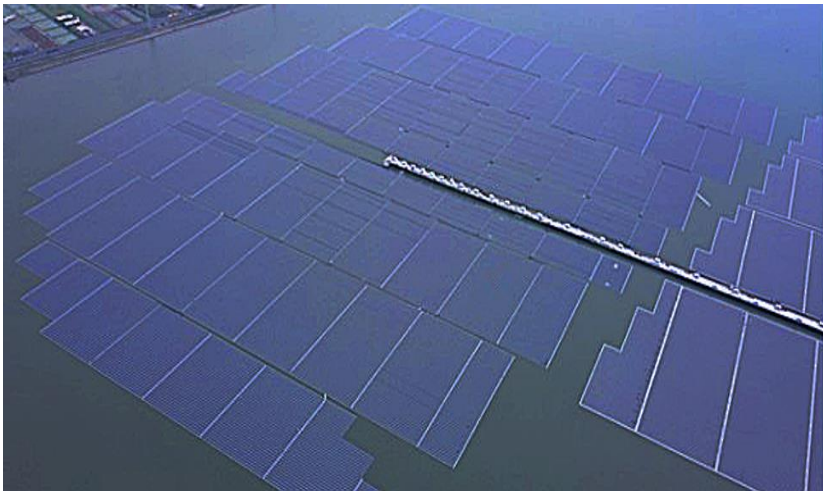


Image Courtesy: Water Resouces Agency

Figure 10 Changhua Coastal Industrial Park’s OFPV

doi:10.6342/NTU202400056

In contrast to OFPV installations in other countries, such as Singapore (5 MWp) and the Netherlands (8.5 kWp), where contractors typically locate them near the sea, the implemented OFPV system is positioned within the intertidal zone. This strategic placement allows the system to float on the water during high tide and rest on the ground at low tide. This approach streamlines large-scale construction and maintenance operations, guaranteeing minimal disruption to shipping safety. Since its inauguration in February 2021, the grid-connected system can provide electricity to approximately 41,000 households.

5.2 Methodologies

5.2.1 Energy Production

The power generation process depends on management decisions and various climatic factors, such as typhoons and earthquakes. Over 30 years, the total electricity production amounts to 5,435 GWh, as determined by Equation (14) (Bureau of Energy, 2022).

$$P_p \equiv C_{ic}\,(kWp) \times G_{efh}\,(h/day) \times 365.25\,(day/year) \times T_{lc}\,(years) \times S_e \times (1+\alpha) \times (1-D_r) \times (1-M_{dt}) \quad (14)$$

P_p: 30-year Period of Power Production

C_{ic}: Solar Module Installation Capacity (kWp)

G_{efh}: Effective Daily Electricity Generation Hours (h/day)

doi:10.6342/NTU202400056

T_{lc}: Life Cycle Duration (years)

S_e: System Efficiency (assumed at 75%) (Bhandari et al., 2015)

α: Diode Ideality Factor (estimated at 11%) (Choi, 2014)

D_r: Solar Module Decay Rate (decreasing by approximately 1% annually over 30 years) (Staebler & Wronski, 1977)

M_{dt}: System Downtime (Assumed at 5%) (Ortiz et al., 2009)

5.2.2 Defining Boundaries and Normalizing Primary and Secondary Data

This study centers on the solar panel factory situated in Tainan, Taiwan—a publicly listed corporation recognized for its proactive engagement in LCEA and distinguished administrative practices. Renowned as one of the top ten global producers of solar cells and panels, the company's prominence underscores the significance of our investigation. Our research scope encompasses a thorough examination of primary and secondary energy consumption data spanning the entirety of the plant's lifecycle. This analysis extends to evaluating energy usage across various stages, including raw material procurement, manufacturing processes, transportation, product utilization, as well as maintenance and repair activities.

It is crucial to emphasize that data collected from diverse sources must undergo normalization procedures to ensure accuracy and coherence. This normalization process

doi:10.6342/NTU202400056

enhances the reliability of the datasets, thereby establishing a robust and credible foundation for subsequent analyses and conclusions.

5.2.3 Calculation of EPBT and EROI

In assessing the viability of a new photovoltaic (PV) project, investors must ascertain the project's EPBT and EROI.

EPBT denotes the duration necessary for a power system to generate energy equivalent to the energy consumed during its production phase (Bhandari et al., 2015). Typically, researchers express EPBT in years, with a shorter payback period indicating more efficient energy recovery. Equation (15) (Bhandari et al., 2015) outlines the methodology for calculating EPBT.

$$P_{pb} = \frac{E_{im}}{\mathrm{Annual}(E_{out} - E_{lc})} \tag{15}$$

P_{pb} represents the energy payback period, E_{im} is the energy required to provide that energy (embedded energy), E_{out} is the annual energy production, and E_{lc} is the energy consumed during the FPV life cycle. Adding solar cell and cell raw material, we can achieve the P_{pb} (Louwen et al., 2015) about 1.38 years (local insolation:1278 kW/m^2•year), which complies with the upper limit of previous studies.

EROI is a pragmatic metric for evaluating energy economics and ecological energetics investments. It quantifies the ratio between the net energy output generated by the system (Eout-Elc) over its lifecycle and the energy input required to generate that

doi:10.6342/NTU202400056

output (Eim) (Bhandari et al., 2015). Equation (16) (Bhandari et al., 2015) delineates the equilibrium between the available energy resources derived from a defined set of energy sources.

$$E_{eir} = \frac{E_{out} - E_{lc}}{E_{im}} \quad (16)$$

E_{eir} represents the EROI, where E_{out} denotes the annual energy production, E_{lc} signifies the energy consumed throughout the FPV lifecycle, and E_{im} represents the energy required to provide that energy (i.e., embedded energy). When EROI exceeds 1, the total energy output surpasses the input energy, signifying energy efficiency. Moreover, a higher EROI value corresponds to enhanced energy output efficiency. Notably, the disparity between the total output and input energy must exceed one, as net energy equals an EROI value of 1 (Bhandari et al., 2015). According to Equation (6) (Bhandari et al., 2015), the calculated EROI stands at approximately 22.4 (local insolation: 1278 kW/m^2•year), aligning with the superior outcomes observed in prior research endeavors.

5.2.4 Evaluation of ER in LCEA-Based OFPV Systems and Flow Chart

This case study conducts a comprehensive analysis of LCEA and ER within the framework of the OFPV system deployed in the Changhua Coastal Industrial Park, covering a 30-year operational period. The research methodology entails the following sequential steps:

(1) Calculation of power generation.

doi:10.6342/NTU202400056

(2) Collection and normalization of primary and secondary data.

(3) Conduct LCEA analysis.

(4) Determine EPBT and EROI values.

Figure 17 depicts the research flow chart, illustrating the systematic progression of these analytical procedures.

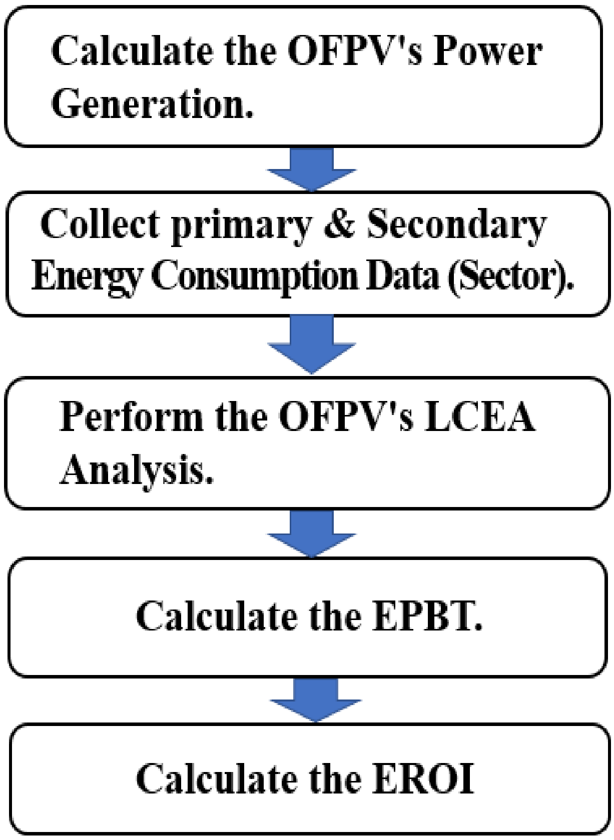


Figure 11: Flow Chart of LCEA and ER Analysis for OFPV Systems

doi:10.6342/NTU202400056

國立臺灣大學 · 愛國 · 勤學 ·

5.3 Results

5.3.1 LCEA Analysis

This study thoroughly examines LCEA and ER within the OFPV system at the Changhua Coastal Industrial Park. The LCEA analysis centers on assessing the EPBT and EROI of the targeted OFPV system over a 30-year operational period.

Throughout the LCEA analysis, the researcher extracts 15 years of meteorological data, which undergoes rigorous scrutiny through time-series trend testing and auto-correlogram analysis. Additionally, the technical specifications for high-efficiency solar modules, as mandated by the Bureau of Energy (2022), are thoroughly reviewed. Acquiring standardized activity data from the organization and applying a meticulous normalization process to primary and secondary datasets ensures consistency and reliability. This comprehensive approach bolsters the analytical framework, emphasizing the methodological rigor employed to derive meaningful conclusions.

Energy consumption stems from various activities, including product production and the operations of different departments, such as areas and percentages of energy utilization by facilities, including production and air conditioning. The allocation of energy flow and materials' emissions adheres to PCR's computational procedures. Results from the investigation reveal that the power consumption for producing 12,345 modules amounts to 2.5 GWh. In contrast, the air conditioning power consumption is 71.1 MWh

doi:10.6342/NTU202400056

(equivalent to 0.071 GWh), totaling approximately 2.6 GWh **(Table 9)** (Motech, 2023). Consequently, producing 574,603 modules (181 MWp) requires about 119.7 GWh based on proportionality. Combined with the power consumption of the solar cell and its raw materials, estimated at 62.2 GWh (Louwen et al., 2015), this yields a total power requirement of 181.9 GWh to produce 181 MWp solar modules.

In addition, the researcher assumes the system's operational efficiency to be 75%, considering power losses from inverters, transformers, and wiring. This estimation leads to a total power loss of approximately 1358.8 GWh over the 30-year operational lifespan.

Table 9: Electricity Consumption of Solar Modules (Source: Motech, 2023)

Product Name	315 Wp/h Monocrystalline Silicon Solar
Module (Efficiency)	19.36%
Lifespan	30 years
Product Maximum Output Power(Wp/h)	315 Wp/h
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

Table 10 presents the study's calculation results for EPBT and EROI. The recorded solar radiation in this case is 1278 kW/m²•year, notably lower than the benchmark of 1700 kW/m²•year set by Bhandari et al. (2015), Alsema and Frankl (1998), and Louwen et al.

doi:10.6342/NTU202400056

(2015) for optimal sunshine conditions. Upon recalculating the study results under these specified conditions, EPBT decreases from 1.38 to 1 year, while EROI increases from 22.4 to 29.8. Figure 18 illustrates the comparison results between this study and Bhandari et al. (2015) under various photoelectric conversion efficiencies of monocrystalline modules.

Table 10: Results of EPBT and EROI Calculations

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

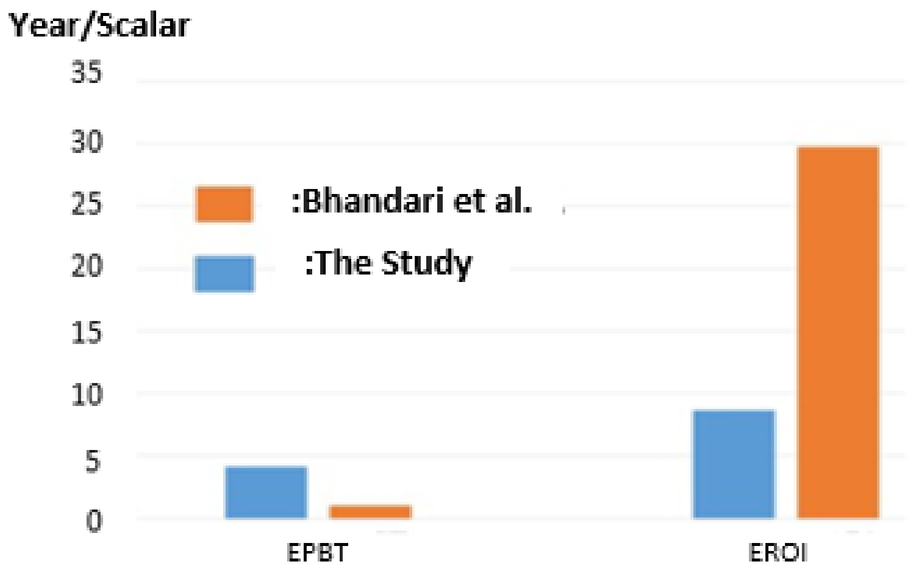


Figure 12: Comparison of EPBT and EROI between this study and Bhandari et al. (2015)

doi:10.6342/NTU202400056

5.4 Discussion

With the ongoing advancements in PV technology, including technologies like SHJ, PERC, high-efficiency N-type, and perovskite solar cells, alongside the adoption of thin silicon wafers and the transition from silver-based to copper-based metallization, it becomes imperative to reassess the ER of PV systems to provide stakeholders with informed decision-making.

As Brockway et al. (2019) highlighted, the EROI of fossil fuels exceeds 25:1 at the primary energy stage and hovers around 6:1 at the final stage. The EROI of fossil fuels may be more comparable to that of renewable energies than previously presumed. Meanwhile, Bhandari et al. (2015) concluded that the mean harmonized EPBT and EROI for various PV technologies range from 1.0 to 4.1 years and 8.7 to 34.2, respectively. However, Weißbach et al. (2013) proposed that hydro, coal, natural gas, and nuclear power systems surpass PV and wind in terms of efficiency.

Fukurozaki et al. (2013) found that the EPBT for current rooftop mountings ranges from 2.47 to 3.13 years, encompassing processes from metallurgical silicon growth to power generation. The analysis must encompass the primary energy requirements of cell raw materials and the production of system components such as module aluminum frames, cables, inverters, and transformers. Furthermore, consideration of the energy requirements throughout the transportation, installation, and disposal phases is essential.

doi:10.6342/NTU202400056

Thus, the reliability and validity of PV system ER analysis depend on clearly defined boundary settings within the LCEA process and subsequent vertical integration. Multiple factors shape research outcomes, encompassing project scale, system efficiencies (e.g., transformer and inverter efficiency), copper wire diameter and wiring length, solar module conversion efficiency, equipment installation location (radiation), onshore or offshore installation patterns, framework lifespan, and weak-light effects.

Despite the prevailing belief that PV ER indicators lag behind those of fossil fuels, the continuous evolution of PV technology underscores the necessity to reevaluate it for all concerned parties.

5.5 Summaries

Traditionally, people perceive that PV exhibits lower ER than fossil fuels, particularly in the final stage, where the EROI of conventional energy declines. This study actively investigates the influence of solar module technology innovation on ER through comprehensive LCEA assessments, focusing on the ER indicators of OFPV systems in Case Study 2. Comparisons are drawn with prior research, such as the work by Bhandari et al. (2015), to assess whether PV technology advancements lead to enhanced ER performance. Their earlier findings reported an EPBT of 4.1 years and an EROI of 8.7, assuming a 13% efficiency for monocrystal modules. They emphasized the importance of improving the embedded energy of PV systems through solar technology innovation

doi:10.6342/NTU202400056

for ER performance. A comparative analysis reveals substantial improvements in EPBT (reduced by approximately one year) and EROI (increased to about 29.8). This study unequivocally reaffirms and strengthens this conclusion. The proposed methodology holds promise for significantly contributing to future ER analyses of PV installations, providing valuable insights for investors contemplating photovoltaic projects.

While acknowledging limitations in the study scope, such as the exclusion of transportation and final disposal stages, the study argues that these aspects are relatively insignificant (less than 1% of the LCEA cut-off rule) in the system's lifecycle. As the fabrication of solar cells occurs in the manufacturer's overseas factory, the survey scope is limited to solar modules. However, to present the LCEA outcomes more accurately, the researcher incorporates previous findings on the energy consumption of solar cells into the study (Louwen, 2015). The impact of LCEA boundary setting and proposed future work includes conducting an ER investigation across the entire production chain in vertical segments and enhancing the robustness of LCEA assessments.

The study's methodologies have practical implications for related ER research and aid investors in decision-making for future PV projects. They offer practical benefits for ER-related studies and facilitate investors' decision-making for future funding in OFPV or other PV schemes (Alsema et al. (1998); Brockway et al. (2015); Bhandari et al. (2019)).

doi:10.6342/NTU202400056

Chapter 6 Case Study 3: Determine the Optimal Scheme for FPV

6.1 Study Area

In this study, the author conducted a comparative economic analysis of the FPV installations at the Agongdian Reservoir **(Figure 7)** and the Yamakura Dam **(Figure 19)**.

Image Courtesy: Kyocera TCL Solar

Figure 13: FPV Installation at Yamakura Dam

The latter, built in 1964, serves as a local industrial water source, with a water storage area boundary of approximately 61 hectares (Chiba Prefecture Water Works Bureau, 2022). PV units were installed on 18 hectares of the dam, making it Japan's most significant FPV deployment, generating approximately 15,636 MWh of electricity annually and supplying power to 4,700 local households (Kyocera TCL Solar, 2022). For international investors, carefully evaluating the advantages and disadvantages of the PV project site is crucial, as it directly impacts the profitability and willingness of

doi:10.6342/NTU202400056

transnational investors to invest. This study assumes that investors encounter and must address the challenges of selecting an optimal FPV implementation plan at the Agongdian Reservoir and the Yamakura Dam. The researcher chose these two sites for economic comparison due to their status as the largest FPV deployments in their respective countries and their nearly identical sunshine conditions.

6.2 Choosing Comparative Targets

This case chose to compare the Agongdian Reservoir and the Yamakura Dam for several reasons:

(1) They represent the most costly onshore FPV installations in their respective countries.

(2) They experience nearly identical insolation conditions.

(3) Both have achieved successful grid connections.

(4) Both sites face land scarcity and negligible water resources.

6.3 Financial Metrics

6.3.1 NPV, IRR, and BCR

The NPV calculates the future cash flows of an investment and discounts them back to their present value at the initial investment date. A positive NPV suggests that the investment outcome will increase the enterprise value. Conversely, suppose the NPV of the investment evaluation is negative. In that case, it indicates that the investment will decrease the enterprise

doi:10.6342/NTU202400056

value, and investors should refrain from accepting it (Thomson et al., 1999).

Equation (17) assists in assessing the costs and benefits over each investment period (in years) (Thomson et al., 1999).

$$\text{NPV} = \sum_{t=1}^{N} \frac{N_t}{(1+\ i)^t} \qquad (17)$$

In this context, NPV stands for net present value. N represents the evaluation periods, t denotes the construction and operation period, N_t represents the Net Cash Flow in year t, and i represents the discount rate. The IRR is the discount rate at which the discounted NPV value equals zero. Equation (18) presents an investment evaluation method for determining IRR, quantifying the return on investment independently of external factors such as financial risks (Hartman & Schafrick, 2004).

$$\text{NPV} = \sum_{t=1}^{N} \frac{N_t}{(1+\ Irr)^t} = 0 \qquad (18)$$

In this case, N represents evaluation periods, t denotes the construction and operation period, Nt stands for Net Cash Flow in year t, and Irr signifies IRR.

The BCR plays a pivotal role in cost-benefit analysis, measuring the balance between benefits and costs in discounted present value (Zangeneh et al., 2010). It evaluates the discounted value of increased benefits compared to total costs. A higher BCR signifies a more favorable return on funding, with a BCR exceeding 1 indicating a profitable investment. Conversely, the BCR must be at least 1 for a project to be profitable. Equation 1 provides the calculation method for BCR, while Equation (19) illustrates how to determine it (Kiran, 2022).

doi:10.6342/NTU202400056

$$BCR = \frac{\sum_{t=1}^{N} B_t(1+i)^{-t}}{\sum_{t=1}^{N} C_t(1+i)^{-t}} \quad (19)$$

In this circumstance, N represents evaluation periods, t signifies the operation period (when cash flow occurs), Bt denotes the cash flow (benefits) of period t, C_t represents the cash flow (costs) of period t, and i signifies the discount rate. The PBP indicates the years required to recoup the initial cash investment (Zangeneh et al., 2010). It is the year when the cumulative cash flow exceeds zero.

Equations (20) and (21) determine the net cash flow for each year from the start of the investment.

$$Y_{fnc} = Y_{fci} - Y_{fco} \quad (20)$$

Y_{fnc} represents the first net cash flow year, Y_{fci} denotes the first cash inflow year, and Y_{fco} refers to the first cash flow outflow year. Then, the cumulative cash flow, denoted as Y_{acf}, equals the sum of Y_{fnc} and Y_{snc}. So forth up to Y_{nnc} , where Y_{fnc} represents the first net cash flow year, Y_{snc} represents the second cash inflow year. and Y_{nnc} signifies the nth net cash flow year.

$$Y_{acf} = Y_{fnc} + Y_{snc} + \ldots + Y_{nnc} \quad (21)$$

Equation (22) elucidates the correlation between yearly operating gain and factors such as effective insolation hours, system efficiency, PV unit attenuation, and system maintenance. Equation (23) quantifies the reduction in CO_2 emissions over 25 years

doi:10.6342/NTU202400056

(Bureau of Energy, 2007), providing researchers with tools to assess associated benefits.

$$R_{op} \equiv C_{ins}\ (kWp/h) \times G_{effh}\ (h/day) \times 365.25\ (days/year) \times T_{lc}\ (years) \times S_{e} \times (1+\alpha) \times (1-D_{ar}) \times (1-M_{dt}) \times P_{hep} \quad (22)$$

$$V_{era} \equiv C_{ins}\ (kWp/h) \times G_{effh}\ (h/day) \times 365.25\ (day/year) \times T_{lc}\ (years) \times S_{eff} \times (1+\alpha) \times (1-D_{ar}) \times (1-M_{dt}) \times F_{ecec} \quad (23)$$

In this situation, where R_{op} signifies yearly operating revenue. C_{ins} represent the solar module installation capacity (kWp/h). G_{effh} denotes effective daily electricity generation hours (h/day). T_{lc} refers to the lifecycle period (years). S_{eff} stands for system efficiency. This study bases its calculation on 75% efficiency. α represents the diode ideality factor. D_{ar} indicates the decay rate of solar modules, which decreases annually by 1% (Staebler & Wronski, 1977). M_{dt} represents system downtime, estimated at 5%, influenced by management and climatic factors such as typhoons and earthquakes. P_{hep} signifies the average household electricity bill. V_{era} denotes the yearly CO_2 emission reduction amount (kg). F_{ecec} represents the ECEC.

Equation (24) outlines the methodology for calculating the annual average operating margin. It illustrates the annual investment profit that investors remain liable to pay corporate tax on.

$$P_{gp} = R_{aor} - E_{aoe} \quad (24)$$

doi:10.6342/NTU202400056

P_{gp} symbolizes the annual gross revenue. R_{aor} denotes the annual operating revenue. E_{aoe} represents the annual operating expenses.The **capital recovery factor (CRF)** indicates the ratio determining the constant annuity to the present value of achieving that annuity over a regular interval, like monthly, quarterly, or yearly. Users must multiply the CRF factor (F_{crf}), expressed as equation (25), to achieve an equal yearly cash present value.

$$F_{crf} = \frac{i \times (1+i)^{n}}{(1+i)^{n}-1} = \frac{i}{1-(1+i)^{-n}} \quad (25)$$

"i" indicates the appropriate discount rate, n to the project lifespan. To obtain the project's return, WACC is an apt discount rate (Rothwell, 2004).

Determining a scheme's WACC is crucial as it is an enterprise's discount rate to estimate its NPV. An inferior WACC means the industry can convene investors at a lower cost. In contrast, a higher WACC implies compensating investors with higher returns. As most companies(programs) yield capital from debt and equity, to express the company cost in a single figure, one has to weigh the costs of debt and equity proportionally based on how much they acquire financing through each source (Corporate Finance Institute, 2022).

Simon and Blume (1994) employed equations (26) and (27) to express the relationship between the Fcrf and WACC.

$$F_{crf} = \frac{WACC \times (1+WACC)^{n}}{(1+WACC)^{n}-1} = \frac{WACC}{1-(1+WACC)^{-n}} \quad (26)$$

where WACC (= $R_{ir} \times L_{lr} + R_{oc} \times C_{ocr}$)

doi:10.6342/NTU202400056

$$= R_{ir} \times L_{lr} + (R_{ir} + \beta) \times C_{ocr} = (R_{rf} + \alpha) \times L_{lr} + (R_{rf} + \alpha + \beta) \times C_{ocr} \quad (27)$$

During the bulk purchase period (N), the bank interest rate (R_{ir}), the loan ratio of the investment (L_{lr}), the return on own capital (R_{oc}), the investment ratio of own capital (C_{ocr}), the risk premium (β), the risk-free interest rate (R_{rf}), and the overweight for credit risk (α) are active components. Additionally, the sum of the loan ratio of the investment (L_{lr}) and the investment ratio of own capital (C_{ocr}) equals one.

6.3.2 Comparison of Financial Factors and Weights through Metrics and Binary Analysis among Examined FPVs (Financial Performance Variables

The intricate dynamics among evaluation criteria exert a profound impact on FPV projection. This phenomenon eludes complete explication through hierarchical models (Saaty, 1980). In this study, the author employed the ANP approach and supermatrix methodology to calculate the relative weight of features and uncover dependencies among metrics and the weights of analyzed FPVs. The supermatrix, consisting of multiple submatrices, is organized as pair-comparison sub-matrices within a 2-by-2 block matrix (Varadarajan, 2004), playing a pivotal role as a fundamental tool for binary comparison of financial factors to determine their dependencies and subsequent weight allocations. In scenarios devoid of correlation among elements, the pairwise comparison value of the submatrix registers as 0. Each scale within the matrix of one cluster delineates the influence of elements in other clusters, termed external dependencies (Brunelli, 2018).

doi:10.6342/NTU202400056

When the **Inconsistency Index (InCI)** equals or falls below 0.1, logical errors between metrics are absent (Saaty, 1996). As depicted in **Figure 20**, the arrows connecting S3 and S5 signify an external feedback relationship; additionally, S5 is depicted with a rounded arrow, symbolizing an internal dependence relationship (Saaty, 1996)

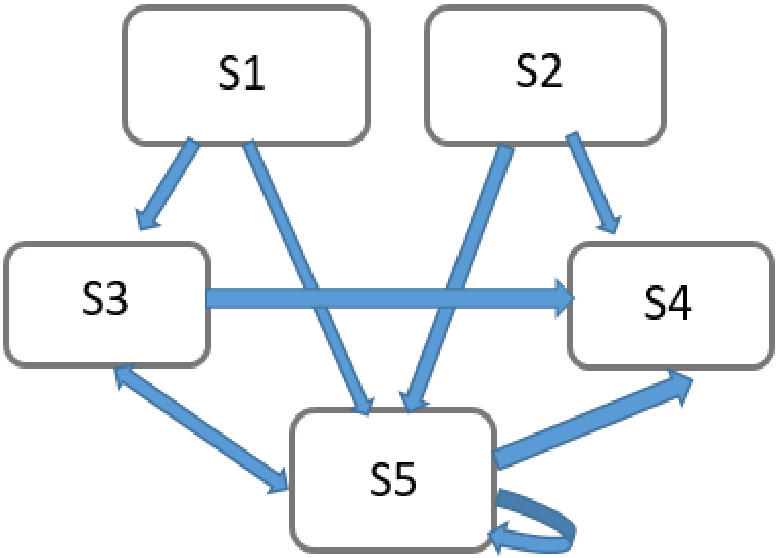


Figure 14: Diagram Illustrating Dependency and Feedback Network Structure (Saaty, 1996)

The ECEC serves as an indicator of the status of GHG emission management. Since 2005, Taiwan has progressively established goals for ECEC regulation. As of 2021, Taiwan's ECEC stood at 0.509 kg CO_2e/kWh (Bureau of Energy, 2022), representing a marginal increase of 1.4% compared to the previous year. This metric amalgamates figures from sales attributed to direct supply, public electricity transfer, or clean energy, showcasing a downward trajectory since 2017 (Council for Economic Planning and Development, 2022). Conversely, Japan, influenced by the aftermath of

doi:10.6342/NTU202400056

the Fukushima nuclear disaster, recorded an ECEC of 0.538 kg CO_2e/kWh in 2020 (Electricity MaP, 2020).

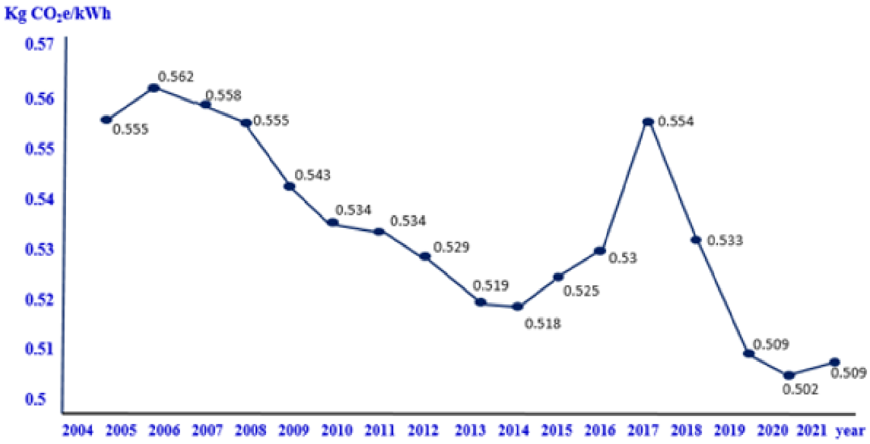


Figure 15: Graph depicting the Carbon Emission Coefficient of Electricity across Multiple Years (Council for Economic Planning and Development, 2022)

Equation (28) calculates the volume of CO2 emissions per kilowatt-hour (kWh) by dividing the total fuel consumption of Taipower, synergy industries, and private power plants by the overall power generation, as stipulated by the Electricity Industry Law for the description of ECEC (Sultan et al., 2021).

$$\text{ECEC} = \frac{CO2_{tpc} - CO2_{el}}{CO2_{t}} \tag{28}$$

CO_{2tpc} signifies the carbon emissions attributable to the power generation industry. Simultaneously, self-use energy producers vend electricity, contributing to carbon emissions associated with public electricity sales, denoted as CO_{2el}. Additionally, CO_{2t} denotes the total carbon emissions from public electricity sales.

doi:10.6342/NTU202400056

6.4 Methodologies

Utilizing the Analytic Network Process (ANP) for assessing metric weights and employing time series analysis-based financial indicators, this study conducts a comparative analysis between two 10 MWp FPV sites—Agongdian and Yamakura Dam—to ascertain an optimal scheme. The outlined methodology comprises the following steps:

(1) Collect and compile Taiwan's recent 180-month insolation data: Acquire and compile 180 months of recent insolation data for Taiwan, considering the similar insolation conditions at both sites. Subsequently, conduct a thorough examination of the time series trend and its autocorrelation for statistical analysis.

(2) Evaluate predetermined metrics: Evaluate predetermined metrics potentially influencing FPV benefits based on their respective attributes.

(3) Execute supermatrix computations: Perform supermatrix computations to compare metrics pairwise, deriving individual metric weights and elucidating the interdependence among the metrics.

(4) Estimate the Inconsistency Index (InCI): Estimate the InCI to ascertain the consistency of the pairwise comparison matrix, ensuring that the InCI value aligns with the prescribed criterion of ≤ 0.1, indicative of consistency within an acceptable range.

doi:10.6342/NTU202400056

(5) **Use ECEC trend analysis:** Utilize ECEC trend analysis to project the CO_2 reduction effect and assess the FPV project's benefits.

(6) **Calculate financial indicators and juxtapose and compare the yearly concise accounting statement and financial indicators:** Calculate financial indicators and conduct a comparative analysis of yearly concise accounting statements and financial indicators.

(7) **Perform sensitivity analysis of metrics weights.**

This study presents a comprehensive case study employing ANP methodology to evaluate metric weights and time series analysis-based financial indicators, facilitating a comparative analysis between the Agongdian and Yamakura Dam FPV sites for optimal scheme determination. **Figure 22** depicts the detailed procedural flow.

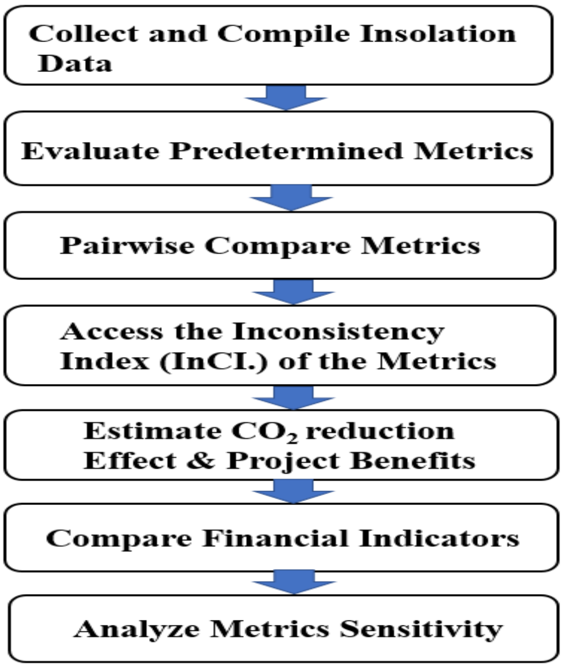


Figure 16: Flow Chart for Determining the Optimal FPV Scheme

doi:10.6342/NTU202400056

6.5 Results

(1) Relative Weights of Predetermined Metrics and Inconsistency Test

The analysis reveals that the metrics concerning system capacity, installation costs, bank rates, and ETS and electricity bills significantly influence FPV operational gains. As depicted in **Table 11**, the most heavily weighted metrics are ETS and electricity Bills. In contrast, the bank rate holds the least weight. Specifically, ETS and electricity bills exhibit the most substantial impact on FPV deployment. At the same time, bank rates have a comparatively minor influence. Furthermore, with an Inconsistency Index (InCI) of less than 0.1 (0.0218), it is evident that logical inconsistencies among the metrics are absent (Saaty, 1996).

Table 11: Inconsistency Index of FPV Metrics: 0.0218

Metric	Normalized	Idealized
System cap.	0.23	0.54
Install. cost	0.23	0.54
Bank interest	0.12	0.29
ETS & Electricity	0.42	1.000

(2) Cost Investigations and Assumptions

This study assumes the absence of natural disasters at both sites during future operations to facilitate the financial analysis of the two schemes. The FPV systems utilize identical primary components, such as inverters and 315Wp monocrystalline

doi:10.6342/NTU202400056

solar modules installed at Agondian Reservoir, ensuring compliance with technical specifications as the system has consistently performed well since the grid connection. The following outlines the assumptions:

I. The lifespan of the FPV system is projected to be 25 years.

II. The system's depreciation period is 25 years, irrespective of residual value.

III. The following parameters are established (based on annual income):

(a) The module's annual attenuation rate is 1% (Staebler & Wronski, 1977).

(b) Annual operating costs and system maintenance expenses are estimated at 3% in Taiwan (Directorate General of Budget, Accounting and Statistics, 2023) and 5% in Japan (Ministry of Health, Labour & Welfare, 2023). (The average salaries in Taiwan and Japan are approximately US$1,540 and US$2,518, respectively.)

(c) The rental fee for the water area of both projects is assumed to be 8.9% (Water Resources Agency, 2021).

(d) The capital investment ratio is 60% (with a bank loan comprising 40% of the investment amount).

(e) Enterprise loan bank rates are estimated at 2.498% in Taiwan (Central Bank, Taiwan, 2022) and 1.475% in Japan (CEIC Data, 2022).

(f) Annual insurance expenses are estimated at 0.5% of the system's initial installation cost (Ijiri, 1979).

doi:10.6342/NTU202400056

(g) Exchange rates considered for accounting purposes are USD/NTD: 1:29.5 and USD/JPY: 1:126.4. The USD/TWD exchange rate has fluctuated between 27.6 and approximately 32 (Tradingview, 2022), while the USD/JPY exchange rate has varied from close to 110 to about 150 yen (Anue, 2022). Accordingly, this study adopts 126.4 yen (the average value from January to April 2022) as the base for calculation. Items (1) to (4) align with the annual operating revenue of FPV Phase I at Agongdian Reservoir (Water Resources Agency, 2021).

(3) Annual Summary Financial Statement

To generate the yearly financial statement, the investigator takes the following steps:

(a) Calculation of operating gains and carbon credits.

(b) Determination of installation costs, capital costs, and taxes based on previously established cost assumptions.

By utilizing equation (18) and considering the average household electricity prices in Taiwan (approximately US$0.11/kWh) (TPC, 2022) and Japan (US$0.24/kWh) (TEPCO, 2022), annual operating gains and total operating gross profits for 25 years can be computed (NEDO, 2022). Additionally, with the ECECs of Taiwan and Japan in 2021 being 0.509 CO_2e/kWh and 0.538 CO_2e/kWh, respectively, and employing equation (19), the CO_2 emission reduction effect for both sites over the 25-year lifespan can be

doi:10.6342/NTU202400056

determined. This study adopts a carbon credit value of US$19 per ton, consistent with Switzerland's rate, to quantify the benefits derived from carbon credits.

The Climate Investment Funds (CIF) conducted a financial analysis for the 10 MWp FPV investment at Ramgiri (in Andhra Pradesh, India). The analysis revealed that FPV costs approximately US$1,000-1,200 per kWp. Moreover, costs are decreasing due to China's aggressive pursuit of larger installations, with other countries like Singapore and England closely following suit (CIF, 2017). As of March 2021, the National Renewable Energy Laboratory (NREL) compiled a list of US FPV-installed projects with sizes exceeding 100 kWp. While most existing FPV installations have capacities below 5 MWp, plans for installations exceeding 10 MWp have increased since 2017. After assessing factors such as site specifics, floating structure types, anchoring solutions, and other cost-affecting variables, the technical report completed in October 2021 by Ramasamy (2021) indicates that the cost of a 10MWp FPV installation is US$1,290 per kWp.

Additionally, the author assumes α risk and β risk parameters of WACC to be 3% and 5.31%, respectively (Corporate Finance Institute, 2022), with Fcrf values set at 0.098 and 0.090. Consequently, investigators can anticipate annual loan capital costs of US$505.7 million and US$464.4 million, respectively. Regarding corporate income taxation, Japan has three tax components: corporate tax (national tax) (Japan National Tax Agency, 2022), prefectural inhabitant tax (Chiba Prefecture, 2022), and corporate

doi:10.6342/NTU202400056

business tax (the latter two being local taxes). In contrast, Taiwan imposes only a corporate tax at a rate of 20% (National Taxation Bureau of Taipei, 2022). Japan's national tax adopts a progressive tax rate, with a 15% tax rate applied to profits up to 8 million yen (approximately US$63.3 thousand) and a 23.2% rate for profits exceeding this threshold. The prefectural inhabitant tax is established at 1.8%, while the corporate business tax is 1.0%. In summary, the investor is exempt from tax obligations for the Agongdian FPV owing to its net profit before tax status. Conversely, the Yamakura FPV must pay approximately US$311.3 thousand in taxes annually. **Table 12** presents the concise statements of the two schemes.

Table 12: Annual Summary of Financial Statement

Unit: kUSD/Year

	Agongdian	Yamakura
Operating revenue (+)	1260.0	2750.0
Carbon credit (+)	110.7	117.2
Operational cost (-)	37.8	137.5
Maintenance cost (-)	37.8	137.5
Rent (-)	112.1	244.8
Depreciation cost (-)	516.0	516.0
Gross profit	667.0	1831.4
Gross profit (%)	52.9	66.6
Interest expense (-)	128.9	76.1
Insurance expense (-)	64.5	64.5
Capital cost (-)	505.7	464.4
Net profit before tax	-32.1	1226.4
Net profit after tax	-32.1	915.1
Net profit (%)	0	33.3

doi:10.6342/NTU202400056

(4) Financial Indicators and Breakpoint Analysis

In the post-Feed-In-Tariff (FIT) era, funding for FPV in Japan proves more favorable compared to Taiwan, owing to the latter's current household electricity bill of approximately US$0.11 per kWh, significantly lower than that of most developed countries, resulting in a non-profit situation. Conversely, financial indicators in Japan demonstrate that investing in FPV yields more significant benefits. It evidences the Yamakura Dam scheme's shorter PBP of 9.0 years, modest IRR at 10.1%, and BCR exceeding 1 (1.69 at a discount rate of i=10%), compared to the Agongdian Reservoir scheme's PBP of 26.7 years, negative IRR (-0.50), and BCR of 1.30 at the same rate. Additionally, the NPV at i=5% for Agongdian Reservoir is negative (-6,079.9), while Yamakura's is positive (7,269.8) **(Table 13)**. External factors such as the Russia-Ukraine war in the past year and persistently high oil and natural gas prices have contributed to Taiwan Power Company's prolonged financial losses, with electricity tariffs facing upward pressure. **Table 12** illustrates that when the electricity bill increases by more than 2.55%, i.e., a slight rise from the current US$0.11 to US$0.113, funding FPV becomes a profitable venture.

Equation (29) defines the breakeven point: the sales level at which total revenue equals total cost, representing a zero-profit scenario. This equation is a crucial indicator in management accounting, typically employed by researchers to determine breakeven

doi:10.6342/NTU202400056

points. **Figure 23** reveals that the breakeven sales amount for Yamakura FPV is approximately US$664.8 thousand (Zheng et al., 2015). It suggests that achieving a power generation level of 48.5% under the specified conditions at Yamakura Reservoir FPV would lead to profit-loss equilibrium. Further increases in power generation would result in profitability. However, the Agongdian Reservoir FPV fails to achieve profitability at the breakeven point.

$$\text{Break-even Sales Amount} = \frac{\text{Fixed Costs}}{1 - \frac{\text{Variable Costs}}{\text{Sales}}} \tag{29}$$

Table 13: NPV, IRR, and BCR AnalysisUnit:

kUS$/Year

	Agongdian	Yamakura
Investment	12900	12900
PBP	26.7	9.0
Discount Rate(i)	NPV	
5%	-6079.9	7269.8
7%	-7260.8	3777.4
10%	-8507.6	90.1
IRR (%)	-0.50	10.1
BCR (i=5%)	1.32	1.71
BCR (i=7%)	1.31	1.70
BCR (i=10%)	1.30	1.69

doi:10.6342/NTU202400056

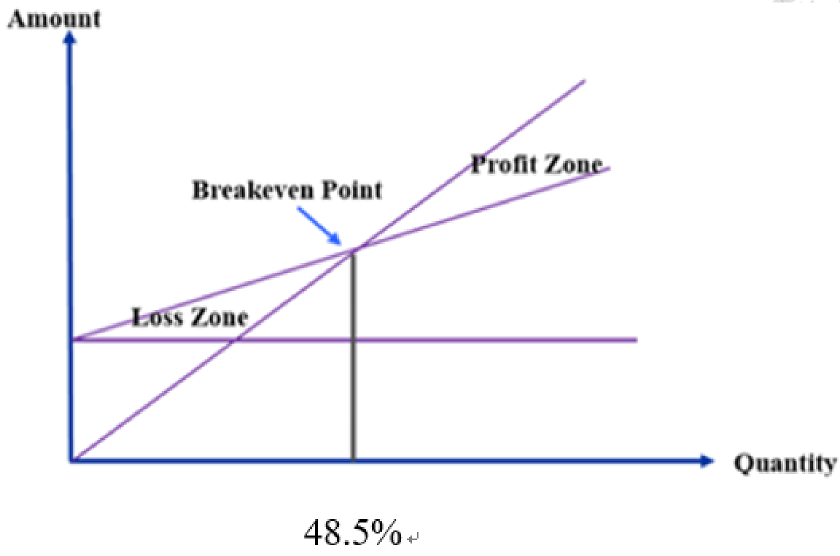


Figure 23: Breakeven Point Analysis for Yamakura FPV

(5) Analysis of Metric Weights Sensitivity

In this study, different weight conditions are assigned to various factors within the ANP model to conduct sensitivity analysis (Saltelli, 2002; Saltelli et al., 2008). This process elucidates how weight variations under diverse conditions impact the results, thereby enabling the recalibration of outcomes under alternative assumptions to gauge the influence of specific variables. Researchers can utilize sensitivity analysis for various purposes (Pannell, 1997), including:

(1) Strengthen the robustness of model analysis: Ensuring that inputs meet stringent conditions to discern variations between them and the output.

(2) Test the model or system's robustness in the face of uncertainty.

(3) Enhance comprehension of the relationship between input and output variables within a system or model.

doi:10.6342/NTU202400056

(4) Mitigateg uncertainty by pinpointing model inputs significantly contributing to output uncertainty.

Table 14: Sensitivity Analysis of Metric Weights versus Gross Profit Analysis of Yamakura Reservoir FPV

Unit: kUS$/Year

Metric	Original Weight	+5%	-5%	+10%	-10%
System cap.	0.23	-645 +645		-1290	+1290
Install. cost	0.23	-645 +645		-1290 +1290	
Bank interest	0.12	-3.8	+3.8	-7.6	+7.6
ETS & Electricity	0.42	+137.5	-137.5	+275	-275 -

Tables 12 and 14 demonstrate that a 10% increase in the ETS and electricity bill leads to a potential rise in net profit from 33.3% to 40.7%, accompanied by a decrease in the PBP from the initial nine years to 7.9 years. Conversely, a 10% increase in system capacity or installation cost reduces after-tax net profit from the original USD 915.1 thousand to -47.5 thousand and an increase in PBP from the initial 9 to 27.5 years. Conversely, future advancements in solar engineering and technology, such as a 10% improvement in solar module conversion efficiency and a corresponding reduction in system cost, can elevate the project net profit to US$1877.7 thousand, increasing the net profit rate from the initial 33.3% to 68.3%, and significantly reducing PBP from 9 to 5.4 years.

doi:10.6342/NTU202400056

6.6 Discussion

Taiwan's reliance on energy imports, accounting for about 97% of its energy raw materials, contrasts with its relatively low electricity bills compared to most countries globally. However, this has led to long-term operational losses for Taipower, highlighting the need for sustainability and a shift towards a more conducive environment for a low-carbon economy.

However, the European Union (EU) plans to introduce a carbon border adjustment mechanism (CBAM). It will mandate companies to disclose carbon emission data starting in 2023 (Gore, 2021). This move suggests that the Emissions Trading System (ETS) holds the potential to facilitate FPV deployment and foster international collaboration toward global decarbonization efforts (Yasuo, 2021).

Additionally, given the susceptibility of photovoltaic power generation to uncertainties such as extreme climates, there is a pressing need to intensify research efforts on energy storage systems to mitigate their impact.

6.7 Summaries

Through the implementation of time series forecasting and ANP analyses, the author has forecasted time series trends, conducted autocorrelation for statistical analysis, and incorporated metric weights to ensure the objectivity of evaluation results. Moreover,

doi:10.6342/NTU202400056

comparing and analyzing the financial indicators of both schemes aids in determining optimal funding strategies.

The investigation revealed that Taiwan's NPV remains adverse even at a discounted rate of 5%. In comparison, Japan remains positive even at a discount rate of 10%. Furthermore, Agongdian's Internal Rate of Return (IRR) of -0.50% and Benefit-Cost Ratio (BCR) of 1.32 (at a 5% discount rate) are inferior to Yamakura's 10.1% and 1.71, respectively, indicating the higher profitability of investing in FPV in Japan. Additionally, the findings underscore the significance of rent costs and suggest that increasing the investment loan ratio to expand the project scale with the same capital could enhance profitability.

Moreover, since the original Agongdian and Yamakura FPV investors were private companies and there was limited published financial information, acquiring more comprehensive data would enhance the study's robustness. Furthermore, the study did not account for uncertain factors like extreme weather conditions. While the research successfully identifies the optimal alternative, conducting a thorough assessment of all costs and benefits, especially concerning environmental and risk analyses, remains challenging. Hence, future research should delve deeper into factors of uncertainty affecting the system and the implications of future advancements in solar technology. The approach proposed in this study provides a holistic perspective for evaluating the

doi:10.6342/NTU202400056

economic merits of alternatives, assisting in scheme selection, and determining the feasibility of project funding.

doi:10.6342/NTU202400056

Chapter 7 Conclusions

In this comprehensive series of case studies, the author advocates a synthesis method incorporating time series analysis and **Exceedance Probability** to enhance the reliability analysis of FPV systems, thereby ensuring their heightened robustness and dependability. The study's results make substantial contributions by examining the correlation between preceding and lagging data, assessing series data for upward trends and consistency, **generating daily and monthly power duration curves to provide a balance indicator, and scrutinizing power supply reliability.** Local power companies can optimize power supply based on these findings. Furthermore, the presented approaches hold the potential to facilitate the expansion of FPV systems to areas with insufficient power yet abundant water bodies.

Another study in Chapter 5 challenges conventional beliefs that PV exhibits lower ER than fossil fuels, especially in the final stage. It explores the influence of solar module technology innovation on ER through extensive LCEA assessments. The author underscores the significant impact of LCEA boundary settings, emphasizing the necessity for more precise boundary definitions in future studies. Additionally, comparing previous studies reveals superior EPBT and EROI due to PV technology innovation by evaluating the ER of the 181 MWp OFPV system at Changhua Coastal Industrial Park.

It elucidates that preceding research posited that the pivotal element for enhancing the ER

doi:10.6342/NTU202400056

of solar modules was rooted in embedded energy rather than advancements in module technology. Moreover, **it addresses the bias suggesting that solar power's ER is inferior to conventional energy's.**

The third case study compares the financial gains of FPV of Taiwan’s Agongdian Reservoir and Japan’s Yamakura Dam using ANP and CBA to determine what factors influence investment decisions and which scheme is optimal. The methodologies presented in this research provide comprehensive views and achieve the impact factors of PV funding projects. They help determine the optimal investment. The study reveals Japan's FPV investment to be more profitable than Taiwan's, offering substantial evidence for the significance of rent cost and the consequence of ETS and electricity bills. **It helps stakeholders comprehend advantages and determine a favorable funding plan.** It also explicates the potential benefits of carbon trading on FPV funding to help investors make decisions.

However, as the sample data is limited to fifteen years, a more extended time-scale sampling could enhance the investigation's effectiveness. Future research may involve studying the optimal installation ratio for FPV systems on water bodies, considering factors such as the impact of water quality and economic maximization.

In addition, **the fluctuations in solar power generation between sunny and cloudy conditions highlight the significance of weather patterns and atmospheric**

doi:10.6342/NTU202400056

factors in determining the reliability and consistency of solar energy as a renewable power source. Researchers and industry stakeholders often analyze these variations to enhance the predictability and efficiency of solar energy systems in diverse weather conditions. It should be an issue that peers should not ignore in future research.

A complete LCEA ensures a thorough understanding of the product's sustainability and allows for more informed decision-making regarding improvements or alternatives in the production process. Case study 2, limited by investigation of the manufacturer's products produced, does not vertically integrate the various stages of production for a product. Additionally, the scope of the study does not include the final transportation and disposal stages of the system; the author notes that considering the energy consumption of these stages, although insignificant and not estimated in this study according to the 1% cutoff rule, could enhance the accuracy of PV ER assessment if improved since they would have a limited and potentially skewed understanding of its energy efficiency and environmental impact. Future work should investigate the entire production chain in vertical segments for a more accurate LCEA assessment.

On the other hand, due to acknowledging limitations in financial information availability, the study recommends obtaining more data for a comprehensive analysis. It does not consider uncertain factors such as extreme weather, prompting further research on their impact on the system and advancements in solar technology.

doi:10.6342/NTU202400056

In conclusion, the case studies in this dissertation collectively contribute to advancing renewable energy knowledge, offering practical insights that can shape the future of renewable energy initiatives and propel the transition towards cleaner and more efficient energy systems. The research on Power Supply Reliability Analysis on FPV, ER assessment on OFPV based on LCEA perspectives, and Comparative Economic Analysis of the FPVs of the Agongdian Reservoir and Yamakura Dam presents valuable contributions to the renewable energy domain. Each study addresses critical aspects of floating photovoltaic systems, providing insights crucial for informed decision-making and strategic planning in the renewable energy sector.

doi:10.6342/NTU202400056

References

1. Ahmed, A., Elsakka, M., Elminshawy, N., Mohamed, A., Sundaram, S. (2023) Recent Advances in Floating Photovoltaic Systems. *The Chemical Record*, 23(12), e202300229. https://doi.org/10.1002/tcr.202300229
2. 相原良太, 横山明彦, 野見山史敏, & 小杉成史 (2012)太陽光発電が大量導入された電力系統における揚水発電所の最適運用計画.電気学会論文誌 B (電力・エネルギー部門誌), 132(1),pp.86-94.

   Aihara, R., Yokoyama, A., Nomiyama, F. (2012) IEEJ Transactions on Power and Energy, 132(1). https://doi.org/10.1541/ieejpes.132.86
3. Akpeji, K. O., Olasoji, A. O., Gaunt, C. T., Oyedokun, D. T., Awodele, K. O., Folly, K. A. (2020) Economic impact of electricity supply interruptions in South Africa. SAIEE Africa Research Journal, 111(2), pp. 73-87. https://ieeexplore.ieee.org/abstract/document/9099495
4. Alsema, E.A., Frankl, P., Kato, K. (1998) Energy payback time of photovoltaic energy systems: Present status and prospects. https://dspace.library.uu.nl/handle/1874/7943
5. Ang, A. H-S., Tang, W. H. (1984) A Review of: "Probability Concepts in Engineering Planning and Design", Volume II: Decision, Risk, and Reliability, John Wiley & Sons, New York.
6. Annema, J. A., Mouter, N., Razaei, J. (2015). Cost-benefit analysis (CBA), or multi-criteria decision-making (MCDM) or both: politicians' perspective in transport policy appraisal. Transportation research procedia, 10, pp. 788-797. https://doi.org/10.1016/bs.atpp.2020.07.005
7. António F. de O. Falcão (2010) Wave energy utilization: A review of the technologies, Renewable and Sustainable Energy Reviews, 14 (3), pp. 899-918. https://doi.org/10.1016/j.rser.2009.11.003
8. Anue. https://invest.cnyes.com/forex/detail/USDTWD/technical#fixed (retrieved on May 18, 2022).
9. Aragonés-Beltrán, P., García-Melón, M., Montesinos-Valera, J. (2017) How to assess stakeholders' influence in project management? A proposal based on the Analytic Network Process. *International Journal of Project Management*, 35(3), 451-462. https://doi.org/10.1016/j.ijproman.2017.01.001
10. Asplund, D., Eliasson, J. (2016) Does uncertainty make cost-benefit analyses pointless?. *Transportation Research Part A: Policy and Practice*, 92, pp. 195-205. https://doi.org/10.1016/j.tra.2016.08.002
11. Atlason, R., Unnthorsson, R. (2014) Ideal EROI (energy return on investment) deepens the understanding of energy systems. Energy 67: 301–45. https://doi.org/10.1016/j.energy.2014.01.096

doi:10.6342/NTU202400056

12. Azli, N. A.; Salam, Z.; Jusoh, A.; Facta, M.; Lim, B. C.; Hossain, S. (2008) Effect of fill factor on the MPPT performance of a grid-connected inverter under Malaysian conditions, Proceedings of the IEEE 2nd International Power and Energy Conference (PECon’ 08), pp. 460-462, IEEE, Johor Bahru, Malaysia, December 2008. https://doi.org/10.1109/PECON.2008.4762509
13. Bailey, R. L., Dell, T. R. (1973) Quantifying diameter distributions with the Weibull function. *forest science*, 19(2), pp. 97-104. https://doi.org/10.1093/forestscience/19.2.97
14. Bax, V., van de Lageweg, W. I., van den Berg, B., Hoosemans, R., Terpstra, T. (2022) Will it float? Exploring the social feasibility of floating solar energy infrastructure in the Netherlands. *Energy Research & Social Science*, 89, 102569. https://doi.org/10.1016/j.erss.2022.102569
15. Behura, A. K., Kumar, A., Rajak, D. K., Pruncu, C. I., Lamberti, L. (2021) Towards better performances for a novel rooftop solar PV system. *Solar Energy*, 216, 518-529. https://www.sciencedirect.com/science/article/pii/S0038092X2100061X
16. Beiter, P., Cooperman, A., Lantz, E., Stehly, T., Shields, M., Wiser, R., ... Kikuchi, Y. (2021) Wind power costs driven by innovation and experience with further reductions on the horizon. *Wiley Interdisciplinary Reviews: Energy and Environment*, 10(5), e398. https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wene.398
17. Benysek, G., Pasko, M. (2012) *Power theories for improved power quality*. Heidelberg: springer. https://link.springer.com/content/pdf/10.1007/978-1-4471-2786-4.pdf
18. Bhandari, K.P, Collier JM, Ellingson RJ, et al. (2015) Energy payback time (EPBT) and en.ergy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and metaanalysis. Renewable Sustainable Energy Rev 47: 133–141. https://doi.org/10.1016/j.rser.2015.02.057
19. Biancardo, S. A., Gesualdi, M., Savastano, D., Intignano, M., Henke, I., Pagliara, F. (2023) An innovative framework for integrating cost-benefit analysis (cba) within building information modeling (bim). *Socio-Economic Planning Sciences*, 85, 101495. https://doi.org/10.1016/j.seps.2022.101495
20. Biswas, A., Husain, D., Prakash, R. (2021) Life-cycle ecological footprint assessment of grid-connected rooftop solar PV system, International Journal of Sustainable Engineering, 14(3), pp. 529-538. https://doi.org/10.1080/19397038.2020.1783719
21. Blanchard, O., Gollier, C., Tirole, J. (2023). The Portfolio of Economic Policies Needed to Fight Climate Change. https://doi.org/10.1146/annurev-economics-051520-015113

doi:10.6342/NTU202400056

22. Bongaerts, J.C., Drebenstedt, C. (2023). Life Cycle Assessment for the Primary Raw Materials Extraction Industry. In: Benítez-Andrades, J.A., García-Llamas, P., Taboada, Á., Estévez-Mauriz, L., Baelo, R. (eds) Global Challenges for a Sustainable Society . *EURECA-PRO 2022. Springer Proceedings in Earth and Environmental Sciences. Springer, Cham.*https://doi.org/10.1007/978-3-031-25840-4_20
23. Bp (2022) Statistical Review of World Energy, the 71st. edition. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html(retrieved on 26 June, 2023)
24. Box, G. E. P.; Jenkins, G. M.; Reinsel, G. C. (1994) Time Series Analysis; Forecasting and Control, 3rd. Edition, Prentice-Hall, Englewood Cliff, New Jersey. https://doi.org/10.1111/jtsa.12194
25. Brockway, P.E., Owen, A., Brand-Correa, L.I., et al. (2019) Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. *Nature Energy*, 4, pp. 612–621. https://doi.org/10.1038/s41560-019-0425-z
26. Brunelli, M. (2018) A survey of inconsistency indices for pairwise comparisons, International Journal of General Systems, 47:8, pp. 751-771. https://doi.org/10.1080/03081079.2018.1523156
27. Bureau of Energy, Ministry of Economic Affairs. https://www.moeaboe.gov.tw (retrieved on September 30, 2022).
28. Bureau of Energy, Ministry of Economic Affairs (2007) Energy Technology Research and Development White Paper 2007. Available from (In Chinese): https://www.moeaboe.gov.tw (retrieved on September 30, 2022).
29. Bureau of Standards and Inspection, Ministry of Economic Affairs. Technical Specifications for high-efficiency solar modules in Taiwan (2016) https://www.bsmi.gov.tw/wSite/mp?mp=2
30. Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., Castell, A. (2014) Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review, Renewable and Sustainable Energy Reviews, 29, pp. 394-416. https://doi.org/10.1016/j.rser.2013.08.037
31. Cantoni, R. (2018) Energy and Civilization. A History (Vaclav Smil, 2017), *Journal of Energy History*. http://www.energyhistory.eu/en/reviews/energy-and-civilization-history-vaclav-smil-2017(retrieved on 24 June, 2023)
32. Carbon Trust (2014) Marine Renewables Commercialisation Fund. https://www.carbontrust.com/client-services/technology/innovation/marine-renewables-commercialisation-fund (retrieved 24 June 2023).

doi:10.6342/NTU202400056

33. Celik, I. et al. (2018) "Energy Payback Time (EPBT) and Energy Return on Energy Invested (EROI) of Perovskite Tandem Photovoltaic Solar Cells," in *IEEE Journal of Photovoltaics*, 8 (1), pp. 305-309. https://doi.org/10.1109/JPHOTOV.2017.2768961
34. Cakmak, E., Cakmak, P. I. (2014) An analysis of causes of disputes in the construction industry using analytical network process. *Procedia-Social and Behavioral Sciences*, 109, 183-187. https://doi.org/10.1016/j.sbspro.2013.12.441
35. Carolus, J. F., Hanley, N., Olsen, S. B., Pedersen, S. M. (2018) A bottom-up approach to environmental cost-benefit analysis. Ecological Economics, 152, pp. 282-295. https://doi.org/10.1016/j.ecolecon.2018.06.009
36. CEIC Data. https://www.ceicdata.com/zh-hans/indicator/japan/bank-lending-rate (retrieved on May 14, 2022).
37. Central Bank, Taiwan. Available online (In Chinese): https://www.cbc.gov.tw (retrieved on April 2, 2022).
38. Central Whether Administration (The name was Central Whether Bureau before the government organized the restructuring in 2023.) Central Weather Bureau. https://www.cwb.gov.tw
39. Central Whether Administration (The name was Central Whether Bureau before the government organized the restructuring in 2023.) (1994) Taiwan's climate in the past century Changes, Central Weather Administration reports (In Chinese).
40. Central Whether Administration (Bureau. Available online (In Chinese): http://www.cwb.gov.tw/V7/climate/monthlyMean/Taiwan_sunshine.htm
41. Chang, K.C., Yan, W.L., Liu, C.W. (2016) Journal of Taiwan Energy, 3 (1) March 2016, pp. 89-101. file:///C:/Users/User/Downloads/2016624154845%20(7).pdf
42. Changhua Coastal Park Service Center (2023) https://www.moeaidb.gov.tw/iphw/changpin/#open-modal
43. Chen, C.F. (2022). Power Supply Reliability Analysis on Floating Photovoltaic Systems through Exceedance Probability Approach. Journal of the Japan Institute of Energy. 101. pp. 138-146. https://doi.org/10.3775/jie.101.138
44. Chen, C.F. (2023). Offshore floating photovoltaic system energy rerurns assessment—A life cycle energy analysis-based perspective. 11(2). https://doi.org/10.3934/energy.2023027
45. Chen, C. F. (2023). A holistic method for determining floating photovoltaic schemes. *MRS Energy & Sustainability*, 10(2), pp. 207-218. https://doi.org/10.1557/s43581-023-00065-z
46. Cheng, F., Patankar, N., Chakrabarti, S., Jenkins, J. D. (2022). Modeling the operational flexibility of natural gas combined cycle power plants coupled with flexible carbon capture and storage via solvent storage and flexible

doi:10.6342/NTU202400056

regeneration. *International Journal of Greenhouse Gas Control*, 118 (103686).
https://www.sciencedirect.com/science/article/pii/S1750583622001049 11

47. Chenya Energy Co., Ltd. (2023)
https://www.bnext.com.tw/article/59283/chenya-energy-aquatic-solar
48. Chen, Y., Jin, Q., Fang, H., Lei, H., Hu, J., Wu, Y., Chen, J., Wang, C., Wan, Y. (2019) Analytic network process: Academic insights and perspectives analysis, Journal of Cleaner Production, 235, pp. 1276-1294.
https://doi.org/10.1016/j.jclepro.2019.07.016
49. Chiba Prefecture Water Works Bureau. https://www.pref.chiba.lg.jp
50. Claus, R., López, M. (2022) Key issues in the design of floating photovoltaic structures for the marine environment, Renewable and Sustainable Energy Reviews,164 (112502). https://doi.org/10.1016/j.rser.2022.112502
51. Chiba Prefecture. https://www.pref.chiba.lg.jp/index.html (retrieved on May 18, 2022).
52. Choi, Y. (2014) A study on power generation analysis of floating PV system considering environmental impact. *Int J Software Eng Appl* 8: pp. 75–84. https://doi.org/10.14257/ijseia.2014.8.1.07
53. Climate Investment Funds (CIF) (2017) Meeting documents/notes on financial and economic analysis.
https://www.climateinvestmentfunds.org/sites/cif_enc/files/meeting-documents /note_on_financial_and_economic_analysis_for_storage_and_floating_solar_appl i cations_07202017.pdf. (retrieved on May 18, 2022).
54. Cookson, R., Mirelman, A. J., Griffin, S., Asaria, M., Dawkins, B., Norheim, O. F., ... , Culyer, A. J. (2017) Using cost-effectiveness analysis to address health equity concerns. *Value in Health*, 20(2), pp. 206-212.
https://www.sciencedirect.com/science/article/pii/S1098301516341675
55. Corporate Finance Institute. "WACC."
https://corporatefinanceinstitute.com/resources/knowledge/finance
(retrieved on May 18, 2022)
56. Council for Economic Planning and Development, Executive Yuan, Available online (In Chinese): https://ws.ndc.gov.tw (retrieved on January 29, 2022).
57. Crow, L. H. (1990) "Evaluating the reliability of repairable systems," *Annual Proceedings on Reliability and Maintainability Symposium*, Los Angeles, CA, USA, 1990, pp. 275-279. https://doi.10.1109/ARMS.1990.67969
58. Daniela-Abigail HL, Tariq R, Mekaoui Amina ElA, et al. (2022) Does recycling solar panels make this renewable resource sustainable? Evidence supported by environmental, economic, and social dimensions. Sustainable Cities Soc, 77. https://doi.org/10.1016/j.scs.2021.103539

doi:10.6342/NTU202400056

59. De Brito, M. A.; Sampaio, L. P.; Junior, L. G.; Canesin, C. A. (2011) Evaluation of MPPT techniques for photovoltaic applications, 2011 IEEE International Symposium on Industrial Electronics, pp. 1039-1044. https://doi: 10.1109/ISIE.2011.5984303
60. DeGraaff, D., Lacerda, R., Campeau, Z. (2011) Degradation mechanisms in Si module technologies observed in the field; their analysis and statistics. In: Presentation at PV Module Reliability Workshop; NREL. Denver, Golden, USA
61. Dexter,F., Ledolter, J. (2023) Exceedance Probabilities of Log-normal Distributions for One Group, Two Groups, and Meta-analysis of Multiple Two-group Studies, With Application to Analyses of Prolonged Times to Tracheal Extubation. Journal of medical systems, 47(1), 49. https://doi.org/10.1007/s10916-023-01935-2
62. Dindi, A., Coddington, K., Garofalo, J.F., Wu, W., Zhai, H. (2022) Policy-Driven Potential for Deploying Carbon Capture and Sequestration in a Fossil-Rich Power Sector, *Environmental Science & Technology*, 56 (14), pp. 9872-9881. https://doi: 10.1021/acs.est.1c08837
63. Di Piazza MC, Luna M, Petrone G, Spagnuolo G (2017) Translation of the single-diode PV model parameters identified using explicit formulas IEEE J. Photovolt, 7 (4), pp. 1009-1016. https://doi.org/10.1109/JPHOTOV.2017.2699321
64. Directorate General of Budget, Accounting and Statistics, Executive Yuan. (retrieved on January 18, 2023). https://eng.dgbas.gov.tw.
65. Dörenkämper, M., Wahed, A., Kumar, A., de Jong, M., Kroon, J. Reindl, T. (2021)
66. The cooling effect of floating PV in two different climate zones: A comparison of field test data from the Netherlands and Singapore, Solar Energy, 219, pp. 15-23. https://doi.org/10.1016/j.solener.2021.03.051.
67. Electricity MaP. 2020. https://app.electricitymap.org/map (retrieved on May 18, 2022).
68. El Hammoumi, A., Chtita, S., Motahhir, S., El Ghzizal, A. (2022) Solar PV energy: From material to use, and the most commonly used techniques to maximize the power output of PV systems: A focus on solar trackers and floating solar panels. Energy Reports, 8, pp. 11992-12010. https://www.sciencedirect.com/science/article/pii/S2352484722017784
69. Elminshawy, N. A., Osama, A., El-Damhogi, D. G., Oterkus, E., Mohamed, A. M. I. (2021) Simulation and experimental performance analysis of partially floating PV system in windy conditions. Solar Energy, 230, pp. 1106-1121. https://www.sciencedirect.com/science/article/pii/S0038092X21009798
70. Ergu, D., Kou, G., Shi, Y., Shi, Y. (2014) Analytic network process in risk assessment and decision analysis. *Computers & Operations Research*, 42, pp. 58-74. https://doi.org/10.1016/j.cor.2011.03.005

doi:10.6342/NTU202400056

71. Esan, A. B., Agbetuyi, A. F., Oghorada, O., Ogbeide, K., Awelewa, A. A., Afolabi, A. E. (2019) Reliability assessments of an islanded hybrid PV-diesel-battery system for a typical rural community in Nigeria. Heliyon, 5(5). https://www.cell.com/heliyon/pdf/S2405-8440(18)38813-3.pdf
72. Eskew, J., Ratledge, M., Wallace, M., Gheewala, S. H., Rakkwamsuk, P. (2018) An environmental life cycle assessment of rooftop solar in Bangkok, Thailand. Renewable Energy, 123, pp. 781-792. https://www.sciencedirect.com/science/article/pii/S0960148118301897
73. Farrar, L. W., Bahaj, A. S., James, P., Anwar, A., Amdar, N. (2022) Floating solar PV to reduce water evaporation in water stressed regions and powering water pumping: Case study Jordan. Energy Conversion and Management, 260 (115598). https://www.sciencedirect.com/science/article/pii/S0196890422003946
74. Fakour, H., Imani, M., Lo, S. L., Yuan, M. H., Chen, C. K., Mobasser, S., Muangthai, I. (2023) Evaluation of solar photovoltaic carport canopy with electric vehicle charging potential. Scientific Reports, 13(1), p. 2136. https://www.nature.com/articles/s41598-023-29223-6
75. Fang, L. H., Abd Rahim, R. B. (2022) Design of Savonius model wind turbine for power catchment. International Journal of Electrical and Computer Engineering, 12(3), 2285. https://doi.org/10.11591/ijece.v12i3.pp2285-2299
76. FitzPatrick, B. (2019). Validity in qualitative health education research. Currents in Pharmacy Teaching and Learning, 11(2), pp. 211-217. https://doi.org/10.1016/j.cptl.2018.11.014
77. Fouad, M. M., Shihata, L. A., Morgan, E. I. (2017) An integrated review of factors influencing the perfomance of photovoltaic panels. Renewable and Sustainable Energy Reviews, 80, pp. 1499-1511. https://www.sciencedirect.com/science/article/pii/S1364032117307803
78. Fu, M., Lin, L., Kong, X., Zhao, W., Tang, L., Li, J., Ouyang, J. (2013) Construction and accuracy assessment of patient-specific biocompatible drill template for cervical anterior transpedicular screw (ATPS) insertion: an in vitro study. PLoS One, 8(1), e53580. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0053580
79. Fukurozaki, S.H., Zilles, R., Luís, I., et al. (2013) Energy payback time and CO2 emissions of 1.2 kWp photovoltaic roof-top system in Brazil. Smart Grid Clean Energy 2: 1–6. https://doi.org/10.12720/sgce.2.2.164-169
80. Gadzanku, S., Mirletz, H., Lee, N., Daw, J., Warren, A. (2021). Benefits and critical knowledge gaps in determining the role of floating photovoltaics in the energy-water-food nexus. Sustainability, 13(8), p.4317.https://doi.org/10.3390/su13084317
81. Gagnon, N., Hall, C.A.S., Brinker, L.A. (2009) Preliminary investigation of energy return on energy 487 investment for global oil and gas production. Energies 2: 490–

doi:10.6342/NTU202400056

503. https://doi.org/10.3390/en20300490
82. Gessert, T.A. (2012) Cadmium telluride photovoltaic thin film: CdTe. Compr Renewable Energy 1: pp. 423–438. https://doi.org/10.1016/B978-0-08-087872-0.00122-0
83. Ghirardi, E., Brumana, G., Franchini, G., Perdichizzi, A. (2021) The optimal share of PV and CSP for highly renewable power systems in the GCC region, Renewable Energy, 179, pp. 1990-2003, https://doi.org/10.1016/j.renene.2021.08.005
84. Gore, T. (2021). The proposal for a Carbon Border Adjustment Mechanism fails the ambition and equity tests. Brussels: Heinrich Böll Stiftung.
85. Gorjian, S., Sharon, H., Ebadi, H., Kant, K., Scavo, F. B., Tina, G. M. (2021) Recent technical advancements, economics and environmental impacts of floating photovoltaic solar energy conversion systems. Journal of Cleaner Production, 278 (124285). https://www.sciencedirect.com/science/article/pii/S0959652620343304
86. Grant, C., Garcia, J., Hicks, A. (2020) Environmental payback periods of multi-crystalline silicon photovoltaics in the United States—How prioritizing based on environmental impact compares to solar intensity. Sustainable Energy Technol Assess, 39. https://doi.org/10.1016/j.seta.2020.100723
87. Gray JL (2011) The Physics of the Solar Cell, in Handbook of Photovoltaic Science and Engineering, John Wiley and Sons. https://doi:1002/9780470974704
88. Guo, B., Ringwood, J. V. (2021) A review of wave energy technology from a research and commercial perspective. IET Renewable Power Generation, 15(14), 3065-3090. https://ietresearch.onlinelibrary.wiley.com/doi/full/10.1049/rpg2.12302
89. Hagmann, D., Ho, E. H., Loewenstein, G. (2019) Nudging out support for a carbon tax. Nature Climate Change, 9(6), pp. 484-489. https://doi.org/10.1038/s41558-019-0474-0
90. Haigh, I.D., Wijeratne, E.M.S., MacPherson, L.R. (2014) Estimating present day extreme water level exceedance probabilities around the coastline of Australia: tides, extra-tropical storm surges and mean sea level. Clim Dyn 42, pp.121–138. https://doi.org/10.1007/s00382-012-1652-1
91. Hall, C.A.S., Lambert, J.G., Balogh, S.B. (2014) EROI of different fuels and the implications for society. Energy Policy 64: 141–152. https://doi.org/10.1016/j.enpol.2013.05.049
92. Hammoumi, A.E., Chalh, A., Allouhi, A., Motahhir, S., Ghzizal, A. E., Derouich, A. (2021) Design and construction of a test bench to investigate the potential of floating PV systems, Journal of Cleaner Production, 278 (123917). https://doi.org/10.1016/j.jclepro.2020.123917
93. Hancock, D. R., Algozzine, B., Lim, J. H. (2021). Doing case study research: A practical guide for beginning researchers.

doi:10.6342/NTU202400056

https://books.google.com.tw/books/publisher/content?id=1280
94. Hartman, J. C., Schafrick, I. C. (2004) The relevant internal rate of return. The Engineering Economist, 49(2), pp. 139-158. https://doi.org/10.1080/00137910490453419
95. Hashemi, S. H., Karimi, A., & Tavana, M. (2014). An integrated green supplier selection approach with analytic network process and improved Grey relational analysis. International Journal of Production Economics, 159, 178-191. https://doi.org/10.1016/j.ijpe.2014.09.027
96. Hayat, M. B., Ali, D., Monyake, K. C., Alagha, L., Ahmed, N. (2019) Solar energy—A look into power generation, challenges, and a solar-powered future. International Journal of Energy Research, 43(3), pp. 1049-1067. https://onlinelibrary.wiley.com/doi/abs/10.1002/er.4252
97. Hayhoe, K. et al. (2004) Emissions Pathways, Climate Change, and Impacts on California, Proceedings of the National Academy of Sciences of the United States of America 2004, 101, pp. 12422-12427. https://www.pnas.org/doi/abs/10.1073/pnas.0404500101
98. Heffron, R., Körner, M.-F., Wagner, J., Weibelzahl, M., Fridgen, G. (2020)
99. Industrial demand-side flexibility: A key element of a just energy transition and industrial development, Applied Energy, 269 (115026) https://doi.org/10.1016/j.apenergy.2020.115026
100. Huang, M. T., Zhai, P. M. (2021) Achieving Paris Agreement temperature goals requires carbon neutrality by middle century with far-reaching transitions in the whole society. Advances in Climate Change Research, 12(2), 281-286. https://www.sciencedirect.com/science/article/pii/S1674927821000435
101. Huffman DL, Antelme F. (2009) Availability analysis of a solar power system with graceful degradation. In: Proceedings of the Reliability and Maintainability Symposium, Fort Worth, TX. https://doi.org/10.1109/RAMS.2009.4914701
102. Hurwitz, Z. L., Dubief, Y., Almassalkhi, M. (2020) Economic efficiency and carbon emissions in multi-energy systems with flexible buildings. International Journal of Electrical Power & Energy Systems, 123 (106114). https://www.sciencedirect.com/science/article/pii/S0142061519326754
103. Hwang, K. (2016). Cost-benefit analysis: its usage and critiques. Journal of Public Affairs, 16(1), pp. 75-80. https://doi.org/10.1002/pa.1565
104. IEA (2021) Net Zero by 2050 A Roadmap for the Global Energy Sector. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-A RoadmapfortheGlobalEnergySector_CORR.pdf (retrieved on 26 June, 2023)

doi:10.6342/NTU202400056

105. IEC International Standard (1995) Reliability growth— Statistical test and estimation methods, IEC 1164 International Electrotechnical Commission. https://webstore.iec.ch/preview/info_iec61164%7Bed2.0%7Den.pdf
106. Ijiri, Y. (1979) Convergence of cash recovery rate. In Quantitative planning and control. Academic Press, pp. 259-267. https://doi.org/10.1016/B978-0-12-370450-4.50024-8
107. Ingrao, C., Messineo, A., Beltramo, R., Yigitcanlar, T., Ioppolo, G. (2018) How can life cycle thinking support sustainability of buildings? Investigating life cycle assessment applications for energy efficiency and environmental performance, Journal of Cleaner Production, 201, pp. 556-569 https://doi.org/10.1016/j.jclepro.2018.08.080
108. Jackson, A., Jackson, T. (2021) Modelling energy transition risk: The impact of declining energy return on investment (EROI). Ecol Econ 185: 107023. https://doi.org/10.1016/j.ecolecon.2021.107023
109. Japan Dam Foundation, The Yamakura Reservoir, https://www.damnet.or.jp
110. Japan National Tax Agency. https://www.nta.go.jp/taxes/nozei/nofu/01.htm (retrieved on May 18, 2022).
111. Joseph, R., Proverbs, D., Lamond, J. (2015) Assessing the value of intangible benefits of property level flood risk adaptation (PLFRA) measures. *Natural Hazards*, 79, pp. 1275-1297. https://link.springer.com/article/10.1007/s11069-015-1905-5
112. Jouny, M., Luc, W., Jiao, F. (2018) General techno-economic analysis of CO2 electrolysis systems. Industrial & Engineering Chemistry Research, 57(6), pp. 2165-2177. https://pubs.acs.org/doi/full/10.1021/acs.iecr.7b03514
113. Kadoić, N., Begičević Ređep, N. Divjak, B. (2017) Decision making with the analytic network process. *Proceedings of the 14th International Symposium on Operational Research* (pp. 180-186). Retrieved from https://urn.nsk.hr/urn:nbn:hr:211:924942
114. Kamal, M., Rabaia, H., Semeraro, C. et al. (2022) Recent progress towards photovoltaics' circular economy. J Cleaner Prod, 373. https://doi.org/10.1016/j.jclepro.2022.133864
115. Kamuyu, W.C.L., Lim, J. R., Won, C. S., Ahn, H. K. (2018) Prediction model of photovoltaic module temperature for power performance of floating PVs. Energies, 11(2), p. 447. https://www.mdpi.com/1996-1073/11/2/447
116. Katsigiannis, Y. A., Georgilakis, P. S., Tsinarakis, G. J. (2010) A novel colored fluid stochastic Petri net simulation model for reliability evaluation of wind/PV/diesel small isolated power systems. IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, 40(6), pp. 1296-1309.

doi:10.6342/NTU202400056

https://ieeexplore.ieee.org/abstract/document/5545415
117. Kaymak, M. K., Şahin, A. D. (2021) Problems encountered with floating photovoltaic systems under real conditions: A new FPV concept and novel solutions, Sustainable Energy Technologies and Assessments, 47 (101504). https://doi.org/10.1016/j.seta.2021.101504
118. Kececioglu, D. B. (1991). Reliability growth. Reliability engineering handbook, 2, pp. 415-418.
119. Keisang, K., Bader, T., Samikannu, R. (2021) Review of Operation and Maintenance Methodologies for Solar Photovoltaic Microgrids. Frontiers in Energy Research, 9, 730230. https://www.frontiersin.org/articles/10.3389/fenrg.2021.730230/full
120. Kendall, M. G. (1975) Rank Correlation Methods, Griffin, London.
121. Khamharnphol, R., Kamdar, I., Waewsak, J., Chiwamongkhonkarn, S., Khunpetch, S., Kongruang, C., Gagnon, Y. (2023) Techno-Economic Assessment of a 100 kWp Solar Rooftop PV System for Five Hospitals in Central Southern Thailand. International Journal of Renewable Energy Development, 12(1). http://creativecommons.org/licenses/by-sa/4.0/
122. Khan, M.Y. (1999) Theory & Problems in Financial Management. Boston: McGraw Hill Higher Education. https://doi.org/10.1362/026725799784772684
123. Kiran, D.R. (2022) Chapter Twenty-two - Machinery replacement analysis, Principles of Economics and Management for Manufacturing Engineering, Butterworth-Heinemann, pp. 259-267.
124. Kjeldstad, T., Lindholm, D., Marstein, E., Selj, J. (2021) Cooling of floating photovoltaics and the importance of water temperature. Solar Energy, 218, pp. 544-551. https://doi.org/10.1016/j.solener.2021.03.022
125. Koopmans, C., Mouter, N. (2020). Cost-benefit analysis. In Advances in Transport Policy and Planning 6, pp. 1-42. Academic Press. https://doi.org/10.1016/bs.atpp.2020.07.005
126. Kougias, I., Bódis, K., Jäger-Waldau, A., Moner-Girona, M., Monforti-Ferrario, F., Ossenbrink, H., Szabó, S. (2016) The potential of water infrastructure to accommodate solar PV systems in Mediterranean islands, Solar Energy, 136, pp.174-182. https://doi.org/10.1016/j.solener.2016.07.003
127. Kropf, C. M., Ciullo, A., Otth, L., Meiler, S., Rana, A., Schmid, E., ... Bresch, D. N. (2022). Uncertainty and sensitivity analysis for probabilistic weather and climate-risk modelling: an implementation in CLIMADA v. 3.1. 0. Geoscientific Model Development, 15(18), 7177-7201 https://gmd.copernicus.org/articles/15/7177/2022/
128. Kumar, M., Niyaz, H. M., Gupta, R. (2021) Challenges and opportunities towards

doi:10.6342/NTU202400056

the development of floating photovoltaic systems, Solar Energy Materials and Solar Cells, 233 (111408). https://doi.org/10.1016/j.solmat.2021.111408

129. Kumar, M., Meena, R., Gupta, R. (2023) Floating Photovoltaic Systems: An Emerging PV Technology. In Enabling Methodologies for Renewable and Sustainable Energy, pp. 193-211. CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781003272717-12/floating-photovoltaic-systems-manish-kumar-roopmati-meena-rajesh-gupta
130. Kunreuther, H. (2002). Risk analysis and risk management in an uncertain world 1. Risk Analysis: An International Journal, 22(4), pp. 655-664. https://doi.org/10.1111/0272-4332.00057
131. KyoceraTCLSolar. https://global.kyocera.com/newws-archive/2018
132. Lai, X., Yao, J., Jin, C., Feng, X., Wang, H., Xu, C., Zheng, Y. (2022) A review of lithium-ion battery failure hazards: test standards, accident analysis, and safety suggestions. Batteries, 8(11), p. 248. https://doi.org/10.3390/batteries8110248
133. Lambert, J. H., Matalas, N. C., Ling, C. W., Haimes, Y. Y., Li, D. (1994). Selection of probability distributions in characterizing risk of extreme events. Risk Analysis, 14(5), pp. 731-742. https://doi.org/10.1111/j.1539-6924.1994.tb00283.x
134. Lee, N., Grunwald, U., Rosenlieb, E., Mirletz, H., Aznar, A., Spencer, R., Cox, S. (2020) Hybrid floating solar photovoltaics-hydropower systems: Benefits and global assessment of technical potential, Renewable Energy, 162, pp. 1415-1427. https://doi.org/10.1016/j.renene.2020.08.080
135. Li, C., Cao, Q., Wang, F., Xiao, Y., Li, Y., Delaunay, J. J., Zhu, H. (2018) Engineering graphene and TMDs based van der Waals heterostructures for photovoltaic and photoelectrochemical solar energy conversion. Chemical Society Reviews, 47(13), pp. 4981-5037. https://pubs.rsc.org/en/content/articlehtml/2018/cs/c8cs00067k
136. Li, J., Liu, P., Li, Z. (2020) Optimal design and techno-economic analysis of a solar-wind-biomass off-grid hybrid power system for remote rural electrification: A case study of west China. Energy, 208 (118387). https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q
137. Li, S., Cai, Y.-H., Schäfer, A.I., Richards, B.S. (2019) Renewable energy powered
138. membrane technology: A review of the reliability of photovoltaic-powered membrane system components for brackish water desalination, Applied Energy, 253 (113524) https://doi.org/10.1016/j.apenergy.2019.113524
139. Li, X., Yao, X. (2020). Can energy supply-side and demand-side policies for energy saving and emission reduction be synergistic?--- A simulated study on China's coal capacity cut and carbon tax. Energy Policy, p. 138, 111232. https://doi.org/10.1016/j.enpol.2019.111232

doi:10.6342/NTU202400056

140. Lin, C., Madu, C. N., Kuei, C., Tsai, H., Wang, K. (2015) Developing an assessment framework for managing sustainability programs: A Analytic Network Process approach. Expert Systems With Applications, 42(5), 2488-2501. https://doi.org/10.1016/j.eswa.2014.09.025
141. Lin, C. H., Hsieh, W. L., Chen, C. S., Hsu, C. T., Ku, T. T. (2012) Optimization of photovoltaic penetration in distribution systems considering annual duration curve of solar irradiation. IEEE Transactions on Power Systems, 27(2), pp. 1090-1097. https://doi.org/10.1109/TPWRS.2011.2178619
142. Liu, B., Siu, Y.L., Mitchell, G. (2013) Exceedance probability of multiple natural hazards: risk assessment in China's Yangtze River Delta. Nat Hazards 69, pp. 2039–2055. https://doi.org/10.1007/s11069-013-0794-8
143. Liu, C., Zhang, Q., Lei, M.Z., et al. (2022) Employing benefit-sharing to motivate stakeholders' efficient investment in waste photovoltaic module recycling. Sustainable Energy Technol Assess, 51. https://doi.org/10.1016/j.seta.2021.101877
144. Liu, H., Krishna, V., Lun Leung, J., Reindl, T., Zhao, L. (2018) Field experience and performance analysis of floating PV technologies in the tropics. Progress in Photovoltaics: Research and Applications, 26 (12), pp. 957-967. https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3039
145. Louwen, A., Sark, V. W., Schropp, R.E. et al. (2015) Lifecycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs. Prog Photovoltaics Res Appl 23: pp. 1406–1428. https://doi.org/10.1002/pip.2540
146. Loveday, J., Morrison, G. M., Martin, D. A. (2022). Identifying knowledge and process gaps from a systematic literature review of net-zero definitions. Sustainability, 14(5), 3057. https://doi.org/10.3390/su14053057
147. Lu, Y., Khan, Z., Gunduz, H., Wang, W., Li, J., Zhang, X. P. (2019) Economic Performance of Net-Zero Energy Community under Reward-Penalty Mechanism Considering PV System Reliability. Environmental & Climate Technologies, 23(3). https://sciendo.com/
148. Luo, W., Isukapalli, S. N., Vinayagam, L., Ting, S. A., Pravettoni, M., Reindl, T., Kumar, A. (2021) Performance loss rates of floating photovoltaic installations in the tropics. Solar Energy, 219, 58-64. https://www.sciencedirect.com/science/article/pii/S0038092X20312706
149. Mackay, E., Haselsteiner, A. F. (2021) Marginal and total exceedance probabilities of environmental contours. Marine Structures, 75, 102863. https://doi.org/10.1016/j.marstruc.2020.102863
150. Mahmoudimehr, J., Shabani, M. (2018) Optimal design of hybrid photovoltaic-hydroelectric standalone energy system for north and south of Iran, Renewable

doi:10.6342/NTU202400056

Energy, 115, pp. 238-25. https://doi.org/10.1016/j.renene.2017.08.054
151. Malhotra, M. K., Grover, V. (1998) An assessment of survey research in POM: from constructs to theory. Journal of operations management, 16(4), pp. 407-425. https://doi.org/10.1016/S0272-6963(98)00021-7
152. Mann, H. B., Econometrica, 13, pp. 245-259 (1945).
153. Manning, M., Johnson, S. D., Tilley, N., Wong, G. T., Vorsina, M., Manning, M., ... Vorsina, M. (2016) Cost-Benefit Analysis (CBA). Economic Analysis and Efficiency in Policing, Criminal Justice and Crime Reduction: What Works?, pp. 35-50. https://doi.org/10.1057/9781137588654_5
154. Maritato, K., Uryasev, S. (2023). Derivative of reduced cumulative distribution function and applications. Journal of Risk and Financial Management, 16(10), p. 450. https://doi.org/10.3390/jrfm16100450
155. Mason, S. J., Galpin, J. S., Goddard, L., Graham, N. E., Rajartnam, B. (2007) Conditional exceedance probabilities. Monthly Weather Review, 135(2), pp. 363-372. https://doi.org/10.1175/MWR3284.1
156. Mazzeo, D., Matera, N., Oliveti, G. (2018). Interaction between a wind-PV-battery-heat pump trigeneration system and office building electric energy demand including vehicle charging. In 2018 IEEE international conference on environment and electrical engineering and 2018 IEEE industrial and commercial power systems europe (EEEIC/I&CPS europe) pp. 1-5. IEEE. https://ieeexplore.ieee.org/abstract/document/8493710
157. Mboumboue, E., Njomo, D. (2016). Potential contribution of renewables to the improvement of living conditions of poor rural households in developing countries: Cameroon′ s case study. Renewable and Sustainable Energy Reviews, 61, pp. 266-279. https://www.sciencedirect.com/science/article/pii/S136403211630020X
158. Menzies, G. F., Turan, S., Banfill, P. F. (2007) Life-cycle assessment and embodied energy: a review. Proceedings of the Institution of Civil Engineers-Construction Materials, 160(4), pp. 135-143. https://www.icevirtuallibrary.com/doi/abs/10.1680/coma.2007.160.4.135
159. Mercure, J. F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., ... Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. Nature Climate Change, 8(7), pp. 588-593. https://www.nature.com/articles/s41558-018-0182-1
160. Meydbray, Y., Wilson, K., Brambila, E., Terao, A., Daroczi, S. (2008) Solder joint degradation in high efficiency all back-contact solar cells, IEEE Photovoltaic Specialists Conference.
161. Micheli, L. (2022) The temperature of floating photovoltaics: Case studies, models and recent findings. Solar Energy, 242, pp. 234-245.

doi:10.6342/NTU202400056

https://doi.org/10.1016/j.solener.2022.06.039
162. Mills, T. C. (2019) Applied time series analysis: A practical guide to modeling and forecasting. Academic press.
163. Ming, B., Liu, P., Guo, S., Zhang, X., Feng, M., Wang, X. (2017) Optimizing utility-scale photovoltaic power generation for integration into a hydropower reservoir by incorporating long-and short-term operational decisions. Applied Energy, 204, pp. 432-445. https://scholar.google.com.tw/scholar?hl=en&as_sdt=0%2C5&q
164. Ministry of Health, Labour and Welfare. https://www.mhlw.go.jp/english/ (retrieved on January 18, 2023).
165. Mohammed, Y. S., Mokhtar, A. S., Bashir, N., Saidur, R. (2013) An overview of agricultural biomass for decentralized rural energy in Ghana. Renewable and Sustainable Energy Reviews, 20, pp. 15-25. https://doi.org/10.1016/j.rser.2012.11.047
166. Morales, M., Quintero, J., Conejeros, R., Aroca, G. (2015) Life cycle assessment of lignocellulosic bioethanol: Environmental impacts and energy balance, Renewable and Sustainable Energy Reviews, (42) pp.1349-1361, https://doi.org/10.1016/j.rser.2014.10.097.
167. Motech Industries, Inc. https://www.motech.com.tw/modules-1.php (retrieved on 30 June, 2023).
168. Mouter, N., Annema, J. A., Van Wee, B. (2013). Attitudes towards the role of Cost–Benefit Analysis in the decision-making process for spatial-infrastructure projects: A Dutch case study. Transportation Research Part A: Policy and Practice, 58, pp. 1-14. https://doi.org/10.1016/j.tra.2013.10.006
169. Mu, E., Cooper, O., Peasley, M. (2020) Best practices in Analytic Network Process studies. Expert Systems With Applications, 159, 113536. https://doi.org/10.1016/j.eswa.2020.113536
170. Murphy, D.J., Hall, C.A.S. (2010) Year in review EROI or energy return on (Energy) invested. Ann N Y Acad Sci 1185: pp. 102–118. https://doi.org/10.1111/j.1749-6632.2009.05282.x
171. Nathan, R., Jordan, P., Scorah, M., Lang, S., Kuczera, G., Schaefer, M., Weinmann, E. (2016) Estimating the exceedance probability of extreme rainfalls up to the probable maximum precipitation. Journal of hydrology, 543, pp. 706-720. https://doi.org/10.1016/j.jhydrol.2016.10.044
172. Najjar, M. K., Figueiredo, K., Evangelista, A. C. J., Hammad, A. W., Tam, V. W., Haddad, A. (2022). Life cycle assessment methodology integrated with BIM as a decision-making tool at early-stages of building design. International Journal of Construction Management, 22(4), pp. 541-555.

doi:10.6342/NTU202400056

https://doi.org/10.1080/15623599.2019.1637098
173. National Taxation Bureau of Taipei, Ministry of Finance. https://www.ntbt.gov.tw/singlehtml/ (retrieved on May 14, 2022).
174. Nesamalar, J.J.D., Suruthi, S., Raja, S.C. (2021) Tamilarasu, K., Energy Conversion and Management, 239 (114188). https://www.sciencedirect.com/science/article/pii/S0196890421003642
175. New Energy and Industrial Technology Development Organization (NEDO). NEDO Available online (In Japanese): https://www.nedo.go.jp/content/100930737.pdf. (retrieved on May 14, 2022)
176. Nippa, M., Patnaik, S., Taussig, M. (2021) MNE responses to carbon pricing regulations: Theory and evidence. Journal of International Business Studies, 52, pp. 904-929. https://link.springer.com/article/10.1057/s41267-021-00403-8
177. Olatomiwa, L., Sadiq, A. A., Longe, O. M., Ambafi, J. G., Jack, K. E., Abd'azeez, T. A., Adeniyi, S. (2022) An overview of energy access solutions for rural healthcare facilities. Energies, 15 (24), 9554. https://www.mdpi.com/1996-1073/15/24/9554
178. Omar, A. Al-Shahri, F.B., Ismail, M.A., Hannan, M.S., Hossain, L., Ali, Q. Al-Shetwi, R.A. Begum, N.F.O. Al-Muhsen, E. S. (2021) Solar photovoltaic energy optimization methods, challenges and issues: A comprehensive review, Journal of Cleaner Production, 284 (125465). https://doi.org/10.1016/j.jclepro.2020.125465
179. Ortiz O, Castells F, Sonnemann G (2009) Sustainability in the construction industry: a review of recent developments based on LCA. Constr Build Mater 23: 28-39. https://doi.org/10.1016/j.conbuildmat.2007.11.012
180. Osman, A. I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., ... & Yap, P. S. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. Environmental Chemistry Letters, 21(2), pp. 741-764. https://link.springer.com/article/10.1007/s10311-022-01532-8
181. Øvergaard, S. (2008) Definition of primary and secondary energy, Standard International Energy Classification (SIEC) in the International Recommendation on Energy Statistics (IRES), Statistics Norway. file:///C:/Users/user/Downloads/LG13_12a.pdf
182. Pal, N., Khan, F. A. (2021) Hydropower technology. In Sustainable Fuel Technologies Handbook, pp. 91-120. Academic Press. https://www.sciencedirect.com/science/article/abs/pii/B9780128229897000056
183. Paltsev, S., Morris, J., Kheshgi, H., Herzog, H. (2021) Hard-to-Abate Sectors: The role of industrial carbon capture and storage (CCS) in emission mitigation. Applied Energy, 300 (117322). https://www.sciencedirect.com/science/article/pii/S0306261921007327

doi:10.6342/NTU202400056

184. Pamponet, M. C., Maranduba, H. L., Neto, A., Rodrigues, L. B. (2022) Energy
185. balance and carbon footprint of very large-scale photovoltaic power plant. International Journal of Energy Research, 46 (5), pp. 6901-6918. https://doi.org/10.1002/er.7529
186. Pannell, D. J. (1997). "Sensitivity Analysis of Normative Economic Models: Theoretical Framework and Practical Strategies". Agricultural Economics. 16: pp. 139–152. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1574-0862.1997.tb00449.x
187. Paridaa, B., Iniyanb, S., Goic, R. (2011) A review of solar photovoltaic technologies, Renewable and Sustainable Energy Reviews, 15 (3), pp. 1625-1636, https://doi.org/10.1016/j.rser.2010.11.032
188. Park, N. G., Zhu, K. (2020) Scalable fabrication and coating methods for perovskite solar cells and solar modules. Nature Reviews Materials, 5(5), pp. 333-350. https://www.nature.com/articles/s41578-019-0176-2
189. Perera, H. D. M. R. (2020) Designing of 3MW floating photovoltaic power system and its benefits over other PV technologies. Int. J. Adv. Sci. Res. Eng, 6, pp. 37-48. https://ijasre.net/index.php/ijasre/article/view/834/1439
190. Piechota, T. C., Chiew, F. H., Dracup, J. A., McMahon, T. A. (2001) Development of exceedance probability streamflow forecast. Journal of Hydrologic Engineering, 6(1), pp. 20-28. https://ascelibrary.org/doi/abs/10.1061/(ASCE)1084-0699(2001)6:1(20)
191. Porporato, A., Ridolfi, L. (1998) Influence of weak trends on exceedance probability. Stochastic Hydrology and Hydraulics 12, pp. 1–14. https://doi.org/10.1007/s004770050006
192. Pouran, H. M., Lopes, M. P. C., Nogueira, T., Branco, D. A. C., Sheng, Y. (2022) Environmental and technical impacts of floating photovoltaic plants as an emerging clean energy technology. Iscience, 25(11). https://www.cell.com/iscience/pdf/S2589-0042(22)01525-5.pdf
193. Rahman, A., Farrok, O., Haque, M. M. (2022) Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic. Renewable and Sustainable Energy Reviews, 161, 112279. https://doi.org/10.1016/j.rser.2022.112279
194. Ramasamy, Vignesh, and Robert Margolis (2021) Floating Photovoltaic System Cost Benchmark: Q1 2021 Installations on Artificial Water Bodies. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-80695. https://www.nrel.gov/docs/fy22osti/80695.pdf
195. Ranjbaran, P., Yousefi, H., Gharehpetian, G.B., Astaraei, F.R. (2019) A review on floating photovoltaic (FPV) power generation units, Renewable and Sustainable

doi:10.6342/NTU202400056

Energy Reviews, 110, pp. 332-347. https://doi.org/10.1016/j.rser.2019.05.015
196. Recchia, C. (2016) Vermont Comprehensive Energy Plan. Vermont Department of Public Service. https://publicservice.vermont.gov/about_us/plans-and-reports/department-state-plans/2016-plan
197. Reich, N.H., van Sark, W.G.J.H.M., Alsema, E.A., Lof, R.W., Schropp, R.E.I., Sinke, W.C., Turkenburg, W.C. (2009) Crystalline silicon cell performance at low light intensities, Solar Energy Materials and Solar Cells, 93 (9), pp. 1471-1481, https://doi.org/10.1016/j.solmat.2009.03.018
198. Ritchie, H., Roser, M., Rosado, P. (2022) – "Energy." [online] Our World in Data. https://ourworldindata.org/energy (retrieved on 24 June, 2023)
199. Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., ... & Zickfeld, K. (2018) Mitigation pathways compatible with 1.5 C in the context of sustainable development. In Global warming of 1.5 C, pp. 93-174. Intergovernmental Panel on Climate Change. http://www.ipcc.ch/report/srl5/
200. Rontard, B., Hernández, H. R. (2022) Political construction of carbon pricing: Experience from New Zealand emissions trading scheme, Environmental Development, 43 (100727). https://doi.org/10.1016/j.envdev.2022.100727
201. Rothwell, G. (2004) Nuclear power economics. Encyclopedia of energy, 4, pp. 383-394.
202. Saaty, T. L. (2004) Fundamentals of the analytic network process—Dependence and feedback in decision-making with a single network. Journal of Systems science and Systems engineering, 13, pp. 129-157. https://doi.org/10.1007/s11518-006-0158-y
203. Salary Explorer. http://www.salaryexplorer.com/salary-loc=107&loctype=1&job=12678&jobtype=3 (retrieved on May 18, 2022).
204. Salas, J. D. (1993) Analysis and modelling of hydrological time series. Handbook of hydrology, 19. https://cir.nii.ac.jp/crid/1573668924863168256
205. Salehi, M. Filimonau, V., Asadzadeh, M., Ghaderi, E. (2021) Strategies to improve energy and carbon efficiency of luxury hotels in Iran, Sustainable Production and Consumption, 26, pp. 1-15, https://doi.org/10.1016/j.spc.2020.09.007
206. Santafé, M. R., Soler, J. B. T., Romero, F. J. S., Gisbert, P. S. F., Gozálvez, J. J. F., Gisbert, C. M. F. (2014). Theoretical and experimental analysis of a floating photovoltaic cover for water irrigation reservoirs. Energy, 67, pp. 246-255. https://doi.org/10.1016/j.energy.2014.01.083
207. Sarker, P., Lester, H.D. (2019) Post-Disaster Recovery Associations of Power Systems Dependent Critical Infrastructures. *Infrastructures* , 4(30). https://doi.org/10.3390/infrastructures402003

doi:10.6342/NTU202400056

208. Saaty, T. L. (1980). The Analytic Hierarchy Process Mcgraw Hill, New York. Agricultural Economics Review, 70, 34.
209. Saaty, T. L. (1996). Decision making with dependence and feedback: The analytic network process (Vol. 4922, No. 2). Pittsburgh: RWS publications. ISBN 0-9620317-9-8.
210. Saltelli, A. (2002). Sensitivity analysis for importance assessment. Risk analysis, 22(3), pp. 579-590. https://doi.org/10.1111/0272-4332.00040
211. Saltelli, A.; Ratto, M.; Andres, T.; Campolongo, F.; Cariboni, J.; Gatelli, D.; Saisana, M.; Tarantola, S. (2008). Global Sensitivity Analysis: The Primer. John Wiley & Sons.
212. Shabani, M., Mahmoudimehr, J. (2019) Influence of climatological data records on design of a standalone hybrid PV-hydroelectric power system. Renewable Energy, 141, pp. 181-194. https://www.sciencedirect.com/science/article/pii/S0960148119304665
213. Shivam, K., Tzou, J. C., Wu, S. C. (2021) A multi-objective predictive energy management strategy for residential grid-connected PV-battery hybrid systems based on machine learning technique. Energy Conversion and Management, 237, 114103. https://doi.org/10.1016/j.enconman.2021.114103
214. Shubbak, M. H. (2019) Advances in solar photovoltaics: Technology review and patent trends. Renewable and Sustainable Energy Reviews, 115, 109383. https://www.sciencedirect.com/science/article/pii/S136403211930591X
215. Simon, C. P., Blume, L. (1994). Mathematics for economists (Vol. 7). New York: Norton.
216. Singh, G. K. (2013) Solar power generation by PV (photovoltaic) technology: A review. Energy, 53, pp. 1-13. https://doi.org/10.1016/j.energy.2013.02.057
217. Smil, V. (2016) Energy Transitions: Global and National Perspectives (Second expanded and updated edition). http://vaclavsmil.com/2016/12/14/energy-transitions-global-and-national-perspectives-second-expanded-and-updated-edition/(retrieved on 24 June, 2023)
218. Solaclad, Next Generation Solar Energy. https://www.solaclad.com/ (retrieved on 24 June, 2023)
219. Southern Water Resources Bureau of the Ministry of Water Resources, Ministry Economic Affairs, https:// www.rasb.gov.tw (accessed on June 12, 2022) (in Chinese)
220. Staebler, 1. L., Wronski, C. R. (1977) Reversible conductivity changes in discharge-produced amorphous Si. Applied physics letters, 31(4), pp. 292-294. https://doi.org/10.1063/1.89674
221. Stavins, R. N. (2022) The relative merits of carbon pricing instruments: Taxes versus trading. Review of Environmental Economics and Policy, 16(1), pp. 62-82.

doi:10.6342/NTU202400056

https://www.journals.uchicago.edu/doi/abs/10.1086/717773
222. Sulaeman, S., Brown, E., Quispe-Abad, R., Müller, N. (2021) Floating PV system as an alternative pathway to the amazon dam underproduction. Renewable and Sustainable Energy Reviews, 135 (110082). https://www.sciencedirect.com/science/article/pii/S1364032120303737
223. Sultan, S., Kim, J. H., Kim, S., Kwon, Y., Lee, J. S. (2021) Innovative strategies toward challenges in PV-powered electrochemical CO2 reduction. Journal of Energy Chemistry, 60, pp. 410-416. https://doi.org/10.1016/j.jechem.2021.01.043
224. Taiwan Bureau of Energy, Ministry of Economic Affairs (2016) Photovoltaic Two-year Promotion Plan. https://www.moeaboe.gov.tw
225. Taiwan Power Company (TPC), https://www.taiwanstat.com/ realtime/power/ (retrieved on January 14, 2022)
226. Tan, K. M., Babu, T. S., Ramachandaramurthy, V. K., Kasinathan, P., Solanki, S. G., & Raveendran, S. K. (2021). Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration. Journal of Energy Storage, 39, 102591. https://doi.org/10.1016/j.est.2021.102591
227. Tang, J., Ni, H., Peng, R. L., Wang, N., Zuo, L. (2023) A review on energy conversion using hybrid photovoltaic and thermoelectric systems. Journal of Power Sources, 562, 232785. https://doi.org/10.1016/j.jpowsour.2023.232785
228. Taye, B. Z., Nebey A. H., Workineh, T. G. | Honrubia-Escribano, A. (Reviewing editor) (2020) Design of floating solar PV system for typical household on Debre Mariam Island, Cogent Engineering, 7:1. https://doi.org/10.1080/23311916.2020.1829275
229. Timilsina, G. R., Cornelis van Kooten, G., Narbel, P. A. (2013) Global wind power development: Economics and policies, Energy Policy, 61, pp. 642-652. https://doi.org/10.1016/j.enpol.2013.06.062
230. Tina, G.M., Scavo, F.B. (2022) Energy performance analysis of tracking floating photovoltaic systems. Heliyon, 8 (8). https://doi.org/10.1016/j.heliyon. 2022.06.e10088
231. Thomson, K., De Chernatony, L., Arganbright, L., Khan, S.(1999) The Buy-in Benchmark: How Staff Understanding and Commitment Impact Brand and Business Performance, Journal of Marketing Management, 15:8, pp. 819-835. https://doi.org/10.1362/026725799784772684
232. Thorne, C. R., Lawson, E. C., Ozawa, C., Hamlin, S. L., Smith, L. A. (2018) Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management. Journal of Flood Risk Management, 11, pp. S960-S972. https://onlinelibrary.wiley.com/doi/full/10.1111/jfr3.12218

doi:10.6342/NTU202400056

233. Toklu, E. (2017) Biomass energy potential and utilization in Turkey, Renewable Energy, 107, pp. 235-244. https://doi.org/10.1016/j.renene.2017.02.008
234. Tokyo Electric Power Company (TEPCO). https://www.tepco.co.jp/en/hd/index-e.html. (retrieved on May 14, 2022)
235. Tradingview. https://tw.tradingview.com (retrieved on May 18, 2022).
236. Tran, T. T., Smith, A. D. (2018) Incorporating performance-based global sensitivity and uncertainty analysis into LCOE calculations for emerging renewable energy technologies. Applied energy, 216, pp. 157-171. https://www.sciencedirect.com/science/article/pii/S0306261918301430
237. Tushar, W., Yuen, C., Saha, T.K., Morstyn, T., Chapman, A.C., Alam, M.J.E., Hanif, S., Poor H. V. (2021) Peer-to-peer energy systems for connected communities: A review of recent advances and emerging challenges, Applied Energy, 282, Part A (116131). https://doi.org/10.1016/j.apenergy.2020.116131
238. United Nations. Renewable energy – powering a safer future. https://www.un.org/en/climatechange/raising-ambition/renewable-energy (retrieved on 14 June, 2023)
239. Vakulchuk, R., Overland, I., Scholten, D. (2020) Renewable energy and geopolitics: A review. Renewable and sustainable energy reviews, 122, 109547. https://doi.org/10.1016/j.rser.2019.109547
240. Van de Ven, D. J., Capellan-Peréz, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., Gonzalez-Eguino, M. (2021) The potential land requirements and related land use change emissions of solar energy. Scientific reports, 11(1), 2907. https://www.nature.com/articles/s41598-021-82042-5
241. Varadarajan, V. S. (2004) Supersymmetry for Mathematicians: An Introduction. Courant Lecture Notes in Mathematics 11. American Mathematical Society.
242. Venkatraj, V., Dixit, M. K. (2021). Life cycle embodied energy analysis of higher education buildings: A comparison between different LCI methodologies. Renewable and Sustainable Energy Reviews, 144, 110957. https://doi.org/10.1016/j.rser.2021.110957
243. Wang C, Zhang L, Chang Y, et al. (2021) Energy return on investment (EROI) of biomass conversion systems in China: Meta-analysis focused on system boundary unification. Renewable Sustainable Energy Rev 137: 110652. https://doi.org/10.1016/j.rser.2020.110652
244. Wang, K., Yuan, B., Ji, G., Wu, X. (2018) A comprehensive review of geothermal
245. energy extraction and utilization in oilfields, Journal of Petroleum Science and Engineering, 168, pp. 465-477. https://doi.org/10.1016/j.petrol.2018.05.012
246. Water Resources Agency. Available online (In Chinese): https://www.wrasb.gov.tw(retrieved on September 18, 2021).

doi:10.6342/NTU202400056

247. Water Resources Agency (2023). https://www.wrasb.gov.tw
248. Weißbach, D., Ruprecht, G., Huke, A. et al. (2013) Energy intensity, EROIs (energy returned on invested), and energy payback times of electricity-generating power plants. Energy 43: 53–58. https://doi.org/10.1016/j.energy.2013.01.029
249. Westwood, A. (2004), Ocean power: Wave and tidal energy review, Refocus, 5 (5), pp. 50-55. https://doi.org/10.1016/S1471-0846(04)00226-4
250. Yadav, N., Gupta, M., Sudhakar, K. (2016) Energy assessment of floating photovoltaic system, *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, Bhopal, India, pp. 264-269. https://doi: 10.1109/ICEPES.2016.7915941
251. Yang, Z., Liu, P., Cheng, L., Wang, H., Ming, B., & Gong, W. (2018). Deriving operating rules for a large-scale hydro-photovoltaic power system using implicit stochastic optimization. Journal of Cleaner Production, 195, pp. 562-572. https://www.sciencedirect.com/science/article/pii/S095965261831494X
252. Yasuo, T. Research Institute of Economy, Trade, and Industry (RIETI) Japan should lead the global effort to decarbonize in view of the EU's CBAM proposal. (October 21, 2021). https://www.rieti.go.jp/en/columns/a01_0665.html (retrieved May 14, 2021).
253. Yin, R. K. (2014). Case study research.
254. Yue, C.-D., Huang, G.-R. (2011) An evaluation of domestic solar energy potential in Taiwan incorporating land use analysis, Energy Policy, 39 (12), pp.7988-8002. https://doi.org/10.1016/j.enpol.2011.09.054
255. Zaidi, B. (2018) Introductory chapter: Introduction to photovoltaic effect. Solar Panels and Photovoltaic Materials, pp. 1-8. https://www.sciencedirect.com/science/article/pii/S0959652621034193
256. Zainol, M. Z., Ismail, N., Zainol, I., Abu, A., Dahalan, W. (2017) A review on the status of tidal energy technology worldwide. Sci. Int, 29(3), pp. 659-667. https://www.researchgate.net/publication/317617074
257. Zangeneh, A., Jadid, S., Rahimi-Kian, A. (2010) Normal boundary intersection and benefit-cost ratio for distributed generation planning. European Transactions on Electrical Power, 20(2), pp.97-113
258. Zarmai, M.T., Ekere, N.N., Oduoza, C.F., Amalu, E. H. (2015) A review of interconnection technologies for improved crystalline silicon solar cell photovoltaic module assembly, Applied Energy, 154, pp. 173-182. https://doi.org/10.1016/j.apenergy.2015.04.120
259. Zhang, Z. and Huang, J. (2006). Extremal financial risk models and portfolio evaluation. Computational statistics & data analysis, 51(4), pp. 2313-2338. https://doi.org/10.1016/j.csda.2006.09.042

doi:10.6342/NTU202400056

260. Zheng, D.; Wang, Y.; Zhang X. (2015) Management Accounting Third Edition. Guide Bookstore (In Chinese).
261. Zhou, Z. (2022) The Capacity of Carbon Pricing Mechanism. In Guidebook to Carbon Neutrality in China: Macro and Industry Trends under New Constraints, pp. 45-76. CICC Research, CICC Global Institute, Springer Singapore, https://link.springer.com/chapter/10.1007/978-981-16-9024-2_3
262. Zhou, Z., Carbajales-Dale M (2018) Assessing the photovoltaic technology landscape: efficiency and energy return on investment (EROI). Energy Environ Sci 11: 603–608. https://doi.org/10.1039/C7EE01806A

doi:10.6342/NTU202400056

國立臺灣大學 · 愛國 · 愛人 · 敬業 · 樂群 · 勤勞 · 品學 ·

doi:10.6342/NTU202400056