



Michael Olusegun Banjoko

Innovation Report:
Design of a proof-of-concept Hybrid Solar Concentrator System
Utilising Spectrum Beam Splitting Technology to generate
sustainable heat and electricity, for palm oil processing farms in
South-West Nigeria

School of Aerospace, Transport and Manufacturing

EngD in Sustainable Materials and Manufacturing

Engineering Doctorate
Academic Year: 2017 – 2025

Supervisor: Dr Peter King (Cranfield University)
Associate Supervisor: Professor Chris Sansom (University of Derby)
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the degree of Doctor of Engineering EngD

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Abstract

This research explores the potential of a hybrid solar energy system that combines Concentrated Solar Power (CSP) and Photovoltaics (PV) using spectrum beam-splitting technology to address energy shortages in Nigeria's small-scale agro-industrial sector. By using cold and hot mirrors in a dish-based setup, the system separates the solar spectrum into visible and infrared bands for simultaneous electrical and thermal energy production, enabling cogeneration. Laboratory experiments, backed by theoretical modelling, show that this method can improve overall system efficiency, reduce PV overheating, and offer a reliable, modular, and sustainable energy solution.

The innovation is situated within a design-based, neighbourhood-scale framework that aligns with regenerative sustainability principles. A real-life application is presented using the palm oil processing sector at Owodaiye Farms in Ijebu-Ife, Ogun State, Nigeria, as a demonstrator site. Here, the hybrid system not only meets off-grid energy demands but also catalyses local empowerment, circular economies, and thematic integration within agricultural tourism.

The implications of this work extend beyond energy efficiency: the proposed system offers a replicable model for integrated rural development and community-based renewable energy infrastructure. It bridges the gap between technology and place-based regeneration by framing solar energy as a “Crude Sunlight Refinery”—a novel construct that envisions sunlight as a raw, separable, and usable resource for decentralized processing.

Future research will investigate the scalability of this beam-splitting concept into modular solar refineries featuring fluid-based thermal receivers, enhanced optical coatings, and adaptive tracking mechanisms. Additionally, investigations into policy alignment, climate resilience metrics, and long-term techno-economic feasibility will strengthen its potential deployment across sub-Saharan Africa.

Keywords: beam splitting; global thinking; hybridisation; Integrated farming; local acting; process heat

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To my Lord, my Saviour, my King, my Champion. I bless you here, even as I do all the days of my life.

Genesis 8:22

“While the earth remaineth, seedtime and harvest, and cold and heat, and summer and winter, and day and night shall not cease.”

King James Version (KJV)

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Nomenclature:

Energy Electricity	(E_{el})	kWh
Maximum generator power	(P_{max})	W
Generator efficiency	(η)	
Operation time	(t_{op})	h
Thermal Energy	(E_{th})	kWh
(percentage) reflected UV&VIS:	$(Q_{VIS}^{\rho, Ag})$	%
(percentage) reflected IR:	$(Q_{IR}^{\rho, Ag})$	%
Reflectance (specular):	(ρ)	%
Wavelength	(λ)	μm
effective aperture area of dish concentrator	(A_{Dish}^{eff})	m^2
outer diameter of the dish concentrator	(D_{Dish})	m
projected area of the hot mirror	(A_{HotM})	m^2
length factor	(q_{fl})	[1]
focal length (Dish)	f_{Dish}	m
coordinates Y, X (X along the focal length and Y perpendicular to X)		m
Dish focal length measured from (0,0)	(f_{Dish})	m
The outer position on the rim of the dish mirror	(X_{rim}, Y_{rim})	m
Outer diameter of the dish concentrator	(D_{Dish})	m
Focal length of dish concentrator	(f_{Dish})	m
(UV&VIS fraction) Solar Energy reflected:	(E_{VIS})	kWh/ m^2
(IR fraction) Solar Energy reflected:	(E_{IR})	kWh/ m^2
Monthly solar irradiance (DNI)	(E_{mon}^{sol})	kWh/ m^2
Effective aperture area of the dish concentrator	(A_{Dish}^{eff})	m^2
Reflectance (specular):	(ρ)	%
(percentage) reflected UV&VIS:	$(Q_{VIS}^{\rho, Ag})$	%
(percentage) reflected IR:	$(Q_{IR}^{\rho, Ag})$	%

PV efficiency amb temp relationship	$(\varepsilon_{(ambTem)}^{PV})$	
Ambient Temperature	(T_{amb})	°C
Electrical Energy per month	(E_{month}^{el})	kWh/m ²
Hot mirror transmittance coefficient (VIS)	(f_{VIS})	0.9 const
PV efficiency	(ε_{PV})	>0.15 const
Annual electrical Energy capacity	(E_{year}^{el})	kWh/m ²
PV surface area	(A_{PV})	m ²
Electrical concentration factor	(C_r^{el})	
Thermal Energy per month	(E_{month}^{therm})	kWh/m ²
Hot mirror reflectance coefficient (IR)	(f_{IR})	0.9 const
PV efficiency	$(\varepsilon_{thermRD})$	>0.6 const
Annual thermal Energy capacity	(E_{year}^{therm})	kWh/m ²
Thermal concentration factor	(C_r^{therm})	
Receiver Device area:	$(A_{thermRD})$	m ²
effective hot mirror surface area:	$(\text{eff } A_{HotM})$	m ²
coordinates of the reflection point (hot mirror)	(X_{HotM} / Y_{HotM})	m
sloop of first reflection	(m_1, m_2)	
Height of thermal receiver device	(l_{RD})	m
focal length hot mirror	(f_{HotM})	m
position of hot mirror	$(\text{pos}_{HotM}, 0)$	m

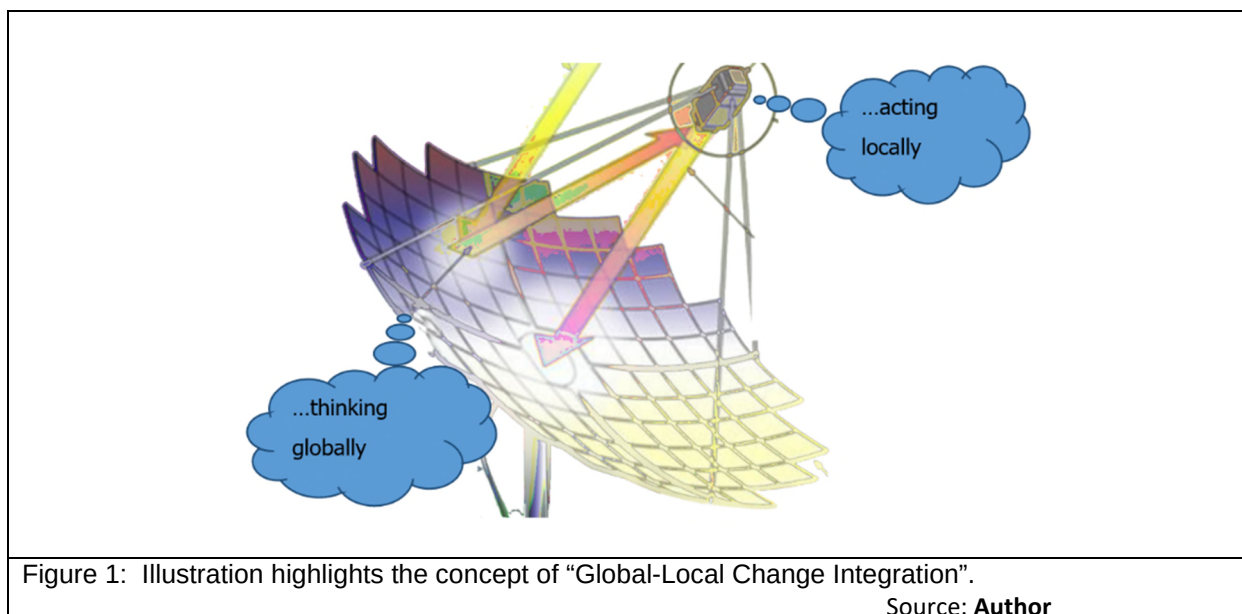
1 Introduction

This chapter aims to 1) introduce the innovation report with an executive summary of the current state of the art and the motivation behind it; 2) present the research aim and objectives; 3) attempt a definition of the innovation report; and 4) outline or provide a depiction of the innovation in the research conducted.

1.1 Global Agenda for Change

The World Commission on Environment and Development (UN) published 1987 its report, "Our Common Future" [1] establishing key areas of future development of the global population, including economic, environmental, and social aspects of life. While each of these areas is in crisis, what makes matters worse is that these crises, according to the commission's chairperson, Glo Harlem Brundtland, are interconnected and can only be solved together [1]. For sustainable development that has significant relevance to current discussions on various industries, it needs to include the palm oil processing in Nigeria, for example [2]. The report underscores the necessity of integrating economic growth with environmental sustainability and social equity. This perspective is particularly relevant given the rising emphasis on sustainable practices within the palm oil sector, particularly with advancements in technology such as Concentrated Solar Power (CSP), which seeks to enhance energy efficiency and support sustainable development goals.

Furthermore, The Brundtland Report [3], formulate its tasks **"a global agenda for change"**. Without due local integration, most global change initiatives are short-lived. The very concept of concentrated solar power systems needs to be embedded in value creation in local communities, especially where local integration of global change is concerned. As shown in Figure 1 it holds a graphic depiction of the phrase 'thinking globally, acting locally' [4].



1.2 Sustainability for Palm Oil Processing

In the scope of palm oil production, sustainable practices have gained traction through initiatives like the Roundtable on Sustainable Palm Oil (RSPO), established in 2004 [5], which aims to promote sustainable production methods, reduce deforestation, and mitigate the environmental impacts of the palm oil industry [6]. Research has shown that RSPO-certified growers have made progress in halting the expansion of oil palm plantations into forested areas, thereby addressing critical environmental issues [7]. Nevertheless, challenges, particularly in the conservation of peatlands and biodiversity, persist, demonstrating the need for comprehensive policies and technological solutions to bolster sustainability [8].

1.3 Research Motivation and Focus

While conventional PV technology holds enormous potential for resolving the ailing electricity situation for residents of Sub-Saharan Africa (SSA), of which Nigeria is a key member, the deployment challenge is far from simple. PV cells in such regions tend to overheat, thus reducing their efficiency [9]. The complementary technology – CSP, though highly promising due to its thermal strengths, is only economically viable for industrial purposes [10]. To meet basic needs such as food sufficiency, palm oil, considered the most efficient crop, has been an integral part of the Nigerian diet [11]. Palm oil processing in Nigeria is an energy-intensive industry, requiring both thermal and electrical power for various stages [12]. To address these energy demands sustainably, a hybrid CSP and PV dish system offers a promising solution.

1.4 Review of Prior Technologies

It appears that various efforts have been made to combine Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies to enhance solar energy utilization. These prior systems have often faced significant limitations in efficiency, scalability, and spectral selectivity. Traditional **hybrid CSP/PV systems** typically adopt series-based or parallel configurations, where the PV cell operates under concentrated irradiance, and residual heat is recovered for thermal applications. However, these configurations often result in reduced PV efficiency due to overheating and non-optimized use of the solar spectrum [13] [14].

Some studies, such as those by Al-Waeli et al. (2017) and Kalogirou (2014), explored the integration of PV panels with linear Fresnel reflectors or parabolic troughs, [15], [14]. While these systems improved total energy yield, they largely treated heat and electricity as by-products of the same irradiance stream, leading to limited spectral control and sub-optimal thermal-to-electrical output ratios [16], [17].

More recently, researchers have examined beam-splitting approaches using spectral-selective filters or dichroic mirrors to divide the solar spectrum into its functional bands [18]. These methods, while promising in theory, remain underdeveloped in practical implementation due to optical alignment challenges, the high cost of precision coatings, and the lack of modular field applications.

What distinguishes this present research is its use of off-the-shelf cold and hot mirrors in a carefully calibrated dish concentrator configuration, which spatially and spectrally separates visible and infrared components for simultaneous use. This results in a functionally decoupled hybrid system, where the PV cell is shielded from excessive infrared heating, and thermal energy is harvested independently, thereby enhancing system efficiency, lifespan, and reducing ground consumption. Moreover, the beam-splitting geometry used here demonstrates an innovative low-cost pathway for deploying solar cogeneration systems in decentralized, small-scale agro-industrial contexts.

This novel approach, supported by experimental validation and practical deployment potential, advances the state of CSP/PV hybrid technologies by transitioning from combined energy collection to deliberate spectral assignment, which could be likened to refining sunlight into usable “fractions”—a conceptual breakthrough introduced here as the **Crude Sunlight Refinery**.

1.5 CSP Hybrid Technology for Palm Oil Processing

The palm oil processing industry in Nigeria requires significant amounts of both thermal and electrical energy for various stages, such as sterilization, digestion, and extraction [19]. In many agricultural settings in Nigeria, including palm oil farms, access to a reliable electricity grid might be limited or inconsistent [2]. Therefore, decentralized or off-grid energy solutions, such as a hybrid CSP/PV system, hold substantial potential for providing a sustainable and reliable energy source. Utilizing solar energy for palm oil processing aligns with global sustainability goals and can reduce the reliance on fossil fuels, which are often associated with environmental concerns and fluctuating costs [19].

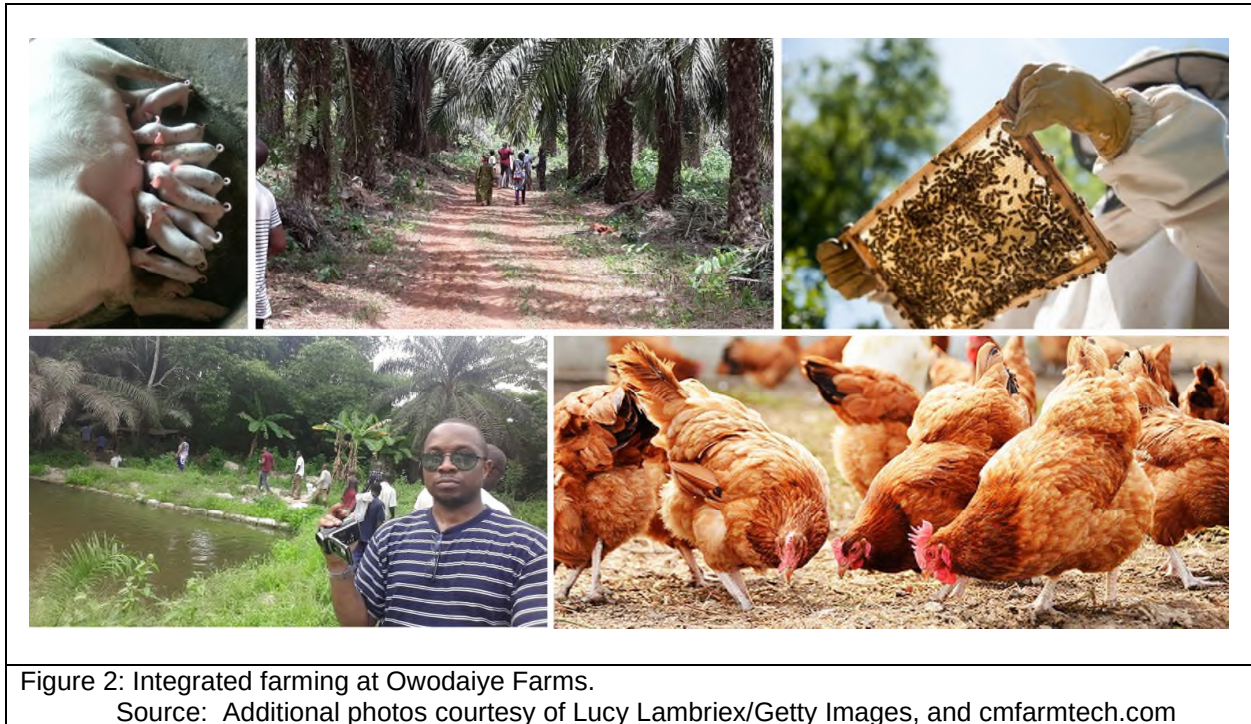
1.6 Research Aims and Objectives

This work is therefore aimed at designing a proof-of-concept hybrid solar concentrator system that uses spectrum beam splitting to generate process heat and electricity for palm oil processing farms in southwest Nigeria. To achieve this, the following objectives have been laid out based on practical and theoretical models, informed by real-world data available from Owodaiye farms.

- The determination of existing and projected energy requirements
- Articulate the parameters surrounding Dish sizing and SBS technology
- Investigate spectrum beam splitting technology through laboratory-scale experiments
- Evaluating the technical performance of the hybrid dish collector
- Present a compelling business model innovation with results and systems analysis
business model innovation, a conclusion, and a robust projection for future work

1.7 Owodaiye Farms

The palm oil processing unit **at Owodaiye Farms** is a small to medium-scale business that operates as part of an evolving integrated farming enterprise established in 1982.



With an estimated palm oil production capacity of 20 tonnes per annum, recent findings confirm the situation on the farm and indicate a significant imbalance between thermal and electrical energy demands [20]. Existing energy sources for palm oil processing at Owodaiye include a 40kVA diesel generator for electrical power and a firewood-powered thermal setup. This recourse to an independent and locally sourced energy supply confirms how abysmally unreliable the supply of power from the national grid is [21]. An approximate average of 95% of thermal energy demand exists compared to merely 5% of electrical energy demand [22] [23]. Regardless of this ratio, the operational reality is undeniable. This thermal-electricity scenario is generic to palm oil processing and thus provides a basis for a CSP/PV hybrid technology to offer a more sustainable solution.

1.8 Current Palm Oil Processing at Owodaiye Farms



Figure 3: Harvesting and processing of Palm Oil. Source: **Author**

Thermal-to-Electrical Energy Fraction

The electric-to-heat ratio in palm oil mills underscores the reliance on thermal processes typically used for steam generation and other heating requirements in palm oil mills. The predominance of thermal expenditures is corroborated by findings from Handaya et al. [24], who note that thermal applications constitute the core energy consumption in palm oil processes, thereby justifying the reliance on thermal generation systems like biomass combustion. Systematic studies reveal that biomass from palm oil waste is critical to meeting thermal demands. For instance, empty fruit bunches (EFB) and palm kernel shells (PKS) serve not only as biomass fuels but also contribute to the energy matrix through integrated systems like combined heat and power (CHP) plants [25].

The Biomass Energy Source

Palm oil mills primarily require thermal energy for processes such as sterilization, digestion, and drying. Electricity is needed for operations like milling, pumping, and lighting [26]. Approximately 1,550 MJ (**430.55 kWh**) of heat per tonne of Fresh Fruit Bunches (FFB) is required, typically supplied by low-pressure boilers fuelled by Mesocarp Fiber (MF) and Palm Kernel Shells (PKS) [27] [26]. In the case of Owodaiye Farms, thermal energy comes from steam boilers powered by heat from firewood. Electricity generation ranges from 43 to 120 kWh per tonne of FFB, achieved through backpressure steam turbines [27].

Opportunity for Energy Integration

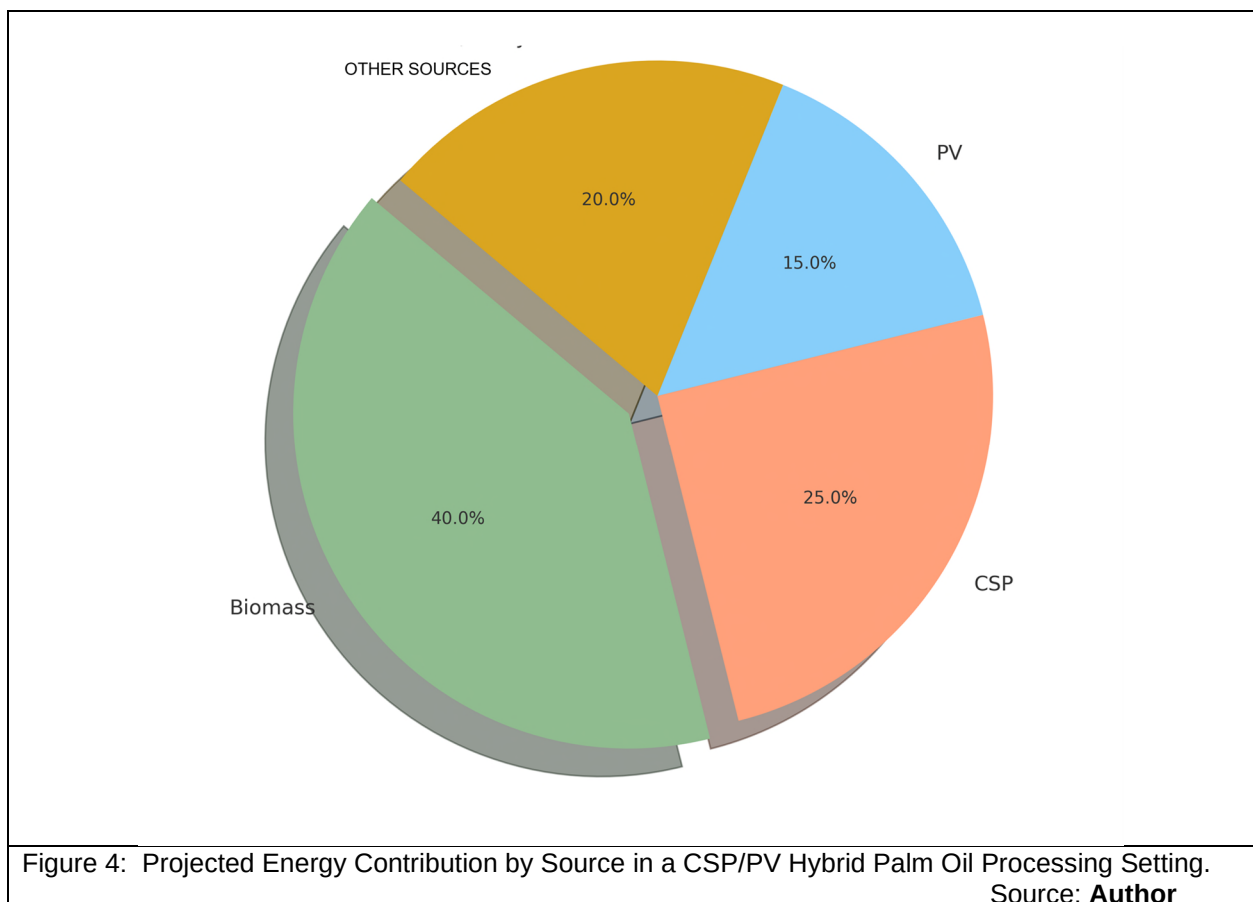
In addressing the transitional energy framework of palm oil processing at Owodaiye Farms, integrating Concentrated Solar Power (CSP) systems with spectrum-beam splitting technology emerges as an innovative solution to reduce dependency on conventional thermal energy sources. This technology utilizes cold/hot mirror dish concentrators to optimize solar radiation absorption, facilitating high-efficiency conversion of solar energy into thermal energy for palm oil processing operations. Energetically, this hybrid system can complement existing thermally driven operations by providing an additional renewable energy source that aligns with the identified thermal energy needs of the palm oil industry [28]. Further, the hybridization of CSP technology can help address energy inefficiencies observed in conventional biomass conversion methods. Studies suggest that such advancements could yield enhancements in energy output while supporting the sustainable growth of the palm oil sector [29]. Ultimately, the implementation of CSP hybrid systems represents a strategic move towards energy diversification, establishing a robust energy infrastructure adapted to the thermal demands of palm oil processing.

1.9 Comparative Case Studies and Deployment Potential

While conventional hybrid solar energy systems often co-locate photovoltaic and thermal collectors, they typically lack **spectral separation** and may require separate tracking or redundant optics. Well-established hybrid PV/T systems—such as the Mediterranean-climate study of Tripanagnostopoulos et al. (2005) [30] and the comprehensive review by Riffat & Ma (2011) [31] highlight practical gains and limitations in dual-output operations. However, these systems do not employ dedicated beam-splitting optics. By contrast, our dish-based CSP/PV hybrid exploits hot/cold mirrors to decouple the spectrum and deliver simultaneous, optimised electrical and thermal energy from the same aperture, offering a step-change in system integration.

1.10 Summary

The current thermal-to-electrical energy ratio of 95% to 5% in palm oil processing illustrates a systemic reliance on thermal energy frameworks. Transitioning towards CSP hybrid systems provides an innovative pathway to achieve higher sustainability profiles in this energy-intensive industry while fostering the reduction of carbon emissions associated with conventional biomass-based energy operations.



2 CSP/PV Hybrid Concentrator Concepts

Concentrated Solar Power (CSP) technologies harness solar energy by employing mirrors to reflect and concentrate sunlight onto a receiver [32]. The concentrated sunlight heats a high-temperature fluid ($> 250\text{ }^{\circ}\text{C}$, synthetic oil or molten salt) within the receiver device, generating thermal energy. This thermal energy can then be used to generate high-pressure steam and drive a steam turbine or engine for electricity generation, or applied directly to industrial processes [32]. Such CSP systems can be configured in various ways, including dish/engine systems suitable for smaller, distributed applications, capable of producing 5 to 25 kW of power per dish [32]. All CSP technologies rely on direct normal irradiance (DNI), which only focuses on a very small area on the receiver device. [33] [34].

PV technology, on the other hand, converts sunlight directly into electricity using semiconductor materials [35]. Solar panels, composed of PV cells, absorb photons from sunlight, causing electrons in the semiconductor material to become energized and flow, creating an electrical current [36]. Different types of solar panels exist, including monocrystalline, polycrystalline, and thin-film, each with varying efficiencies and costs [35]. PV systems are modular and can be scaled to meet diverse energy needs [37]. They are designed to absorb all available light, and their efficiency is influenced by factors like cell type, temperature, and material quality, not by the presence of diffused light itself. [38]

2.1 Rationale for Combining CSP and PV Hybridisation

The integration of CSP and PV techniques into hybrid systems presents a compelling strategy to capitalize on the complementary strengths of both technologies. CSP excels in high-temperature heat generation, while PV is adept at electricity production; however, each has its limitations when used in isolation. By combining these two technologies, hybrid systems can optimize efficiency, reduce costs, and enhance energy reliability.

CSP systems are particularly effective at generating high-temperature thermal energy, which is essential for certain industrial processes (process heat) or for thermal energy storage to produce electricity on demand. However, CSP's high capital costs and reliance on direct sunlight restrict its operational efficiency during cloudy conditions or outside peak sunlight hours [39]. Conversely, PV systems, while relatively inexpensive and capable of generating electricity from diffused sunlight, may struggle to meet high-temperature heating requirements effectively. This inadequacy can lead to inefficient coverage of a facility's thermal and electrical needs [40].

The hybridization of CSP and PV systems addresses the limitations associated with both technologies. By integrating CSP's thermal storage capabilities with PV's immediate electricity generation, hybrid systems can offer a more balanced and flexible response to energy demand. This combination allows for continuous energy production with reduced variability, enabling a consistent supply regardless of weather conditions [41]. Furthermore, the economic viability of such systems enhances as both technologies contribute to a shared infrastructure, leading to lower overall capital and operational expenditures [42].

Several studies have demonstrated that CSP/PV hybrids significantly improve system capacity factors and enable more effective load management [43]. For example, Hamilton et al. highlighted that combining CSP with Thermal Energy Storage (TES), PV, and battery systems allows for a higher capacity factor at lower costs compared to standalone implementations of CSP or PV [44]. Similarly, Iñigo-Labairu et al. confirmed that the integration of electric heaters for thermal storage in CSP-PV plants allows for substantial operational flexibility and economic advantage [45]. Relying on a single solar technology might present limitations. For instance, while CSP can efficiently generate high-temperature heat, it may not optimally cover all the electrical needs of a facility. Conversely, PV systems are a viable technology for electricity generation, but might not be the most efficient solution for high-temperature heating requirements [46]. A hybrid approach combining CSP and PV can overcome these limitations by more comprehensively utilizing the solar spectrum, leading to improved overall efficiency [47]. By directing different portions of the sunlight to the technology best suited for that part of the spectrum, a hybrid system can maximize energy output and potentially enhance reliability [47].

2.2 System Complexity

The integration of both thermal and electrical subsystems using spectrum beam splitting adds a layer of system complexity if compared to each conventional solar PV or CSP system. However, this complexity is justified on engineering grounds as it allows dual utilization of the solar spectrum, thereby improving overall efficiency and system performance [48] [49].

Conventional PV systems convert only a portion of the solar spectrum into useful electricity, while CSP technologies typically focus on thermal energy collection. By employing cold and hot mirrors for spectrum beam splitting, the hybrid system selectively directs short-wavelength light towards PV modules and longer wavelengths towards a thermal receiver [15] [50]. This integrated design leverages the strengths of both subsystems rather than treating them as decoupled entities.

The added complexity results in higher combined efficiency, with experimental results showing increased power outputs at certain focal distances and improved thermal capture. The dual pathway ensures greater utilisation of available solar energy compared to either system operating

alone. In comparison to decoupled alternatives such as stand-alone PV or thermal-only systems, the CSP/PV hybrid system offers better resource utilisation and long-term sustainability [15]. Although the architecture is more complex, performance gains and dual-output benefits justify the engineering effort.

2.3 Principles and Components of a Hybrid CSP/PV Dish System

The hybrid dish system is composed of two different sub-systems, the CSP subsystem and the PV subsystem. When these two systems are combined into a single device, this leads to an overall better performance for the collector area used.

The CSP subsystem of the proposed hybrid design will use a parabolic dish concentrator. This type of concentrator has a parabolic-shaped reflective surface that focuses direct solar radiation onto a single point called the focal point. At this focal point, a solar receiver is positioned to absorb the concentrated solar energy and transfer it to a heat transfer fluid. Several options for the heat transfer fluid exist, including thermal (synthetic) oil, molten salts, and pressurized water. The choice of fluid depends on the desired operating temperature range, which, in this case, must align with the temperature requirements for palm oil processing. The heat carried by the fluid can then be used directly as process heat for stages such as sterilization and digestion, which require high temperatures. To maximize energy capture throughout the day, a dual-axis tracking system is essential. This system allows the parabolic dish to continuously follow the sun's movement in both azimuth (horizontal) and elevation (vertical) directions, keeping the concentrated sunlight focused on the receiver. Dish systems are particularly well-suited for standalone (distributed) applications, as they can achieve the very high temperatures ($>500^{\circ}\text{C}$) needed for the thermal processes in palm oil milling.

The PV subsystem will be integrated into the dish system to generate electricity. This can be achieved by strategically placing high-efficiency PV cells to receive the visible light reflected by the cold mirror [45]. Given the concentrated nature of the sunlight, it is crucial to use PV cells specifically designed for concentrated sunlight, such as multi-junction cells made from materials like Gallium Arsenide (GaAs) or other III-V compounds [47]. These cells offer significantly higher efficiencies under high concentrations compared to conventional silicon-based PV cells [51]. The concentrated sunlight can cause the PV cells to overheat, which reduces their efficiency and lifespan. Therefore, an effective cooling mechanism, such as air or liquid cooling, will be necessary to maintain optimal operating temperatures [52].

2.4 Spectrum Splitting for Optimizing Hybrid Systems

Spectrum splitting is a technique used to divide the solar spectrum, as shown in Figure 5, into different wavelength bands, allowing each band to be converted by the most appropriate technology [53]. Cold mirrors play a crucial role in enabling efficient spectrum splitting in hybrid CSP/PV systems [53]. These specialized mirrors are designed to reflect visible light while transmitting infrared radiation [54]. In a hybrid CSP/PV system, the reflected visible light can be

directed towards PV cells for electricity generation, while the transmitted infrared radiation can be concentrated and used for thermal energy in the CSP subsystem [53]. This selective separation of the solar spectrum ensures that each component of the hybrid system receives the wavelengths it can convert most efficiently, leading to a more optimized overall energy conversion process.

2.5 Understanding the Solar Spectrum

Figure 5, showing the globally accepted standard of the Wavelength Spectrum (280-4,000 nm) of relevant solar radiation, acts as a reference for understanding spectrum-beam splitting SBS. When it comes to palm oil processing, a breakdown is needed to show a build-up of how cold and hot mirrors interact with the solar spectrum to enhance energy utilization. Hot and cold mirrors, acting as “heat control filters,” are examples of dichroic filters used to filter out unwanted energy from a light-emitting source [55].

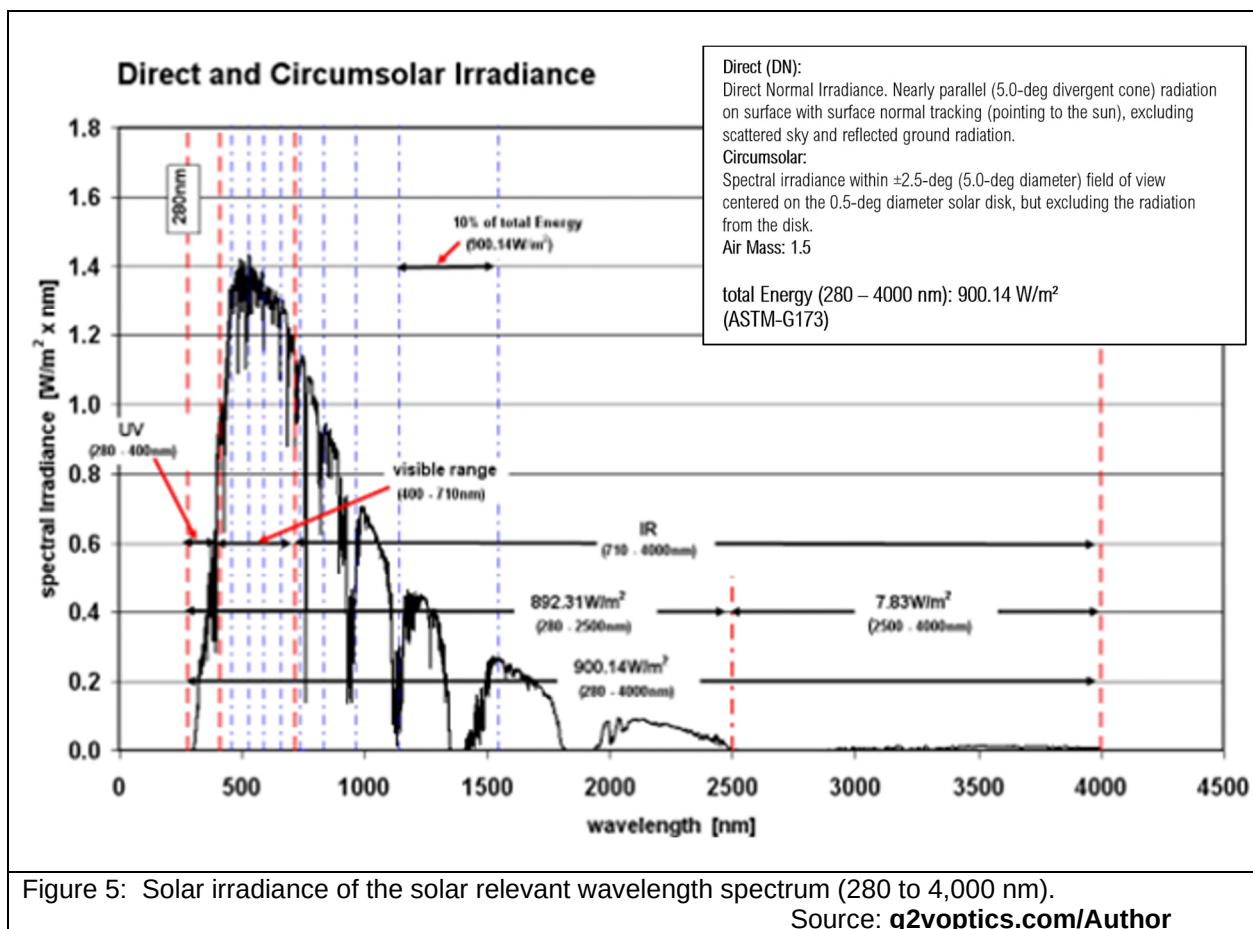


Figure 5: Solar irradiance of the solar relevant wavelength spectrum (280 to 4,000 nm).

Source: g2voptics.com/Author

The vertical red lines in Figure 5 show the spectral bands. For instance, the UV (280–400 nm) band indicates where there is not much useful energy (~<10%). The visible (400–710 nm) band indicates the region of high spectral irradiance, where the potential for PV electricity exists. The Infrared band (IR, 710–4,000 nm) represents the domain for thermal energy.

The energy density of the UV + Visible + NIR (280–2,500 nm) range is approximately 892.31 W/m² (~99.1%), and for Deep IR (2,500–4,000 nm) is approximately 7.83 W/m² (~0.87%). This suggests that the most usable solar energy is in the 280–2,500 nm range.

2.6 Understanding The Air Mass Spectra

The spectrum in Figure 5 is based on the Air Mass 1.5 Spectra - a standard by the American Society for Testing and Materials (ASTM) [56] Fig. 6 sheds further light on how terrestrial solar spectral irradiance acts on the surface of the Earth. It illustrates how sunlight travels through Earth's atmosphere before reaching the surface and how the angle of the sun in the sky—known as the zenith angle—affects the **solar spectral irradiance** we receive.

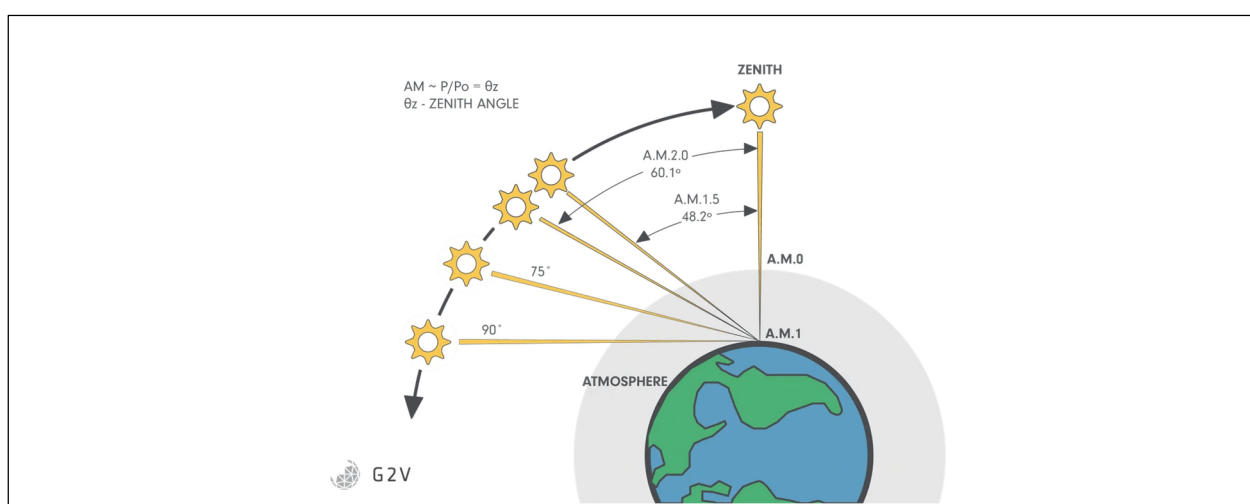


Figure 6: Air Mass 1.5 Spectra Diagram. Source <https://g2voptics.com/solar-simulation/am1.5-spectrum/>

“Air Mass” (AM) is a measure of how much atmosphere sunlight must pass through before reaching us. When the sun is directly overhead (at noon), it passes through the least amount of atmosphere—this is called Air Mass 1 (AM 1). As the sun moves lower in the sky (during the morning or evening), sunlight travels through more atmosphere—this increases the air mass (e.g., AM 1.5, AM 2.0).

The more atmosphere the sunlight travels through, the more it is **scattered and absorbed**, reducing the **intensity** and **quality** of solar energy. For example, **AM 0** refers to sunlight in space (no atmosphere—maximum energy). **AM 1.5** is often used as the standard reference for solar

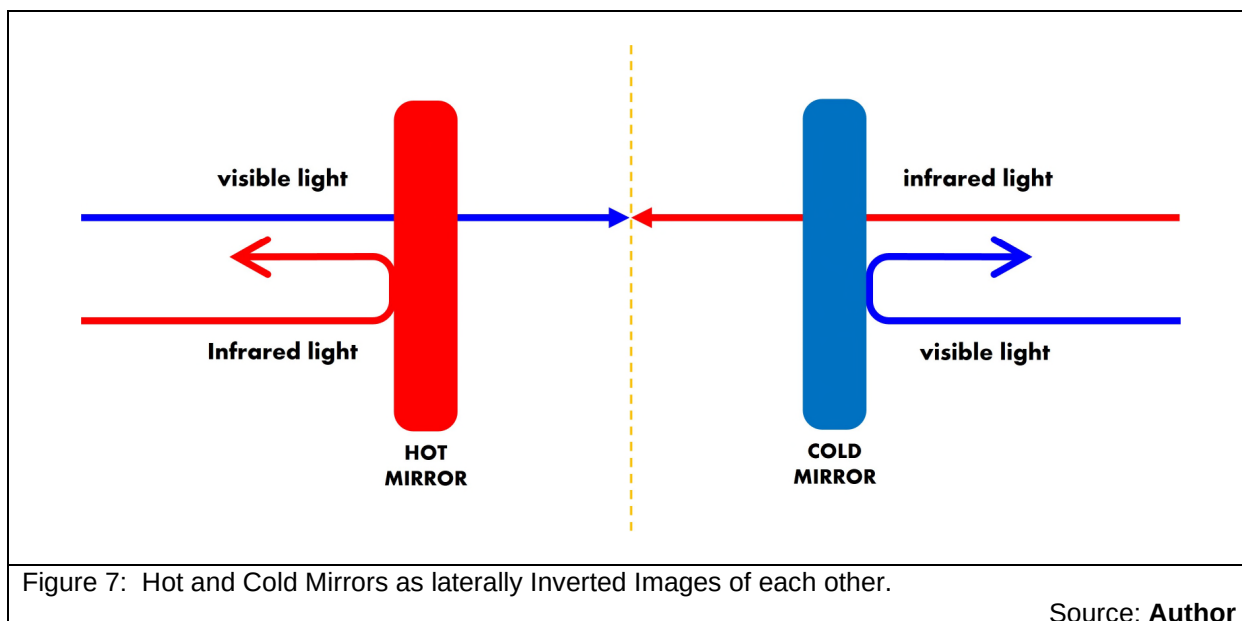
panel testing because it approximates real-world conditions at mid-latitudes when the sun is at a 48.2° angle from vertical.

The **zenith angle (θ_z)** is the angle between the sun and the point directly overhead (the zenith). A smaller zenith angle means the sun is high in the sky, and energy reaches us more directly. A larger zenith angle means sunlight is slanted and passes through more atmosphere, weakening the power reaching the ground.

Understanding this helps us **optimise solar collector orientation**. It also explains why **solar systems produce more power around midday** and why solar concentration and tracking systems are important for maximising energy capture throughout the day.

2.7 Cold and Hot Mirror Integration

When strategically placed within the parabolic dish system, these filters are key components to intercept the focused sunlight before it reaches the primary thermal receiver [47]. The selection of the cold mirror is critical, particularly its cut-off wavelength, which determines how the solar spectrum is split [57]. For a hybrid CSP/PV system, a cold mirror that reflects visible and near-infrared wavelengths (approximately 400-1,100 nm) towards the PV cells and transmits the longer infrared wavelengths for heat generation in the CSP subsystem would be optimal [57]. Key specifications for the cold mirror include the optimal angle of incidence (often designed for 45°), high reflectivity in the desired visible and near-infrared range (ideally above 90%), and high transmissivity in the infrared range (also ideally above 80%) [55]. The performance of the cold mirror directly impacts the overall efficiency of the hybrid system by ensuring that each subsystem receives the most beneficial part of the solar spectrum for its respective energy conversion process.



2.7.1 Cold Mirror:

1. **Reflects** visible light (typically 400–700 nm)
2. **Transmits** infrared (IR > 700 nm)
3. Application: Separates **visible spectrum** for **photovoltaics (PV)**

2.7.2 Hot Mirror:

1. **Reflects** IR (typically 700–2,500+ nm)
2. **Transmits** visible light
3. Application: Redirects the **infrared spectrum** for **thermal heating**

Both mirrors act as **spectrum-beam splitters**, isolating different parts of the spectrum for **targeted energy applications**.

For palm oil processing, both heat (e.g., for sterilization, digestion, drying) and electricity (e.g., for motors, control systems, lighting, and small machines) are required.

The cold mirror reflects wavelengths in the range of **400–700 nm** to a **PV panel**, which then converts the **high-energy visible light** into **electricity**. This provides electricity for powering water pumps, stirring motors for conveyor belts, Sensors and control units, Auxiliary lighting, and communication.

The hot mirror reflects **700–2,500+ nm** to a **thermal receiver** (e.g., Stirling engine, thermal fluid heater) used for heating oil/water in tanks. It also drives a **thermal engine** for powering steam

production for sterilizers, hot water for oil clarification and separation, and heat exchangers for the drying and cooking stages.

2.8 Operational Integration at Owodaiye Farms

Table 1: CSP/PV Systems Allocation

Component:	Solar Spectrum used:	Function:	Technology:
(1)	(2)	(3)	(4)
Cold mirror	400-700 nm (vis)	Electricity	PV panel
Hot mirror	700-2,500+ (IR)	Thermal	Solar Collector and Heat Storage
Dish Concentrator	Solar spectrum (280-2,500+ nm)	Concentrate DNI	parabolic Dish
Beam Splitter	Filtered and direct rays	Spectrum Management	Optical Filter Assembly

This hybrid arrangement ensures enhanced energy utilization from the solar resource. You're not wasting IR on PV (which is inefficient for it), and you're not overheating the PV cells with IR they can't use. Meanwhile, your thermal system is fed a highly concentrated, IR-rich beam.

The application of a spectrum beam-splitting CSP/PV hybrid system at Owodaiye Farms offers several operational benefits that directly address the energy challenges of palm oil processing. First, the approach significantly enhances energy efficiency by dividing the solar spectrum so that each portion is used where it is most effective: the visible band is converted to electricity by high-performance photovoltaic (PV) modules, while the infrared band is transmitted to a thermal receiver to provide process heat. This dual-path conversion enables a higher overall solar-to-useful-energy efficiency compared with conventional PV-only systems [58] [59].

Second, the system contributes to cost-effectiveness by displacing diesel consumption, which has long been the default energy source for small and medium-sized palm oil mills in Nigeria. Diesel prices are volatile due to import dependence and foreign exchange fluctuations; reliance on this fuel significantly raises operating expenses [60] [61]. By relying primarily on solar energy for both power and heat, the hybrid system lowers the life-cycle cost of production and reduces the need for expensive backup generation.

Third, the design strengthens resilience. By producing both electricity and heat from the same solar field and integrating limited thermal storage, the hybrid system enables continuous processing even during periods of solar variability or short-term cloud cover [62]. This resilience

is crucial in rural agro-industrial contexts where grid power is often unreliable or entirely absent [63].

Finally, the system offers improved process matching. Palm oil production requires a steady supply of medium-temperature heat (for sterilisation and clarification) and moderate electrical power (for milling, pumping and lighting). By splitting the solar spectrum and delivering both heat and electricity from one optical source, the system aligns energy supply more closely with the specific demands of palm oil processing [64] [49].

The work at Owodaiye Farms also highlights several innovation opportunities that go beyond conventional rural electrification models. At its core is the novel integration of cold and hot mirrors into a parabolic dish CSP/PV hybrid. While spectrum-splitting has been explored in laboratory optics, its application in an agro-industrial, rural Nigerian setting is new and demonstrates how advanced solar technologies can be adapted to local manufacturing and operational realities [58] [59].

Equally significant is the emerging business case for reducing operating costs by hybridising solar. Many small-scale processors rely on diesel generators and low-efficiency biomass boilers, which carry high and unpredictable fuel costs [61] [60]. A system that combines PV-generated electricity with directly captured thermal energy reduces this dependence and has the potential to stabilise production costs, making small agro-enterprises more competitive and financially sustainable [65].

Finally, the design's scalability is a key attribute. The hybrid dish is modular and can be deployed as single or clustered units, depending on plant size and energy needs. This adaptability allows replication across other rural agro-processing industries — such as cassava drying, grain milling, or shea butter production — and positions it as a replicable solution for broader rural industrialisation across Nigeria and other Sub-Saharan African countries [65] [63].

3 Palm Oil Production in Nigeria

The palm oil processing operation in question (as depicted in section 1.7) requires an “off-grid” energy supply, ideally, a sustainable energy source, provider-independent, and a robust technology. The proposed solution is a solar energy-driven option, which is cost-effective, sustainable, and with a readily available energy source. The energy demand of the operation encompasses electricity and heat (thermal energy) supply. Therefore, a solar collector that combines both energy forms would be preferable. Furthermore, it is anticipated that the efficiency of the collector is crucial, using the right input energy component for the right transfer process.

3.1 Nigeria in the context of solar energy

Nigeria is located in a region with medium solar irradiance, depending on location. The average encompasses variations across the country, with higher values generally observed in the northern regions (up to 1,500 kWh/m²) and lower values in the coastal south (around 1,000 kWh/m²), Figure 7. Direct Normal Irradiance data for these regions indicates good potential for concentrated solar power systems. However, the climatic conditions in Nigeria, including high ambient temperatures and humidity, need to be considered in the design of the hybrid system [66]. High temperatures can negatively impact the efficiency of PV cells, necessitating an effective cooling system for the CPV module. The high humidity can also affect the performance and durability of system components, requiring appropriate material selection and protective measures. Nigeria experiences distinct rainy and dry seasons [66]. During the dry season, dust accumulation on the mirrors of the parabolic dish can reduce their reflectivity, requiring a regular cleaning schedule to maintain optimal performance. Furthermore, Nigeria’s South experiences heavy rainfall during the rainy season [33].

Palm oil-producing regions are typically located in the southern parts of Nigeria, which generally experience lower levels of solar radiation throughout the year [67]. With the medium solar irradiance in these regions, solar energy could be a viable option for power generation and thermal applications [68]. Figure 7 shows global solar irradiance, from which general solar irradiance estimations were taken.

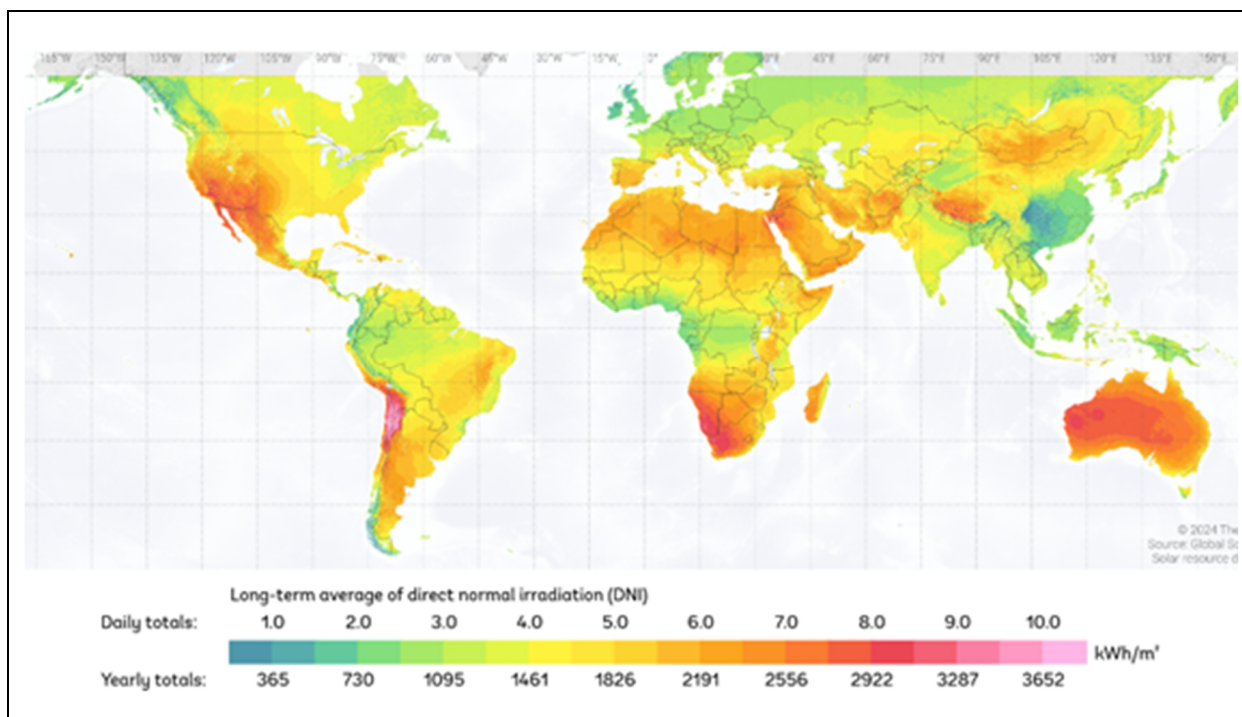
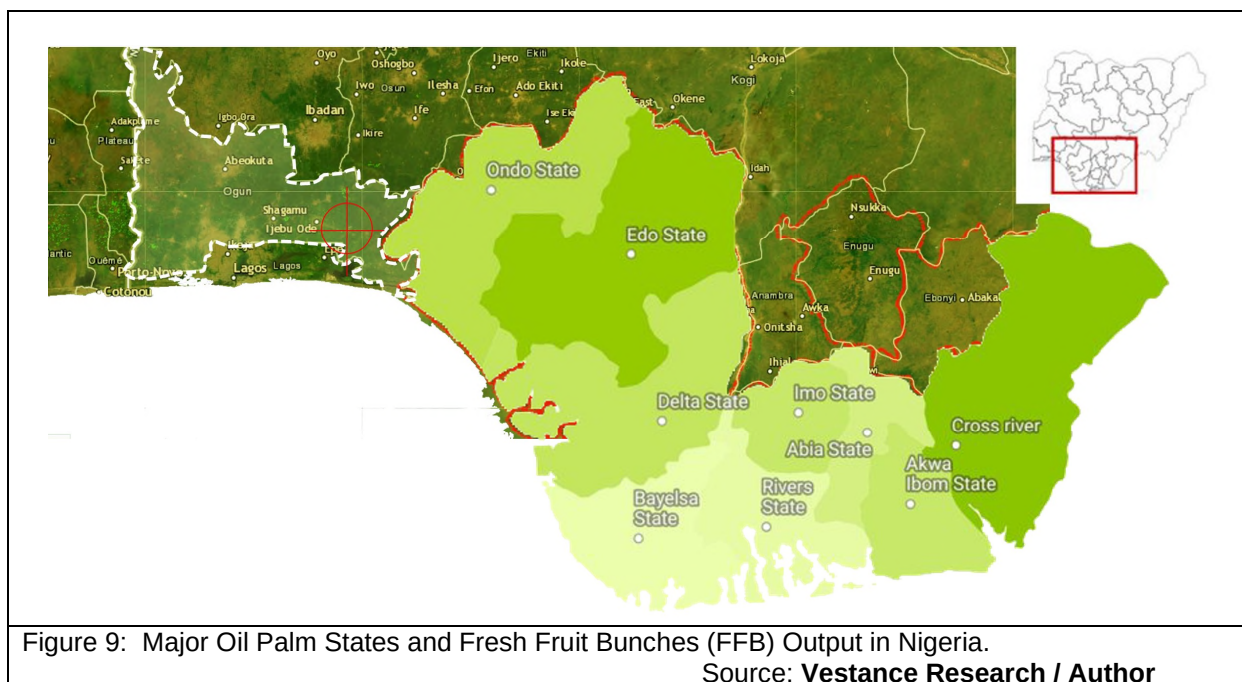


Figure 8: Global Direct Normal Irradiance (DNI) data, published by the World Bank.

Source: globalsolaratlas. Infosource

3.2 Palm Oil Production in Nigeria

The primary palm oil-producing states in Nigeria, Figure 8, are located in the South and include Edo, Akwa Ibom, Ogun, Ondo, Ebonyi, Oyo, Cross River, Osun, and Enugu [69]. These states lie within the tropical climate zone, which is optimal for oil palm cultivation [70]. However, solar irradiance can vary even within these geographically close regions due to local weather patterns and other environmental influences. The Global Solar Atlas [71] estimates at Edo State a yearly DNI of around 806.3kWh/m² (~2.2kWh/m² daily) [72].



Climatic conditions prevalent in Nigerian palm oil regions, such as rainfall, temperature, and humidity, can impact both the oil palm production and the performance of solar energy systems [73]. Oil palm thrives in stable, warm temperatures (ideally 30 to 32°C) and sufficient rainfall [70]. However, the same high temperatures can negatively affect the efficiency of PV cells [74]. Moreover, dust and soiling, which can be significant in agricultural areas, can reduce the performance of both CSP mirrors and PV panels [75]. High humidity and rainfall might increase the need for maintenance due to potential corrosion or the necessity for more frequent cleaning of solar components. Therefore, the design of the hybrid system must consider these environmental factors common in Nigerian palm oil regions to ensure its long-term reliability and efficient operation. Accurate DNI values are thus essential for the subsequent design and performance estimation of the CSP dish component of the hybrid system.

3.3 Palm Oil Processes

Palm oil processing involves several stages, each with specific energy demands. Sterilization, the initial stage, typically requires high-temperature steam treatment of fresh fruit bunches (FFB) to deactivate enzymes that cause oil degradation and to loosen the fruits from the bunch [76]. Temperatures for sterilization usually range from 130-160°C [77], although lower temperature methods (60 to 90°C) for cold-pressed oil production also exist [77]. Digestion follows sterilization, involving heating and mashing the sterilized fruits to release the oil-bearing cells [78]. This stage typically requires temperatures around 90-100°C [79]. Mechanical pressing or extraction is then used to separate the crude palm oil from the digested mash [78], requiring mechanical energy, which is often supplied by electric motors. Subsequent stages include clarification and purification

of the crude oil, which may involve heating to remove impurities [78]. If palm kernel oil (PKO), another lucrative by-product of palm oil processing, is also processed, additional steps like drying, cracking, roasting, and crushing of palm nuts are required, each with its own thermal and electrical energy needs [12].

Studies conducted in Nigeria have quantified the energy consumption in palm oil processing for different scales of operation. Figure 9 shows a flowchart of the two main derivatives of palm oil processing, namely, palm kernel oil (PKO) and crude palm oil (CPO). For palm kernel oil (PKO) processing, total energy expenditure in small, medium, and large-scale mills has been reported as 350.89 MJ/tonne, 230.70 MJ/tonne, and 181.74 MJ/tonne, respectively [80]. The most energy-intensive operations identified were palm-nut cracking, palm-kernel roasting, palm-kernel crushing, and PKO expression [80]. Another study focusing on overall palm oil processing found that boiling of fresh fruit bunches FFB consumed the highest amount of energy (2,007 MJ/tonne), accounting for 74.5% of the total energy consumption, followed by clarification and purification (437.7 MJ/tonne) [78]. Thermal energy, often derived from biomass or fossil fuels, constitutes a significant portion of the energy demand, particularly for sterilization and digestion [78]. Electrical energy is primarily used for powering machinery involved in pressing, pumping, transport, and other mechanical operations [81]. The specific energy requirements for a Nigerian farm will depend on its size and production capacity. A hybrid solar system designed for such an application needs to be scalable to meet these varying energy demands.

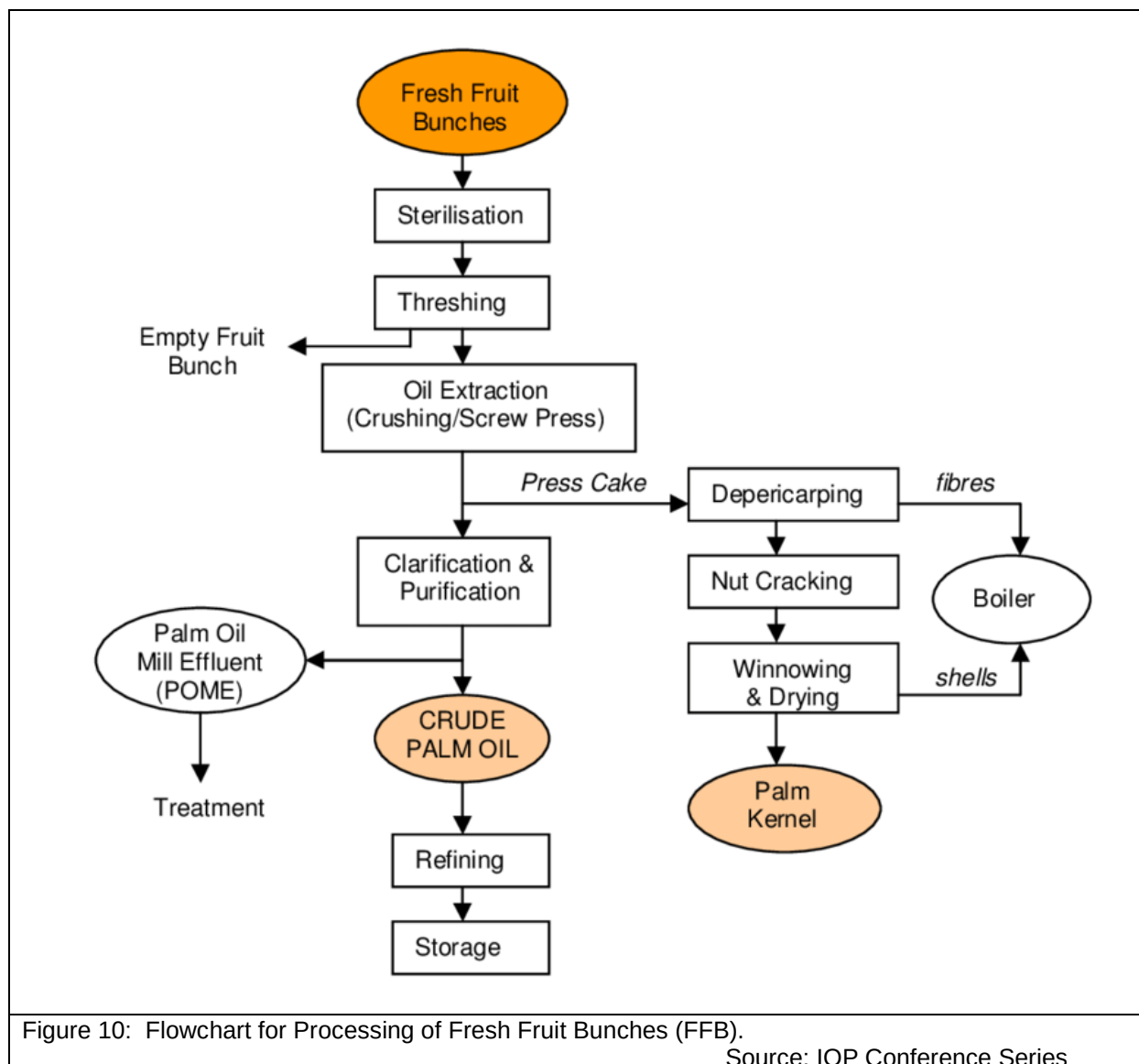


Table 2 summarizes the current energy requirements associated with key processing stages specific to palm oil production at the farm. The total energy requirement, when summed up, is 165 MJ/ton of Fresh Fruit Bunches (FFB). Biomass, especially from the residues generated during processing, is a very viable thermal alternative, compared to firewood, for palm oil production.

Table 2: Current Energy Consumption at Various Stages of Palm Oil Processing

Processing Stage:	Description:	Energy Requirement (MJ/ton FFB):	Form of Energy Used:	Reference:
(1)	(2)	(3)	(4)	(5)
1. Harvesting	Collection and transportation of Fresh Fruit Bunches (FFB)	12.0	manual	[82]
2. Sterilization	Steaming harvested FFB to facilitate oil extraction, using steam generated from firewood	32.0	thermal	[83]
3. Threshing	Separation of palm fruits from the bunches	15.0	electrical	[83]
4. Digestion	Breaking down the palm fruits to facilitate oil extraction	18.0	thermal	[84]
5. Pressing	Extracting oil through mechanical pressing	50.0	electrical	[85]
6. Clarification	Separating crude palm oil from solids and impurities	8.0	thermal	[84]
7. Storage	Application of energy for proper storage conditions before further processing	5.0	manual	[86]
8. Refining	Purifying crude palm oil to meet market standards	40.0	thermal	[82]
9. Packing	Energy required for the packaging of refined palm oil ready for distribution	3.0	manual	[87]

3.4 Palm Oil Processes at Owodaiye Farms, Ijebu-Ife (Nigeria)

The categorization of palm oil processing farms into small, medium, and large scale is foundational for understanding agricultural practice and economics in the region. Based on direct feedback from the management, Owodaiye Farms, for instance, produces approximately 20 tonnes of crude palm oil (CPO) annually, positioning it within the spectrum of these classifications. This section examines the parameters used to categorize such farms, focusing on operational capabilities, annual turnover, energy requirements, and the socio-economic impact on neighboring farms.

3.5 Farm Classification Criteria

The classification of farms significantly relies on the scale of production, which includes:

1. **Small Scale:** Typically, less than 50 tonnes of CPO per year. These farms are often operated by individual or smallholder farmers with limited access to technology and capital.

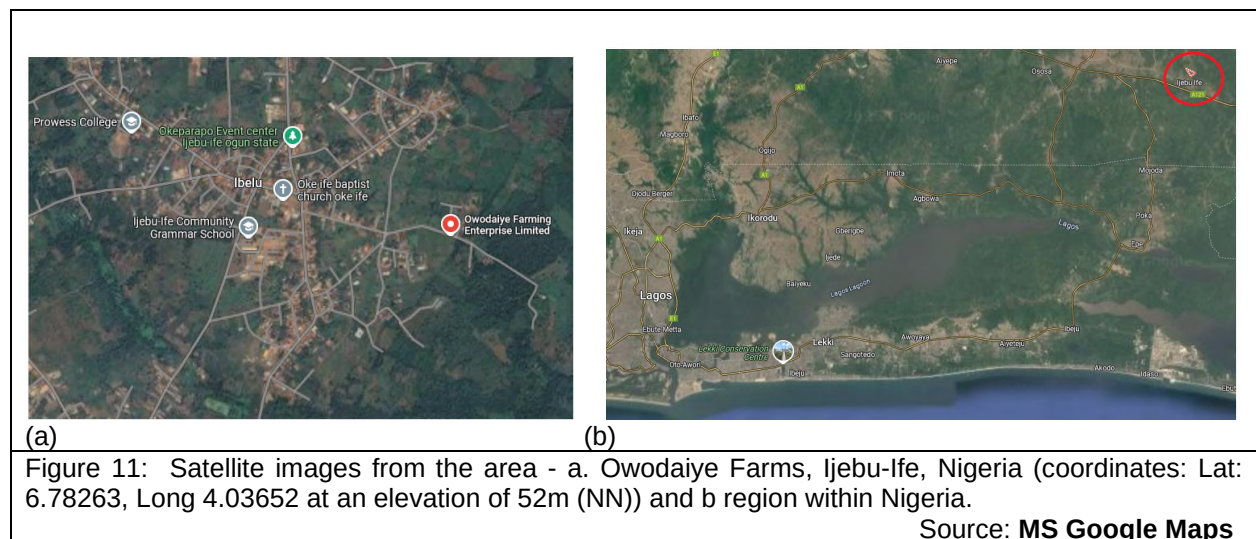
2. **Medium Scale:** Ranges from 50 to 200 tonnes of CPO annually. These farms have more resources, employ a slightly larger workforce, and utilize better technology compared to small-scale farms.
3. **Large Scale:** Exceeds 200 tonnes of CPO annually. These farms often possess extensive land holdings, advanced processing facilities, and employ large numbers of workers.

Owodaiye Farms' annual turnover of 20 tonnes firmly categorizes it as a small-scale farm, reflecting both its production capabilities and operational limitations [88].

The principal climate data of the palm oil farm, including solar irradiance and ambient temperature:

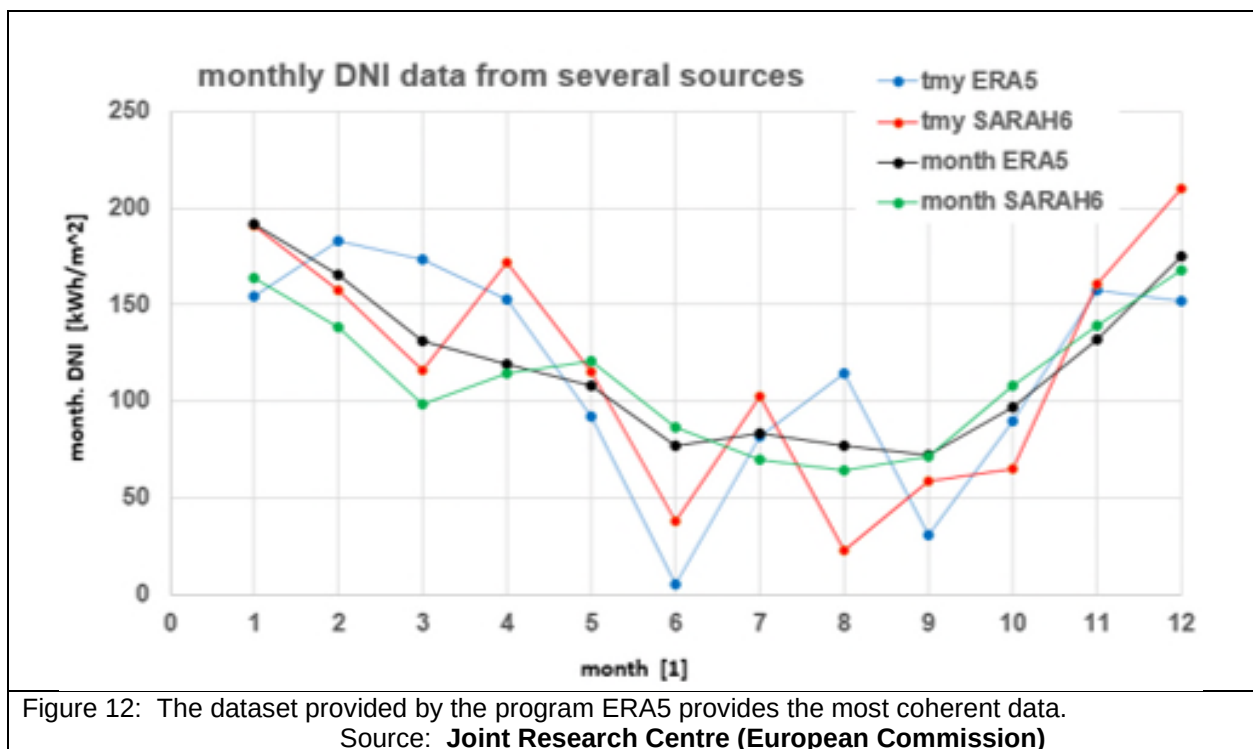
Location:	Owodaiye Farms, Ijebu-Ife, Nigeria
Coordinates:	Latitude: 6.78263, Longitude 4.03652, Elevation (NN): 52m
Solar Radiation (DNI):	1,431kWh/m ² [89]
Ambient temperature (T_{amb}):	26.7°C [89]

Figure 11 shows satellite photos of the area, which highlights the location of the farm, which is close to a community in the southwest of Nigeria.



3.6 Solar Energy Source

The Joint Research Centre [89] provides global climate models, based on data from several years of measurement [90]. A **typical meteorological year (TMY)** is a set of meteorological data with data values for every hour in a year for a given geographical location [91]. Daily, monthly, and yearly data sets, DNI, wind speed, ambient temperature, and relative Humidity (rH) can be created. The data sets were created by models ERA5 and SARA6 and leveraged [90]. The data period varied up to 20 years, allowing for the selection of monthly data. The data sets from the last four years were used and assumed to be the most relevant. For daily data sets, only the representative days of each month [92] are modelled and used for design work. Although TMY SARA6 [91] has several data gaps and is therefore not utilized, but it is still displayed. The four data sets of average monthly DNI are depicted in Figure 12.



The dataset from the month ERA5 is chosen for further analysis because it provides the most consistent data. This is due to ERA5 being a high-resolution, uniform reanalysis dataset that combines extensive observational data with advanced models, making it highly suitable for long-term climate and meteorological studies [93].

Regarding ambient temperature, it should be noted that both monthly data sets yield identical results, despite the use of different models. Additionally, monthly ambient temperatures are plotted in Figure 13.

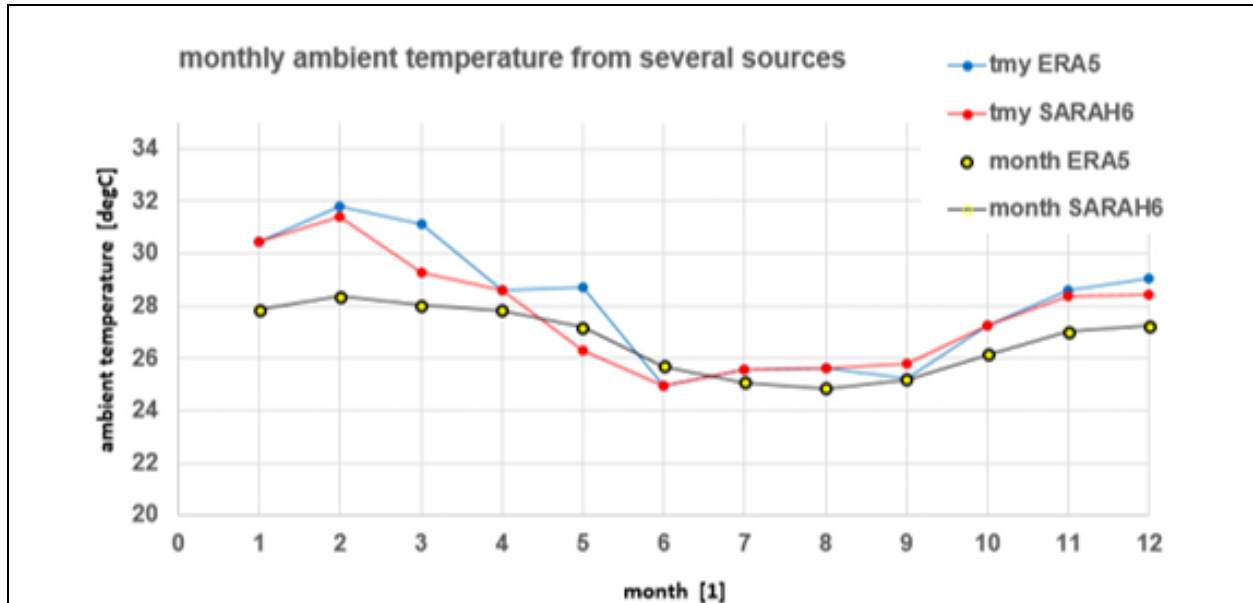


Figure 13: Monthly ambient temperature ranges.

Source: Joint Research Centre (European Commission)

Table 3 summarizes the data in monthly figures.

Table 3: Summary of the study used monthly data, (from model TMY ERA5), [91], and additional data from Appendix B.

Month:	Representative day of month	Solar Energy each month [kWh/m ²]	ambient Temperature [°C]
(1)	(2)	(3)	(4)
January	17	191.88	27.85
February	16	165.44	28.38
March	16	131.66	28.03
April	15	119.04	27.83
May	15	108.55	27.18
June	11	77.41	25.70
July	17	83.48	25.08
August	16	76.95	24.85
September	15	72.28	25.20
October	15	97.36	26.15
November	14	131.74	27.03
December	10	175.36	27.25

A maximal difference of monthly average solar radiation of approximately 120 kWh/m², between January (191 kWh/m²) and September (72 kWh/m²), can be observed. However, the maximum difference in average monthly ambient temperature is 3.5°C, which suggests that an almost constant ambient temperature of approximately 26.7°C can be assumed.

3.7 Energy Requirements

Palm oil production requires substantial energy inputs for **various stages** [94]. These processes use both thermal energies, primarily steam and direct heat, and electrical energy to operate the various machinery involved [95]. The energy requirements for palm oil processing demonstrate a significant reliance on thermal energy, with a typical thermal to electrical energy ratio of approximately 95:5 [85]. This strong emphasis on thermal energy highlights the importance of thermal technologies in palm oil processing, where steam generation and thermal treatments are essential during stages such as sterilization and extraction. [96] [97].

While the 5% contribution from electrical energy may seem minor, it is critical for the operational efficiency and control of palm oil processing systems. Electrical energy supports ongoing operations such as monitoring, controlling machinery, and facilitating process automation. [96], [98].

Currently, the farm of interest uses a diesel generator (40 kW) with an efficiency of 80% for its electricity supply. Furthermore, the diesel generator operates for eight hours per day, five days per week (260 days per year). These are realistic data obtained directly from the current operator on the site.

$$E_{el} = P_{max} \cdot \eta \cdot \frac{t_{op} \cdot day_{op}}{day \cdot year} \quad \text{Eq. 1}$$

Where E_{el} is the Electrical Energy, P_{max} is the maximum generator power, η is the generator efficiency, t_{op} is the operation time per day, day_{op} is the number of operation days per year.

Using the above parameters, Eq. 1 shows that the electrical energy is 66,560 kWh/year. The electricity production represents only 5.53% [12] of total energy demand; therefore, the remaining 94.47% of total energy, the thermal energy (E_{th}) is given by $E_{th} = 66,560 \text{ kWh} \times 94.47/5.53 = 1,137,056 \text{ kWh/year}$.

With these energy requirements in mind, it is important for estimation and even visualisation purposes that a preliminary system sizing and component capture with calculations for a 3m Hybrid CSP/PV Dish, for instance, is embarked upon.

3.8 Preliminary System Sizing and Components Capture

Solar Resource Assessment

For the location in southwestern Nigeria, a Direct Normal Irradiance (**DNI_{avg}**) of 3.7 kWh/m²/day was calculated from data provided by the ERA5 model, accessed by [89]. This corresponds to an average solar power of 0.326 kW/m² (average daylight per day 11.25h, [89]). This solar resource forms the basis for sizing the CSP/PV system components for daily operation.

Parabolic Dish Characteristics

The effective optical power focused by the dish is given by:

	$P_{\text{optical}} = \text{DNI}_{\text{avg}} \cdot A_{\text{dish}} \cdot \rho \cdot \gamma = 0.326 \frac{\text{kW}}{\text{m}^2} \cdot 7.07 \text{m}^2 \cdot 0.85 \cdot 0.9 = 1.762 \text{kW}$	Eq. 2
when:	$\text{DNI}_{\text{avg}} = \frac{\sum P_h^{\text{solar}}}{t_{\text{year}}^{\text{sun}}} = \frac{45.9 \frac{\text{kW}}{\text{m}^2}}{141 \text{h}} = 0.326 \frac{\text{kW}}{\text{m}^2}$ $A_{\text{dish}} = \frac{\pi}{4} D_{\text{dish}}^2 = \frac{\pi}{4} (3 \text{m})^2 = 7.07 \text{m}^2$	

Where DNI_{avg} is the average DNI, A_{dish} is the dish area (dish diameter 3m), ρ is the reflectance of the mirror (85%) and γ is the intercept factor (90%). Also, the sum of all hourly solar power numbers is ($\sum P_h^{\text{solar}}$) and the total amount of daylight time per year is ($t_{\text{year}}^{\text{sun}}$). This results in an average power input of 1.762kW delivered to the focal point during peak conditions [99].

Spectrum Splitting and Cold Mirror

Using a cold mirror for spectral beam splitting, approximately 60% of the solar spectrum is directed to the thermal receiver, while 40% is reflected toward the photovoltaic cell. This results in approximately 1.057kW thermal input and 0.705kW electrical input potential at the collector focus [100]. The optical input is split into thermal and electrical channels by the cold mirror:

$P_{\text{th_in}} = P_{\text{optical}} \cdot 0.6 = 1.762 \text{kW} \cdot 0.6 \approx 1.057 \text{kW}$	Eq. 3
$P_{\text{el_in}} = P_{\text{optical}} \cdot 0.4 = 1.762 \text{kW} \cdot 0.4 \approx 0.705 \text{kW}$	Eq. 4

Spectral Properties

The solar spectrum includes UV (280–400 nm), visible (400–700 nm), and infrared (700–2,500 nm). Cold mirrors reflect the visible range toward the PV module and transmit IR to the heat

receiver. Hot mirrors, used downstream, reinforce IR directionality [101]. Accurate separation ensures optimized use of photons for both thermal and electrical energy pathways.

The solar spectrum is divided as follows:

Wavelength Bands:	Symbol (value):
Ultraviolet (UV)	280-400nm
Visible	400-700nm (reflected to PV)
Infrared (IR)	>700-2,500nm (transmitted to thermal receiver)

The cold mirror reflects the visible range to the PV and transmits IR to the receiver.

Photovoltaic Components

The photovoltaic component is a high-efficiency CPV cell with a nominal efficiency, η_P , of 15.0%. Considering ambient temperature correction ($C_t = 0.9766$), the adjusted efficiency becomes 14.6% [102]. The electrical power output under optimal conditions **is approximately 0.103kW**. A high-efficiency CPV cell is used with 15% base efficiency. Considering a correction factor for temperature:

$$C_t = -0.0048 \times T_{amb} + 1.1206 \rightarrow C_t @ 30^\circ\text{C} \approx 0.9766 \text{ (97.7\%)} \quad \text{Eq. 5}$$

$$\eta_P V_{adj} = 0.15 \cdot 0.9766 \approx 0.1465 \text{ (14.65\%)} \quad \text{Eq. 6}$$

Eq. 4 and Eq. 6

$$P_P V_{out} = P_{el_in} \cdot \eta_P V_{adj} = 0.705\text{kW} \cdot 0.1465 \approx 0.103 \text{ kW} \quad \text{Eq. 7}$$

Thermal Energy Capture

The thermal receiver absorbs approximately 60% of the IR energy delivered by the beam splitter. This results in a usable thermal output **of approximately 0.634kW, which** can be directed toward palm oil processing tasks such as sterilization, digestion, and drying [103] [104].

Equation 3 and a conservative assumption of the receiver device's absorption coefficient (α) of 60%:

$$P_{th-out} = P_{th-in} \cdot \alpha = 1.057\text{kW} \cdot 0.6 \approx 0.634\text{kW} \quad \text{Eq. 8}$$

The combined useful energy output from the PV and thermal receivers is **0.738kW**, resulting in an overall system efficiency of 32.0%. This hybrid approach ensures that a broader portion of the solar spectrum is harvested for productive use in both thermal and electrical domains, maximizing energy return from the dish system [105], [106].

The total useful energy output is (Eq. 7 and Eq. 8):

$P_{\text{total_out}} = P_p \cdot V_{\text{output}} + P_{\text{th_out}} \approx 0.103 + 0.634 = 0.738\text{kW}$	Eq. 9
---	-------

Total collector efficiency is calculated by total output power divided by average solar radiation on unit area (DNI_{avg}) and the aperture area of the concentrator (A_{dish}). System efficiency relative to input solar energy is:

$\eta_{\text{total}} = \frac{P_{\text{total_out}}}{DNI_{\text{avg}} \cdot A_{\text{dish}}} = \frac{0.738\text{kW}}{\left(0.326 \frac{\text{kW}}{\text{m}^2} \cdot 7.07\text{m}^2\right)} \approx 0.32 \quad (32\%)$		Eq. 10
when:	$DNI_{\text{avg}} = 0.326 \frac{\text{kW}}{\text{m}^2}$	see Eq. 2
	$A_{\text{dish}} = 7.07\text{m}^2$	see Eq. 2

3.9 Conclusion and Sizing Insight

The preliminary sizing confirms that a **3 m diameter parabolic dish** coupled with a spectrum beam-splitting receiver can deliver about **0.738 kW of combined thermal and electrical output** under an average direct normal irradiance of approximately **326 W/m²**, consistent with typical clear-sky values for Southwest Nigeria. This results in an overall collector efficiency of **≈32 %**, which is competitive with other small-scale concentrating solar systems reported in the literature. The sizing exercise provides a defensible foundation for cost modelling, TRL planning, and system scaling, ensuring that subsequent techno-economic analyses remain grounded in realistic solar resource and component performance assumptions.

ultraviolet (<400 nm) and mid-infrared (>2.5 μm) regions [109]. For a beam-splitting system, this spectral variation is significant because the cold mirror relies on high visible reflectivity while transmitting infrared to the thermal receiver, and the hot mirror must sustain high infrared transmittance while rejecting unwanted shorter wavelengths.

Dish Size:

The size and capacity of one collector is dependent on the outer diameter of the dish (DDish); therefore, is the most important parameter. The specular reflectance of the solar mirror is also a very important parameter.

Specular Reflectance

This parameter highlights the total fraction of solar radiation that will be reflected. Mirrors with a maximum specular reflectance (ρ) of 96% are commercially available; however, mirrors with lower reflectance are also available. In operation, the reflectance differs from 0.96 to ~ 0.88 , the new mirror and the soiled mirror, respectively. Soiling and degradation of the mirror surface are the main reasons for reduced reflectance. Furthermore, not all mirrors are ideally shaped or manufactured, which is an engineering issue.

Reflective Coating and Specular Reflectance

In general, the reflectance of a mirror is a function of its wavelength λ , measured in nm, the incidence angle θ , and the acceptance angle φ . The acceptance angle φ , as shown in Figure 14, is crucial and defines the angular area around which the perfect specular reflection occurs [110]. Where the specific specular reflectance of silver (Ag) is concerned, its spectral properties, wavelength in particular, were analysed as follows. Due to the absence of measured data, the characteristics were estimated and simplified.

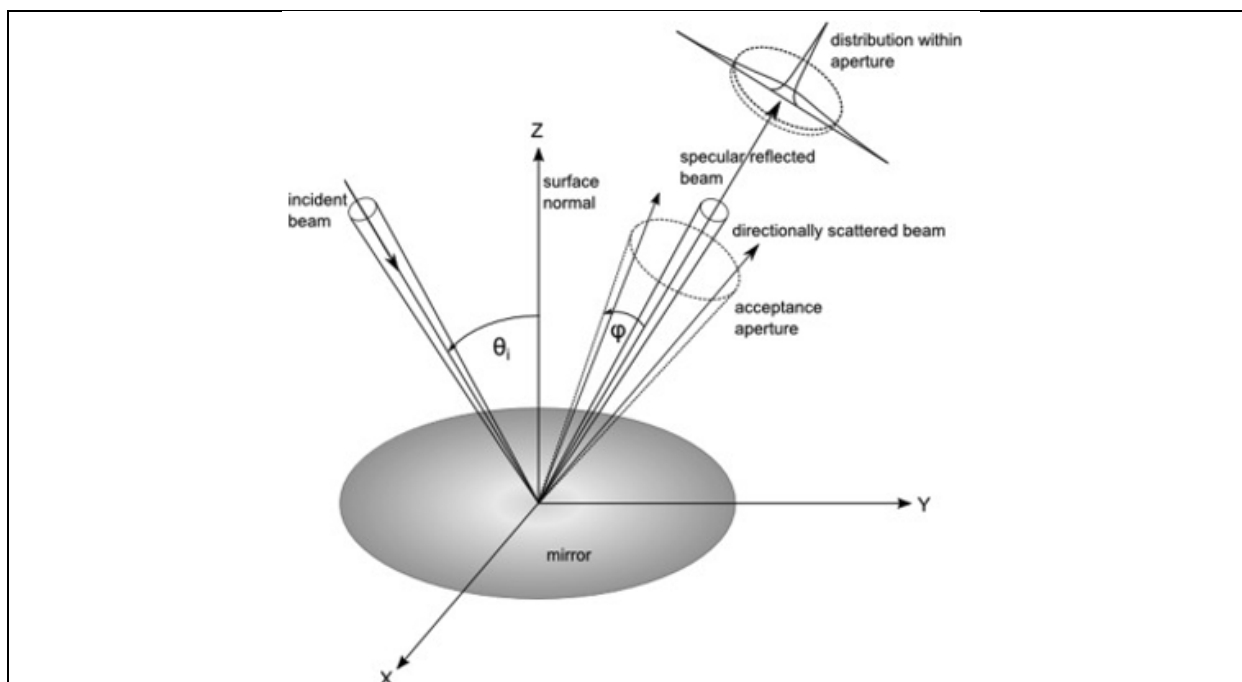


Figure 14: General spectral properties of a solar mirror.

Source: <https://www.sciencedirect.com/science/article/pii/S092702481830312X#bbib51>

From the reflectance diagram, the specific reflectance of silver material was extracted (estimated) in four parts and linearized (linear correlation), see the black line in Figure 15. Afterwards, the solar irradiance was calculated by numerical integration, within the boundaries of VIS (280nm-800nm) and IR (800nm-4,000nm).

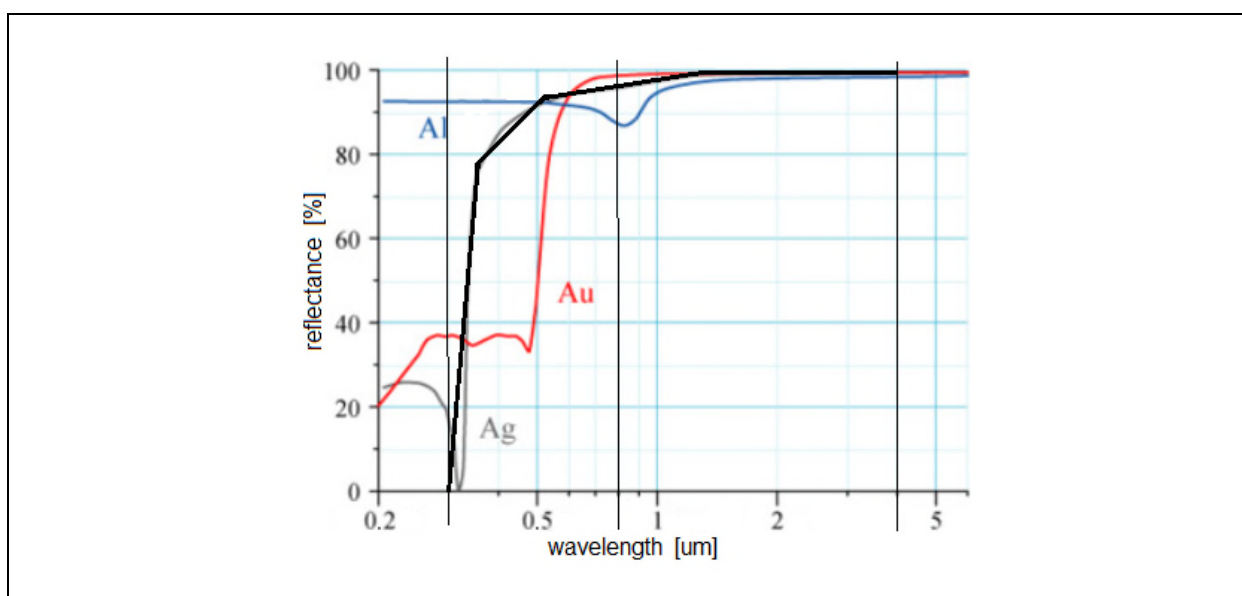


Figure 16: Optical reflection spectra of mirrors coated with Aluminium (Al), Gold (Au), and Silver (Ag), showing the specific reflectance characteristics over the solar wavelength spectrum.

Source: <https://www.zmescience.com>

The ratio of UV&VIS to IR reflection will be taken for further analysis. Of the total reflected solar specular irradiance, the UV&VIS fraction is 12.4% and the IR fraction is 87.57%.

The percentage reflected IR and, respectively, UV & VIS of Ag:

$$Q_{VIS}^{\rho, Ag} = \frac{\sum_{280}^{800} \rho_{(\lambda)}}{\sum_{280}^{4000} \rho_{(\lambda)}} = 0.124 \quad \text{Eq. 11}$$

$$Q_{IR}^{\rho, Ag} = \frac{\sum_{800}^{4000} \rho_{(\lambda)}}{\sum_{280}^{4000} \rho_{(\lambda)}} = 0.875 \quad \text{Eq. 12}$$

Where $Q_{VIS}^{\rho, Ag}$ is the percentage of reflected UV+VIS, $Q_{IR}^{\rho, Ag}$ is the percentage of reflected IR, ρ is the specular reflectance, λ is the wavelength (μm). As the linearization is an estimation, the resulting fraction values are approximations.

Dish Concentrator

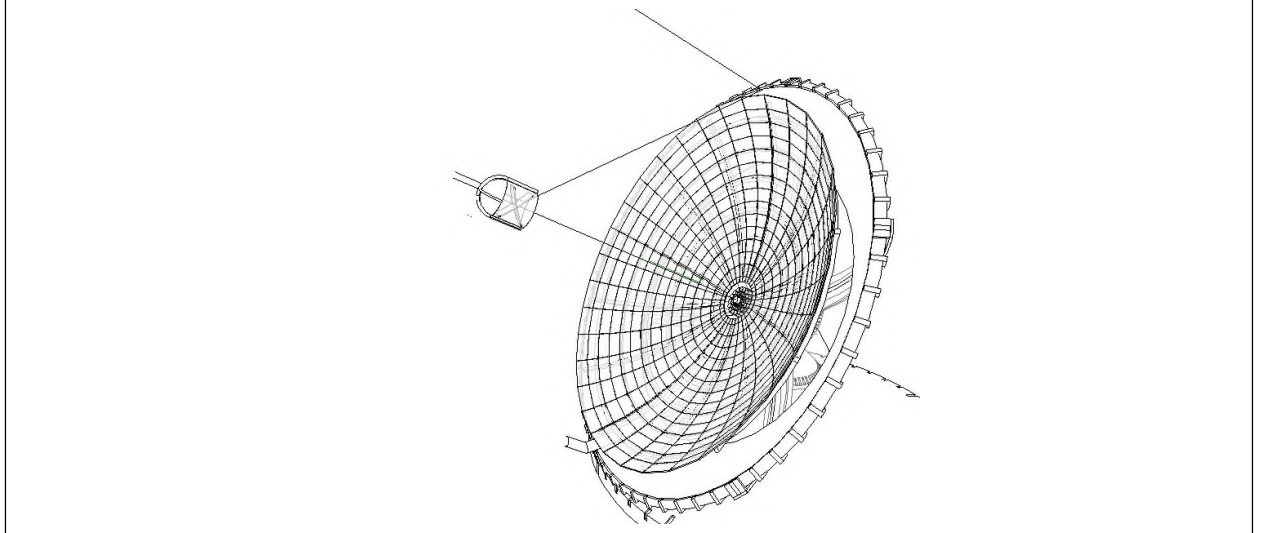


Figure 16: Diagram of the Assumed Dish Concentrator. Source: Author

The assumed solar dish collector has, in addition, as shown in Figure 16, a circular opening in the centre necessary for the receiver device and the protection area of the hot mirror. The larger is used for calculation purposes, and therefore, the effective aperture area, A_{Dish}^{eff} , is calculated as follows:

$$A_{Dish}^{eff} = A_{Dish} - A_{HotM} \quad \text{Eq. 13}$$

where A_{HotM} is the projected area of the hot mirror [111].

Focal-point:

The Dish Concentrator is paraboloid-shaped and has a focal length (f_{Dish}) of 35% of the dish diameter (the factor is freely chosen). However, the focal-point needs to be outside the dish cavity located, otherwise the reflected sun rays cannot reach the hot-mirror surface.

$$f_{\text{Dish}} = q_{\text{fl}} \cdot D_{\text{Dish}} \quad \text{Eq. 14}$$

The length factor (q_{fl}) for focal length (f_{Dish}) is chosen and can be changed. The focal point has the coordinates ($f_{\text{Dish}}, 0$) and f_{Dish} .

Dish Shape:

The dish shape can be expressed as:

$$y = \sqrt{4 \cdot f_{\text{Dish}} \cdot x} \quad \text{Eq. 15}$$

Where the coordinates are Y, X (X along the focal length and Y perpendicular to X) and the dish focal length is measured from (0,0).

Equation of the direction of the First Reflection Ray:

Only one ray, the outermost one, is representative, analysed, and presented.

Coordinate of the outer dish rim position:

$$\text{x-axis: } X_{\text{rim}} = \frac{Y_{\text{rim}}^2}{4 \cdot f_{\text{Dish}}} \quad \text{and} \quad \text{y-axis: } Y_{\text{rim}} = \frac{D_{\text{Dish}}}{2} \quad \text{Eq. 16}$$

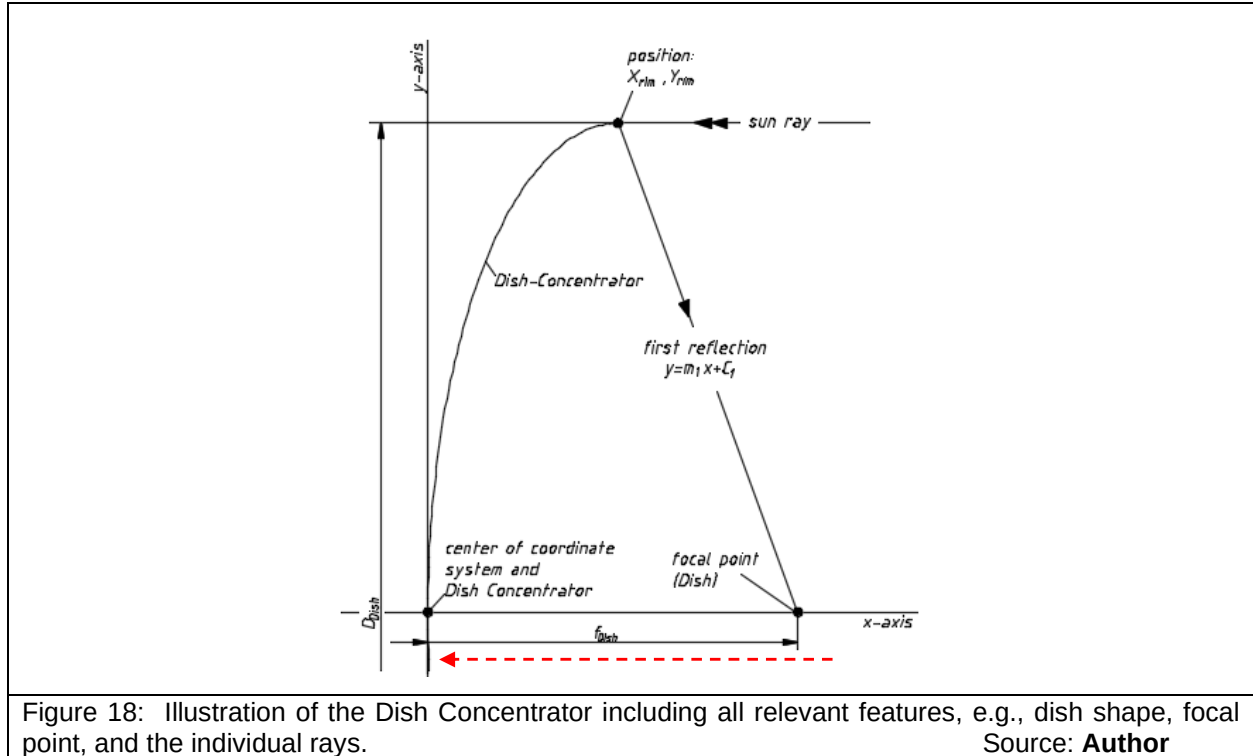
Where the outer position on the rim of the dish mirror is given by $(X_{\text{rim}}, Y_{\text{rim}})$, the outer diameter of the dish concentrator is (D_{Dish}).

The linear equation for the first reflection ray is derived from the sun ray (with Eq. 14, Eq. 15, Eq. 16):

$$y = \left| \frac{1}{\left(\frac{1}{8 \cdot q_{\text{fl}}}\right) - (2 \cdot q_{\text{fl}})} \right| \cdot x - \left(\frac{D_{\text{Dish}}}{\left(\frac{1}{8 \cdot q_{\text{fl}}^2}\right) - 2} \right) \quad \text{Eq. 17}$$

Figure 16 highlights the dimensions. It highlights the parabolic shape of the mirror, the incoming sun ray (on the example of the outermost ray), which is parallel to the x-axis. Furthermore, the illustration shows the focal point and the focal length. As expected, the focal point is located

outside the dish cavity. Furthermore, the ray after the first reflection is highlighted with its equation. The red dashed line is the second reflection from the hot mirror to the thermal receiver device. The ray is not on the X-axis.



4.3 Dish Concentrator Component (Ag-mirror) output energy

The output energy of the Dish Concentrator has to be handled separately due to differences in reflectance. Therefore, for a given solar irradiance (E_{SOL}) the UV&VIS fraction, E_{VIS} :

$$E_{VIS} = E_{SOL} \cdot A_{Dish}^{eff} \cdot \rho \cdot Q_{VIS}^{\rho, Ag} \quad \text{Eq. 18}$$

and for the IR fraction, E_{IR} :

$$E_{IR} = E_{SOL} \cdot A_{Dish}^{eff} \cdot \rho \cdot Q_{IR}^{\rho, Ag} \quad \text{Eq. 19}$$

Table 4: Solar Dish Concentrator Component (silver rear-coated mirror)

Parameter:	Symbol (value):
(1)	(2)
Dish Diameter	D_{Dish} (>3 m)
maximal specular Reflectance	ρ (0.88-0.96)
reflected UV&VIS (percentage)	(Q_{VIS}^{ρ}) (12.4%)
reflected IR (percentage)	(Q_{IR}^{ρ}) (87.57%)
Focal-Length (Dish)	f_{Dish} (>1 m)

Table 5 presents the main solar thermal collector types (low, medium, and high temperature) and their characteristics (temperature classes).

Table 5: Thermal Solar Collector type, their temperature range, and Receiver device.

Temperature Class:	thermal Solar Collector type:	Concentration–Ratio (Cr) and (op. Temp)	Receiver Device:
(1)	(2)	(3)	(4)
Low Temp. ($< 190^{\circ}\text{C}$)	Flat Plate Collector	<1 (27-77°C)	A simple tube receiver or evacuated tube (Linear receiver)
	Vacuum tube collector	<1 (47-187°C)	
Medium Temperature. (240-510°C)	Fresnel-Collector	10–40 (67-270°C)	Receiver tube (Linear receiver)
	Trough-Collector	15–40 (47-400°C)	
High Temperature. ($> 550^{\circ}\text{C}$)	Dish-Collector	100–1,000 (47-950°C)	Central Receiver Unit (Point receiver)
	Solar Tower plant with Heliostat	100–1,500 (130-2,727°C)	

4.4 Beam Splitting

This section is focused on the specifics and physics governing spectrum beam splitting (SBS). It starts with a review detailing the SBS components and then is followed by a laboratory experiment section aimed at establishing, at a proof-of-concept level, that cold and hot mirrors, respectively, do offer a noticeable SBS-based improvement to CSP/PV hybrid systems.

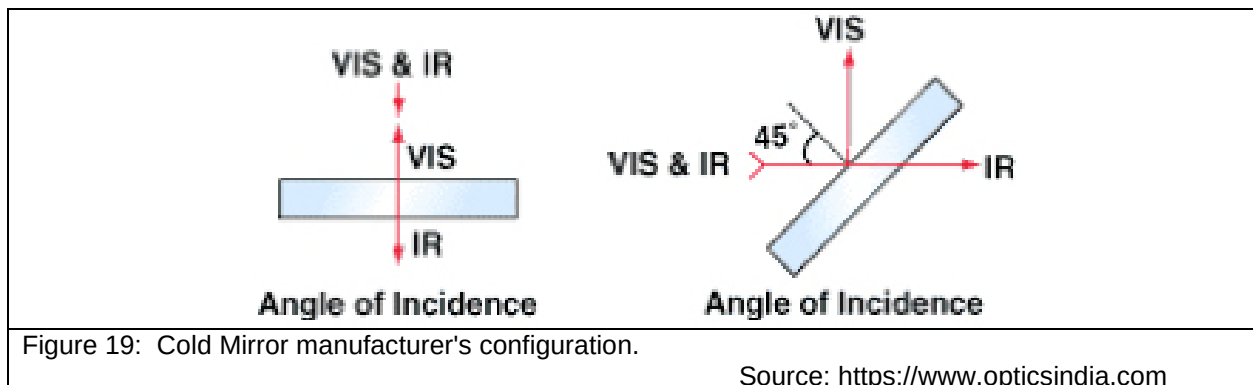
As previously established, SBS devices operate by directing specific bands of the solar spectrum to designated receivers. Cold mirrors reflect the visible spectrum (400–700 nm) while transmitting the near-infrared (NIR) and infrared (IR) components [112]. Conversely, hot mirrors transmit visible light and reflect IR. When arranged optimally in a hybrid configuration, these mirrors enable efficient energy routing, directing visible light to a PV cell and IR to a thermal receiver. In the experiments, dielectric cold and hot mirrors were placed at 45° angles with precision to reflect and transmit spectral bands onto respective devices.

4.4.1 Beam Splitting Component Array

Cold Mirrors

Traditionally, cold mirrors reflect visible wavelengths, UV, and transmit IR, making them useful for the protection of building systems without concerns about heat build-up, especially with the 0°

angle of incidence cold mirrors. The multi-layer dielectric coating on these glass mirrors reflects 90% of visible light while allowing over 80% transmission of IR waves [113]. Cold mirrors are ideal for illumination systems where high-temperature lighting is not desired, making them a viable BS option for PV efficiencies. Exposure to ambient temperatures ranging from -45.5°C to $+232.2^{\circ}\text{C}$ will not damage the mirrors.



Hot Mirrors

Manufactured with incidence angles of 0° , these heat-reflecting mirrors are usable in a variety of optical systems where heat build-up is a concern. Traditionally, hot mirrors are used in projection and illumination systems, where the multi-layer dielectric coating on the mirrors reflects harmful infrared radiation (heat), while transmitting visible light. Hot mirrors make an intelligent addition to optical systems that could otherwise be damaged by excessive heat.

Photovoltaic-Cell

Recent advancements in solar spectral splitting have shown substantial potential for improving photovoltaic cell efficiency by selectively directing optimal wavelengths towards PV cells while rerouting the infrared fraction towards thermal receivers [114] [115]. The relevant characteristics for the PV-cell used in this case are the PV area, the overall efficiency, and performance characteristics regarding to temperature. It needs to be mentioned, PV-cells are absorbing the UV+VIS band of the solar spectrum, and the silver mirror of the dish concentrator, as well as the hot mirror, do not reflect and process the wavelength bands equally. The specific energy of the UV+VIS fraction differs quite significantly from that of solar irradiance.

5 Experimental Work

This chapter presents the experimental validation of the hybrid CSP/PV system. The experiments were conducted using cold mirrors, hot mirrors, and a combination of both, to highlight the extent of the spectral beam splitting effects [116], [117].

5.1 Component Specifications

Solar PV cell specifications

Property:	Info / Value:
Cell Type:	Polycrystalline Silicon
Rated Current:	120mA
Rated Voltage:	2V
Rated Power:	0.24W
Dimensions:	40x40mm
Thickness:	3mm (measured)
Weight:	25g
Measured Efficiency:	10.7%

Cold Mirror Specifications (laser2000.co.uk)

Property:	Info / Value:
Material:	B270 (Super White Glass)
Wavelength Range:	45°
Surface Quality:	80-50, 60-40 (CLDM-50S)
Clear Aperture:	90% of the external dimension of the square inscription circle
Dimensions:	50x50mm +/- 0.3mm
Thickness:	1mm +/-0.1mm
Transmittance range transmission (45° incident):	800-2,000
Transmittance range transmission (45° incident):	> 80%
Cut off range transmission rate (45° incident):	> 90%
Half Maximum Wavelength:	760nm

Hot Mirror Specifications (Edmund Optics Inc. Europe)

Property:	Value:	Property:	Info / Value:
Angle of Incidence:	45°	Coating:	hot mirror, 45°
Substrate:	BOROFLOAT®	Dimensions:	50x50mm
Surface Quality:	80-50	Thickness:	3.3mm
Thickness Tolerance:	+/- 0.2mm	Type:	Dichroic Fiber
Dimensional Tolerance:	+ 0 / - 0.2mm	Coating Specification:	T _{avg} >85% (@400-690nm) R _{avg} >95% (@780-1,125nm) AR: R _{avg} >1% (@ 400-700nm)
Wavelength Range:	400-1,125nm	Surface Flatness:	4-6λ
Coating Type:	dielectric		
Regulatory Compliance:			
RoHS:	compliant	Reach 223:	compliant

Heat Flux Sensor

Property:	Value:
Mass	25g
Dimensions:	40x40mm
Thickness:	2mm
Density:	6,937.5kg/m ³
Heat Capacity:	490J/(kg K)

Sun Simulator

Parameter	Typical Value / Requirement	Notes
Irradiance level	1000 W m ⁻² (1 sun) ±10 %	Set and verified before each run
Spectral standard	AM1.5G	Matches ASTM G-173 global spectrum
Classification	Class AAA	IEC 60904-9 / ASTM E927 compliant
Spatial uniformity	≤ ±2 %	Over a full 200 × 200 mm (or 300 × 300 mm) test area
Temporal stability	≤ ±2 % drift/flicker	During the measurement interval
Beam collimation	≤ ±3° (typical 2–3°)	Near-normal incidence at the test plane
Illuminated area	≥ 200 × 200 mm (or 300 × 300 mm)	Fully covers receiver/test surface
Source type	Xenon lamp with AM1.5G filters or LED array	Both meet the Class A spectral match
Temperature control	25 ± 2 °C at device surface	Measured by the back-surface thermocouple
Calibration	Reference cell/pyranometer (traceable)	Checked pre- and post-experiment

Fresnel Lens

Parameter	Typical Value / Range	Notes
Material	Optical-grade PMMA (Polymethyl methacrylate)	High UV transmission, good mechanical stability
Physical size	50 mm × 50 mm × 5 mm	Square clear aperture; thickness at central groove ~5 mm
Groove pitch	~0.3–0.5 mm	Determines focal length & optical efficiency
Focal length (nominal)	100 mm (±5 %)	Measured from lens rear surface to focus at 1-sun irradiance
Aperture efficiency	85–90 %	Ratio of transmitted, concentrated light to incident
Transmittance (400–1100 nm)	≥ 92 %	High visible and near-IR throughput
Refractive index (at 589 nm)	n ≈ 1.49	Typical for PMMA
Operating temperature	–40 °C to +80 °C	PMMA softens above ~85–90 °C, but fine for sun-simulator testing
UV stability	UV-stabilized PMMA recommended	Prevents yellowing/degradation

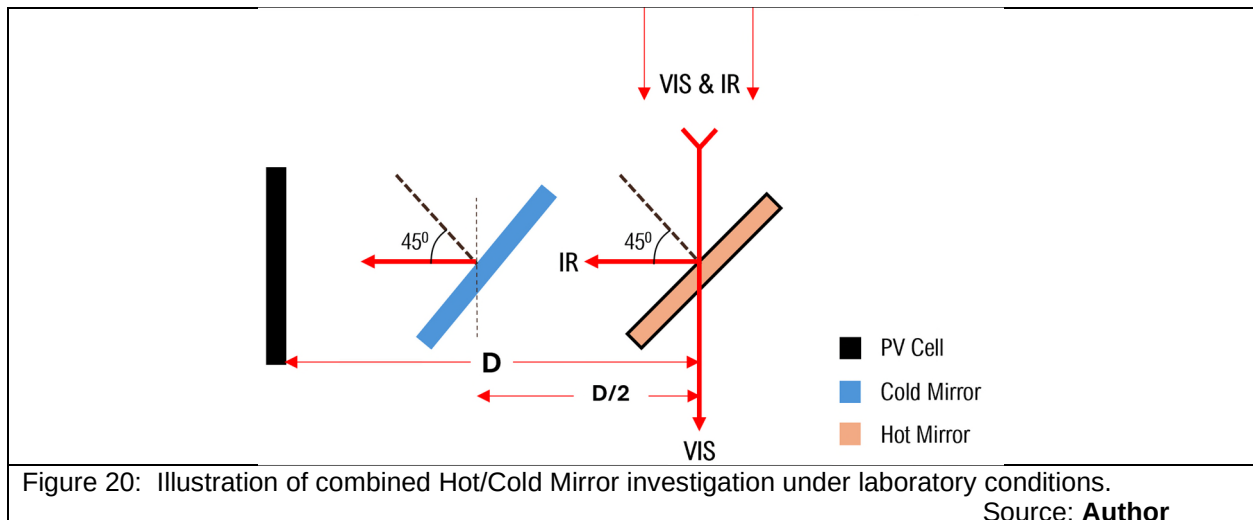
Surface quality	Fine-grooved, polished rear surface	Minimizes scatter and stray reflection
Weight	~10–15 g	For a 50 × 50 × 5 mm plate
Mounting	Clamp or adhesive frame; low stress	Avoids warping and maintains optical alignment
Safety note	A concentrated spot can exceed 100 °C	Use heat sink at focus to prevent damage to the test samples

5.2 Test-Rig Description

The test rig included a **Sun Simulator Specification (1-Sun, AM1.5G)** used to provide standard test irradiance for optical/thermal characterisation. The source delivered continuous-wave (CW) 1-sun irradiance (1000 W m^{-2}) with AM1.5G spectral content, over a uniform illuminated area large enough to fully cover the tested aperture/receiver plane. The beam was collimated to approximate normal incidence (low divergence), and the system was allowed to thermally stabilise after lamp warm-up before measurements. The 2.5 m solar concentrator dish originally planned couldn't be sourced, so a Fresnel lens was used instead. Cold and hot dielectric mirrors were eventually positioned at D and D/2 [118] [49] after a series of test runs. Flux sensors at different focal points (300mm and 400mm), with PV and thermal receivers.

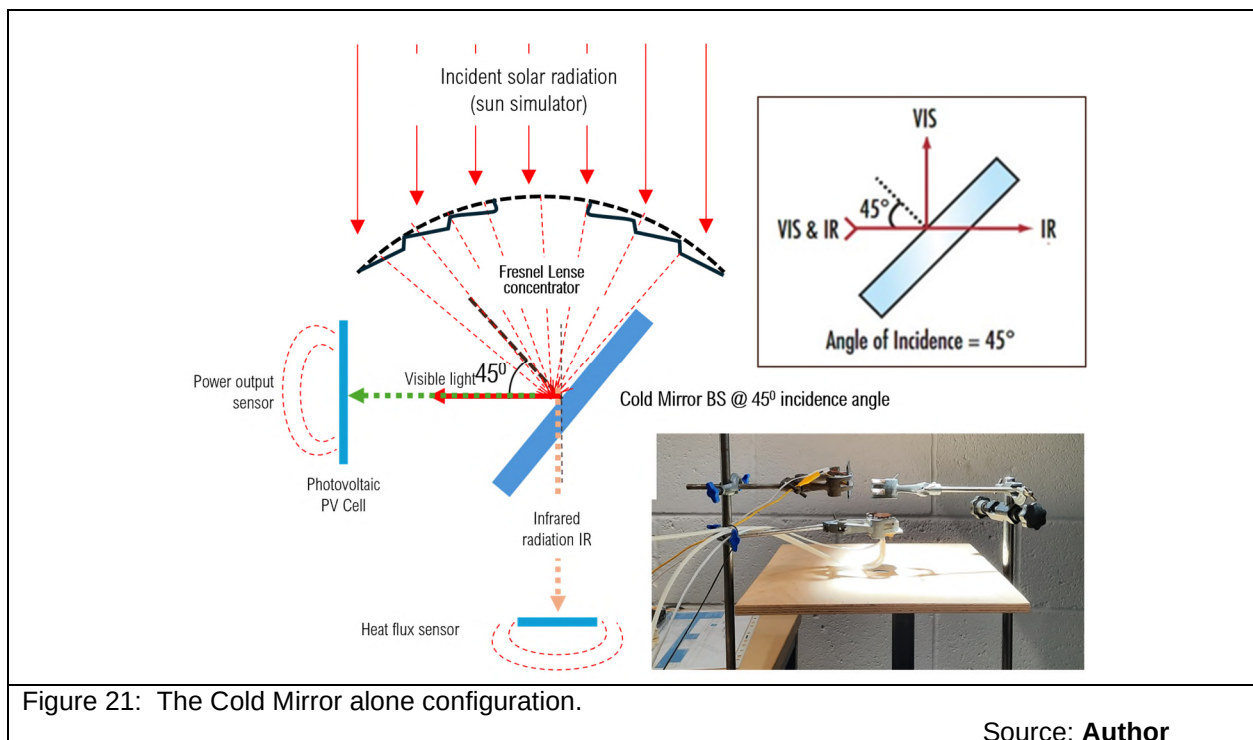
5.3 Output Parameters and Description

Measurements taken include power output, temperature variation, and solar flux intensity under different configurations. Cold and hot mirrors were aligned above a multi-junction PV cell and a heat flux sensor. Data, including current (mA), voltage (V), and temperature (°C) were collected using a precision source meter and a Pico logger. The most significant increase in PV current output occurred from a baseline of 0.04 mA to 19.5 mA [119], and was observed under the combined cold and hot mirror setup.



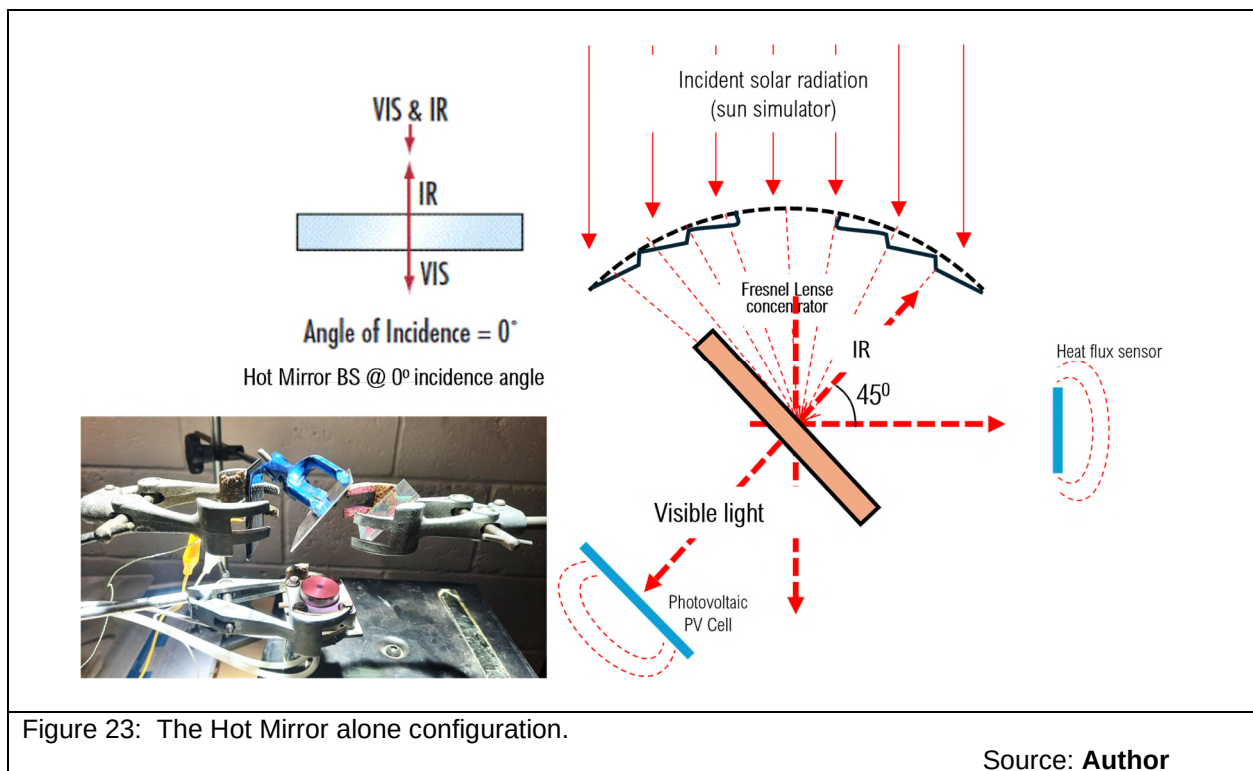
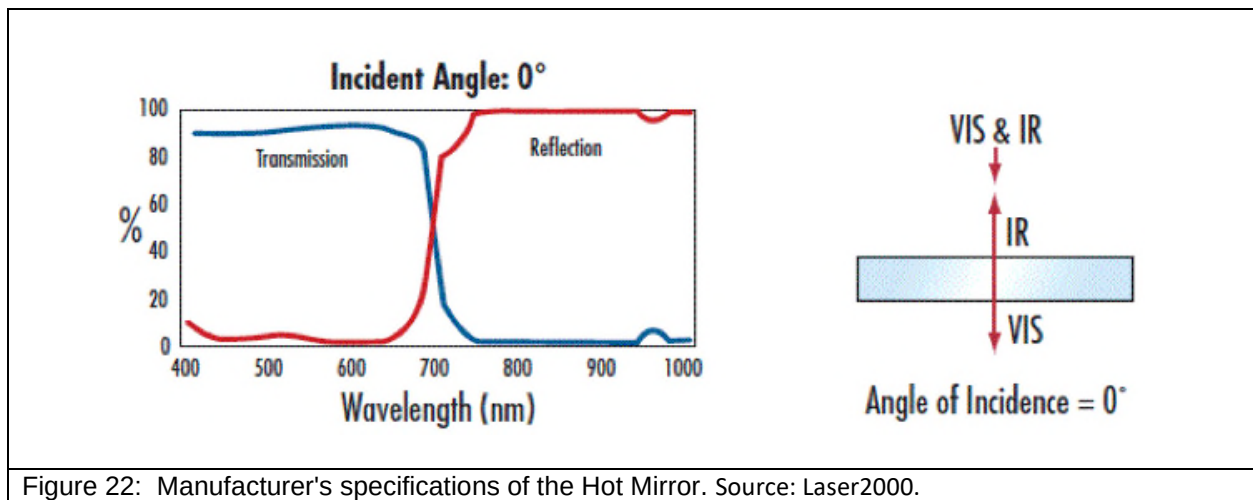
5.4 Cold Mirror setup

Cold mirrors were used to reflect visible wavelengths onto the PV module while allowing infrared to pass through. This led to optimal electrical output with moderate thermal gain [48]. The cold mirror reflected visible wavelengths to the PV cell, resulting in a moderate current rise to 5.72mA under optimal conditions. This setup minimized IR-induced heating and operated best at approximately 27.3°C. The cold mirror configuration achieved a peak current of 5.72mA with a PV voltage of 2.11V and a temperature around 27.3°C. This setup effectively reduced IR-induced heating by reflecting visible light towards the PV cell.



5.5 Hot Mirror setup

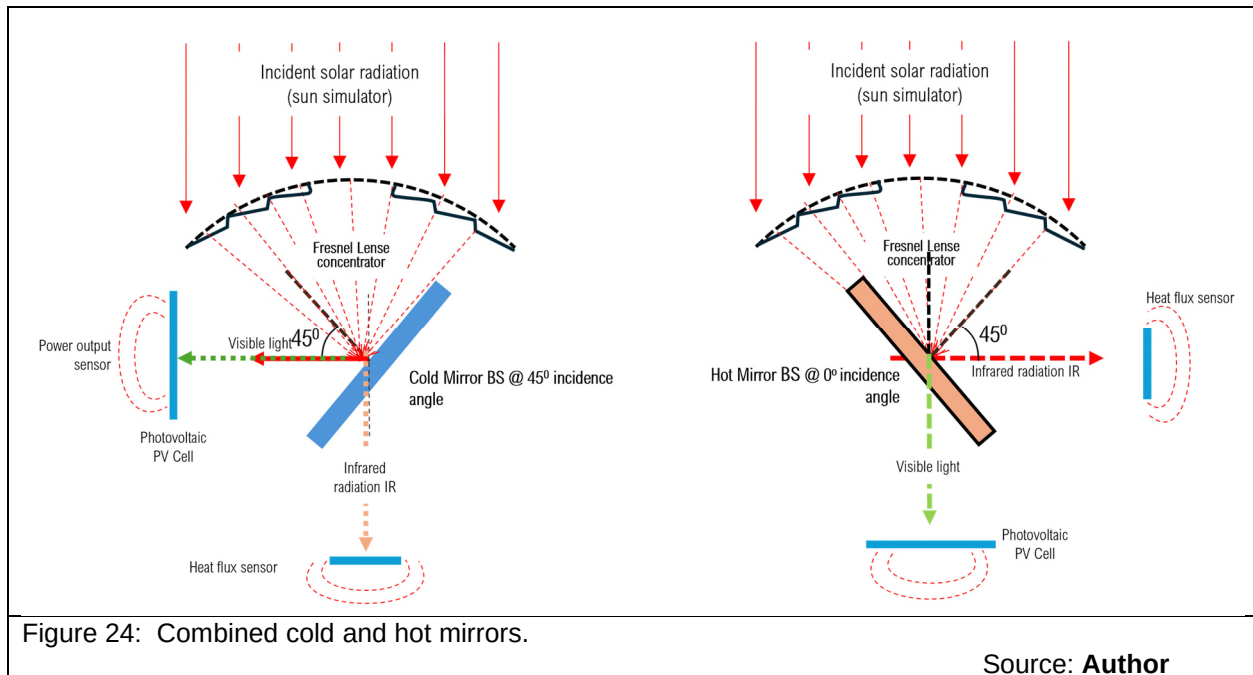
Hot mirrors were used to reflect infrared radiation for thermal applications, allowing visible light to continue to the PV module. The hot mirror alone, with a 0-degree angle of incidence (AOI) produced a comparable current of 5.72 mA, although the partial reflection of IR radiation limited its effectiveness. This configuration did not significantly outperform the cold mirror setup. Relying solely on the hot mirror resulted in similar electrical performance (5.72 mA), as it redirected IR radiation. However, its standalone efficiency was slightly lower due to partial IR interference.



5.5.1

5.6 Combined Cold + Hot Mirror setup

When both mirrors were used sequentially, the system could split and direct energy more efficiently [48] to the respective subsystems. The combination yielded the highest output of 19.5 mA at 2.17 V and approximately 28.5°C. The spectral separation enabled efficient electrical conversion without causing the PV to overheat. Precise angular alignment and spatial placement (distance D) were vital to this performance.



5.7 Performance Comparison and Implications

The table below summarises the performance across different configurations:

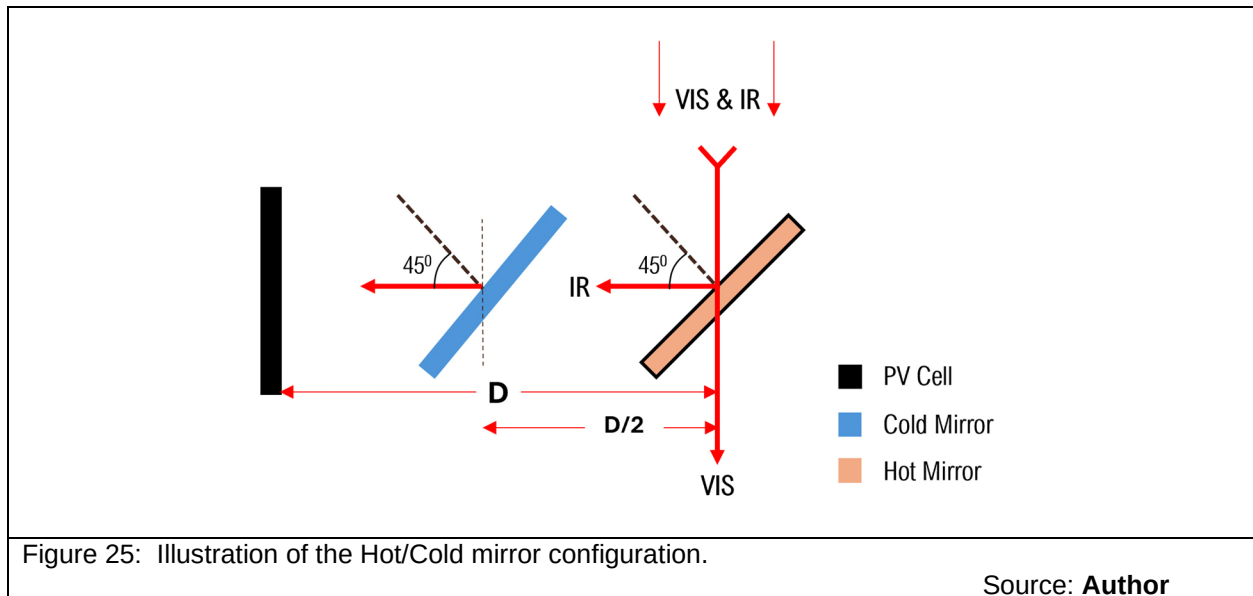
Table 5: The several configurations for the tests.

Mirror Setup:	max Current: [mA]	PV Voltage: [V]	Temperature: [°C]
(1)	(2)	(3)	(4)
Cold Mirror @ 45°	5.72	2.11	27.3
Hot Mirror @ 45°	5.72	2.11	27.3
Cold + Hot Mirror @ 45°	19.5	2.17	28.5
PV only (NTP)	0.04	0.058	18.72
Fresnel On (0mm)	18.83	1.60	27.3
Fresnel On (300mm)	12.00	108.00	26.5
C/H Mirror + Fresnel (0mm)	19.5	2.17	28.5
C/H Mirror + Fresnel (300mm)	4.75	108.00	26.5

5.8 The Hybrid Situation

The hybrid configuration, as shown in Figure 23, produced the highest current of 19.5 mA at approximately 28.5°C. The setup ensures precise spectrum separation, directing visible rays to

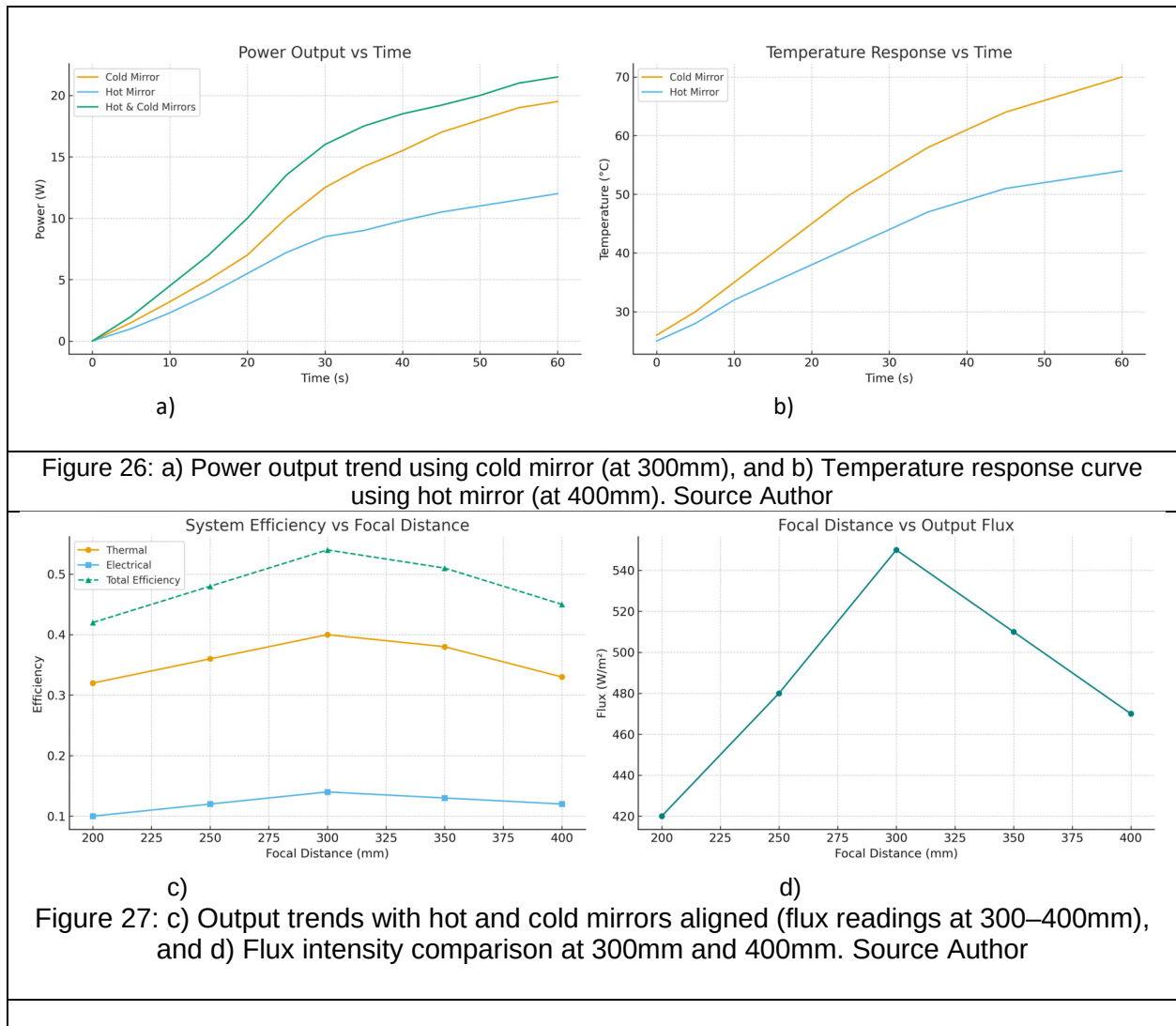
the PV while allowing IR to pass to the heat receiver. The current drops rapidly with misalignment or deviations from equidistance (D).



5.9 Experimental Results

Tests were conducted at both 300mm and 400mm focal points. The 300mm location produced the highest PV output (~19.5 mA), while the 400mm yielded a greater thermal response [120].

The data analysis and performance evaluation follow the solar thermal methodologies described by Duffie and Beckman [33]. Figures 26 a-b, and 27 c-d, presents all four scenarios and results: a) Power output trend using cold mirror (at 300mm), b) Temperature response curve using hot mirror (at 400mm), c) Output trends with hot and cold mirrors aligned (flux readings at 300–400mm), and d) Flux intensity comparison at 300mm and 400mm.



From the experiments, the following statements can be made:

- The cold mirror improved PV output significantly at the D/2 position.
- The hot mirror achieved elevated temperatures useful for thermal capture.
- Combined mirrors led to better spectral management and improved system synergy.
- The system's performance validates the feasibility of thermal-electrical integration under spectrum-splitting conditions [48] [121]

5.10 Conclusion

Spectrum beam splitting using cold and hot mirrors effectively enhances PV performance by routing spectral energy to its most efficient conversion pathway. The experimental findings reveal that a properly aligned beam splitter system can significantly outperform conventional PV-only setups. These results support the integration of hybrid CSP/PV technologies in sustainable agro-

industrial applications, particularly for regions with unreliable grid access. The next section will seek to explore the system-level integration of this beam-splitting device into a full-scale CSP dish system with thermal storage and automation for palm oil processing.

5.11 Reflective Coating and Environmental Durability of Cold/Hot Mirrors

In rural Nigerian climates, optical coatings are exposed to harmattan dust, high humidity (often >80 %), and surface temperatures exceeding 60 °C on concentrator substrates. These factors can degrade performance due to environmental stressors, including dust, humidity, and temperature.

Dust accumulation reduces effective reflectance and transmittance, scattering light, and lowers optical efficiency. Studies in the Sahel show dust can reduce solar reflectance by 5–20 % if uncleaned for several weeks [122] [123]. High humidity can lead to corrosion, as the silver mirror layer is chemically active and can tarnish when exposed to moisture and sulphides, resulting in a loss of reflectance. Thermal cycling due to high daytime temperatures and cooler nights can induce micro-cracking or delamination in coatings if substrate–coating expansion is mismatched.

To mitigate these risks, modern solar-grade silver mirrors incorporate multi-layer dielectric overcoats (e.g., SiO_2 , Al_2O_3) that seal the silver and enhance spectral stability [123] [122]. Edge protection and back-paint systems tested to ISO 9227 (neutral salt spray) and DIN EN 1096-2 (durability of coated glass). Enhanced thermal cycling resistance is demonstrated by accelerated ageing tests at 85 °C/85 % RH. Commercial CSP mirrors (e.g., Flabeg, Rioglass Solar) report solar-weighted reflectance ≥ 93 –95 % with lifetime degradation <2 % over 20 years under desert conditions when cleaned regularly [124].

For rural deployment, dry brushing or soft-wipe cleaning every 2–4 weeks during dusty seasons has been shown to restore >95 % of original reflectance. Manual cleaning is sufficient at small scale; for larger arrays, simple wiper/brush systems can be mounted. Water use is modest; in arid conditions, compressed air or soft dry cleaning is recommended to reduce abrasion. O&M studies show that annual cleaning labour of 112 h/year per 50 kW system is adequate to maintain optical efficiency in West African dust conditions.

5.12 Thermal and Spectral Stability of Dichroic (Hot/Cold) Mirrors

Dichroic cold and hot mirrors typically use dielectric interference coatings (e.g., $\text{TiO}_2/\text{SiO}_2$ multilayers) with spectral stability to ~ 300 °C and lifetime >20 years if periodically cleaned [122] [123]. These coatings show minimal spectral drift after humidity–heat testing at 85 °C/85 % RH for 1,000 h [123]. Thus, the beam-splitting elements can sustain the high ambient temperatures and humidity seen in Nigeria if protected with edge seals and periodic maintenance.

While the addition of spectrally selective mirrors increases system complexity, the materials and protective coatings used in modern CSP optics are well-proven in harsh desert and semi-tropical environments. Dust and humidity are managed through routine manual cleaning and durable multi-layer coatings. Thermal stability of both cold and hot mirrors is well-documented, with minimal spectral drift below 300 °C. Degradation rates (<2 % over 20 years in tested CSP fields) suggest the mirrors will not be the limiting factor in long-term performance if local cleaning is maintained. This evidence shows the durability risk is manageable and does not outweigh the performance and cost gains provided by the integrated optical design.

6 Energy Turnover over the whole Collector

This chapter presents a comprehensive analysis of the energy turnover of the full hybrid CSP/PV system using a parabolic dish collector with integrated spectrum beam splitting. Using engineering simulations and calculations, the monthly energy conversion and distribution through the collector, splitter, and receiver components can be examined. This includes both thermal and electrical outputs, evaluated against system demand in a palm oil processing context.

Equations 10 and 13 provide a comprehensive view of the solar energy transition as it moves through various components of the solar collector, including the dish concentrator, the hot mirror, the PV collector, and the thermal receiver device. Because a silver mirror exhibits significant variations between the UV+VIS and IR fractions of the solar spectrum, these fractions are addressed differently. Table 7 offers an overview of energy density, making it applicable to all sizes of solar collector designs. Furthermore, the solar energy input is presented as monthly data. Due to the substantial differences across months, yearly totals are derived by summing all 12 monthly values.

Table 6: Overview of the solar energy reduction at every component.

Wavelength band: [nm]	solar Energy [W/m ²]	Reflected by Dish Concentrator	Processes by hot mirror	PV-cell	thermal Receiver Device	total efficiency
(1)	(2)	(3)	(4)	(5)	(6)	(7)
280–4,000 (UV+VIS+IR)	899.558	---	---	---	---	---
280-800 (UV+VIS)	112.5 (12.5%)	106.9W/m ² (95%)	transmitted 96.2W/m ² (90%)	>28.9W/m ² (>30%) *	---	25.7% **
800-4,000 (IR)	787.1 (87.5%)	747.7W/m ² (95%)	reflected 673.0W/m ² (90%)	---	> 504.7W/m ² (>75%)	64.1% **

Note (*): There are no losses due to higher operational temperature.

The assumption is that the 15% refers to the total wavelength spectrum. I filter out only the visibility part of the total spectrum, and the total efficiency is calculated by dividing 1% of the Solar energy of 899.558w/W/m².

6.1 Operational Conditions

Furthermore, according to the literature, PV-cell efficiency is highly dependent on the operating temperature; it decreases with increasing op temp. However, this effect is related to the IR-fraction, and after the hot mirror reflects the majority of it, it will not reach the PV-cell and will not affect the operational temperature. Therefore, it is assumed that the effective operational temperature of the PV-cells in the location of interest (Chap. 3.3) is the ambient temperature or insignificantly higher (depending on the session and the effective PV air convection characteristics). According to the ambient temperature has the average figure is $26.7^{\circ}\text{C} \pm 1.9\text{K}$.

From a typical PV cell, the operational temperature versus power characteristic [125] the relative efficiency can be estimated as shown in Figure 24. By allowing visible light to reach the PV cells and reflecting infrared radiation, hot mirrors facilitate enhanced energy absorption, maximizing the efficiency of the concentrating solar setup. However, this configuration necessitates larger mirror areas to maintain effective thermal concentrations, demanding more area within the collector. While increasing the area of the hot mirror, that of the associated thermal receiver, and enhancing the overall output at Cr 1000, it reduces the effective area of the dish concentrator, potentially impeding thermal capacity [126]. The difference in temperature capacity between these configurations, even at a moderate Cr of 1000, may not warrant the increase in setup complexity and cost [127].

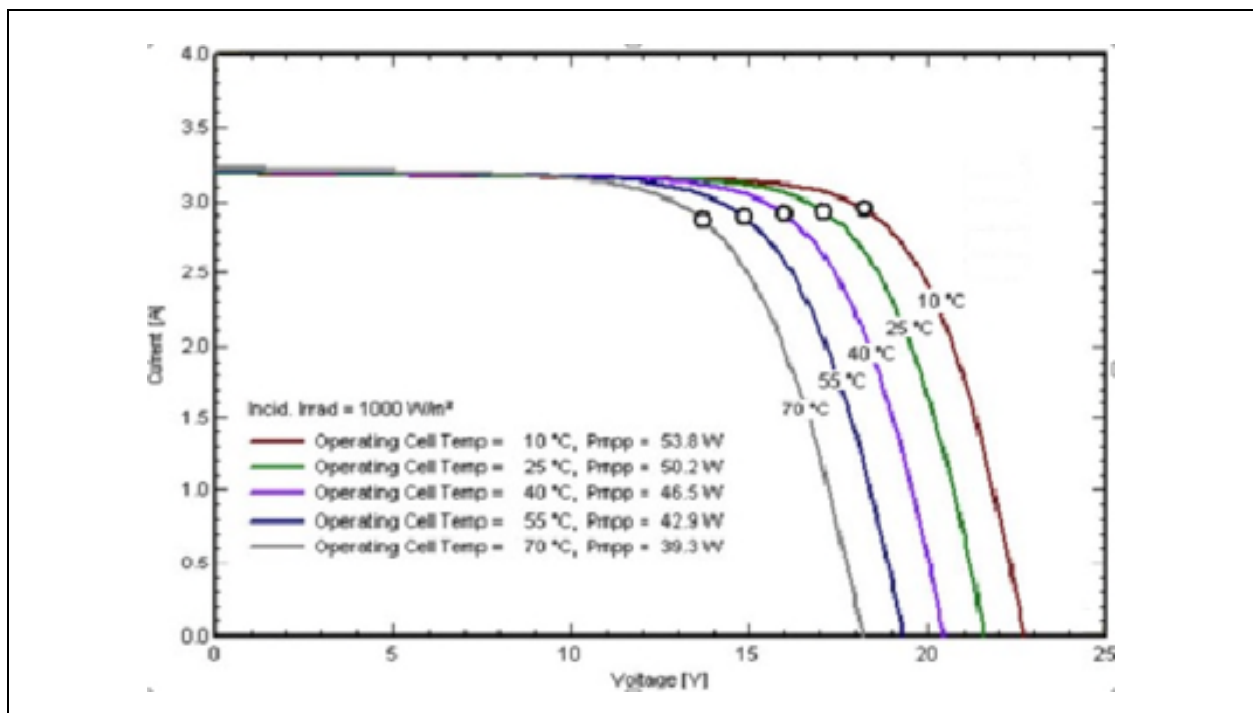


Figure 28: Operational temperature versus output power diagram of a typical PV cell.

Source: Proceedings of the 1st International Conference on Emerging Trends in Energy Conservation – ETEC (Courtesy of Fesharaki et al)

The efficiency ($\epsilon_{(ambTem)}^{PV}$), based on an operational temperature of 25°C, can be formulated as follows:

$$\epsilon_{(ambTem)}^{PV} = -0.0048 \frac{1}{\text{deg C}} \cdot T_{amb} + 1.1206 \quad \text{Eq. 20}$$

This linear correlation estimates the PV efficiency ratio to that of an operational temperature close to 25°C. Because the average operational temperature is already close to 25°C, the difference in effective efficiency is minimal, 0.99 +/- 0.14. Therefore, the ambient temperature influence on the PV-cell efficiency is negligible, and PV-cell cooling is not required.

6.1.1 PV Efficiency

A fundamental parameter to intestinal the performance of a PV-cell is operational efficiency. Several technologies provide various data, which are reciprocally related to the cost. Also, to mention the difference in efficiency under lab conditions and such of the same technology and commercially available. A survey, presented in Wilson et al. 2020 [128] highlights the differences in operational PV efficiencies.

Table 7: Overview of currently (2025) commercially available PV-technologies and, for comparison, additional high-performing PV technologies, [128]

Commercially Availability:	PV-cell technology:	Opt. Efficiency:	spec System Cost:
(1)	(2)	(3)	(4)
available	Copper Indium Galium (Di) Sellnide (CIGS)	12%-18.2%	1.32\$/W (16%)
	Cadmium Telluride (CdTe)	15.3%-18.2%	1.05\$/W (18%)
	Crystalline Silicium Cell (c-Si) (*)	14%-23%	0.91—0.97\$/W (22%-25%)
not available (Small-scale production or space application)	III-V	< 30 %	101\$/W (33%)
	Perovskites	< 25%	1.31\$/W (13%)

Note (*): Including passivated emitter and rear cell (PERC), interdigitated back contact (IBC), PERT/PERL, silicon heterojunction (SHJ) designs.

Based on the data in Table 7, an operational efficiency ϵ_{PV} for available PV cells of at least 15% can be drawn [37].

6.1.2 Total Electrical Energy Capacity

$$E_{\text{month}}^{\text{el}} = E_{\text{SOL}} \cdot A_{\text{Dish}}^{\text{eff}} \cdot \rho \cdot Q_{\text{VIS}}^{\rho, \text{Ag}} \cdot f_{\text{VIS}} \cdot \epsilon_{\text{PV}} \quad \text{Eq. 21}$$

The ambient temperature input value is the average ambient temperature of a specific month.

6.1.3 Yearly electricity generation

By adding all monthly electricity capacity data, the yearly generated total electricity can be calculated:

$$E_{\text{year}}^{\text{el}} = \sum_{n=1}^{12} E_{\text{month}}^{\text{el}} \quad \text{Eq. 22}$$

6.1.4 Electrical Concentration Factor

Due to different component areas, the concentration factor needs to be stated separately. Therefore, the electrical concentration factor:

$$C_r^{\text{el}} = \frac{A_{\text{Dish}}^{\text{eff}}}{A_{\text{PV}}} \quad \text{Eq. 23}$$

It must be noted that (C_r^{el}) is highly dependent on the collector design. However, in this case where an effective dish area = 7.1m² (D_{Dish} : 3,000m) and an A_{PV} of 0.0016m² (40x40mm) an C_r^{el} of > 4,000 can be expected.

Heat Transfer Fluid (HTF): Thermal oil is a suitable option for temperatures up to 400°C [129].

6.2 Thermal Receiver Device

The component's thermal energy absorbing capability mainly governs the performance of the thermal receiver device. The losses expected are mainly due to heat losses (convection) and the lack of absorption. At absorption temperatures higher than 120°C, synthetic oil is used, and in the case of 400°C molten salt, which significantly increases the cost, and is mainly used for heat storage in large solar fields for electricity generation [129].

6.2.1 Component Absorbance Efficiency

An assumed component efficiency, which includes absorption, conduction, and convection, will be higher than 70%. The heat losses can be managed by adequate insulation and a preferred

position behind the dish concentrator. It would be a wind-protected, adapted absorbing surface and an optimized heat exchanger, which will add to the assumed component efficiency number, $\epsilon_{\text{therRD}} \geq 0.6$.

6.2.2 Monthly thermal Energy Generation

Calculated the absorbed energy as follows:

$$E_{\text{month}}^{\text{therm}} = E_{\text{SOL}} \cdot A_{\text{Dish}}^{\text{eff}} \cdot \rho \cdot Q_{\text{IR}}^{\rho, \text{Ag}} \cdot f_{\text{IR}} \cdot \epsilon_{\text{thermRD}} \quad \text{Eq. 24}$$

6.2.3 Yearly thermal Energy

By adding all monthly thermal Energy data, the yearly generated thermal energy can be calculated:

$$E_{\text{year}}^{\text{therm}} = \sum_{n=1}^{12} E_{\text{month}}^{\text{therm}} \quad \text{Eq. 25}$$

6.2.4 Thermal Concentration Factor

Due to different component areas, the concentration factor also needs to be stated separately. Thermal Concentration Factor:

$$C_r^{\text{therm}} = \frac{A_{\text{Dish}}^{\text{eff}}}{A_{\text{thermRD}}} \quad \text{Eq. 26}$$

6.3 Spectrum Filter (Hot Mirror) Component

The hot mirror is represented by several parameters, from which the aperture area and the paraboloid-shaped surface are the important ones. In addition, the hot mirror distance to the focal point is crucial. Furthermore, the reflectance/transmittance characteristics also need to be established.

6.3.1 Hot Mirror Surface Size

The hot mirror surface has a length of 50mm and a square area (2,500mm²). The effective hot mirror surface area is circular with a diameter of 50mm and therefore an effective hot mirror surface area of 1,963mm² (eff A_{HotM}). The correct position is also along the x-axis.

6.3.2 Spectral Properties

Hot mirrors reflect infrared light while transmitting visible light at a specific wavelength. The transition is not exactly and cannot be accurately described with an “alternated function”, however an approximation is assumed is enough accurate for this analysis. Also, when IR band has a lower boundary at 700nm, the hot mirror reflects wavelengths from 800nm upwards. There is a gap. Furthermore, a constant characteristic can be considered even at higher wavelengths the reflectance is decreasing. The radiation beyond 2,500nm is negligible. For simplicity session the reflectance capacity of UV&VIS and transmittance capacity of IR, and rate changes due to the incidence angle are not taken into consideration. The hot mirror chosen has the following behaviour:

IR-Band: Reflective characteristics:

Wavelength range (approximated):		800-4,000nm
Reflectance Coefficient (IR-Band):	(f_{IR})	90%
Losses:		10%

UV&VIS-Band: Transmittance characteristics:

Wavelength range (approximated):		300-800nm
Reflectance Coefficient (UV+VIS-Band):	(f_{VIS})	90%
Losses:		10%

Figure 25 and Figure 26 visualize the spectral properties and the approximation used in the model.

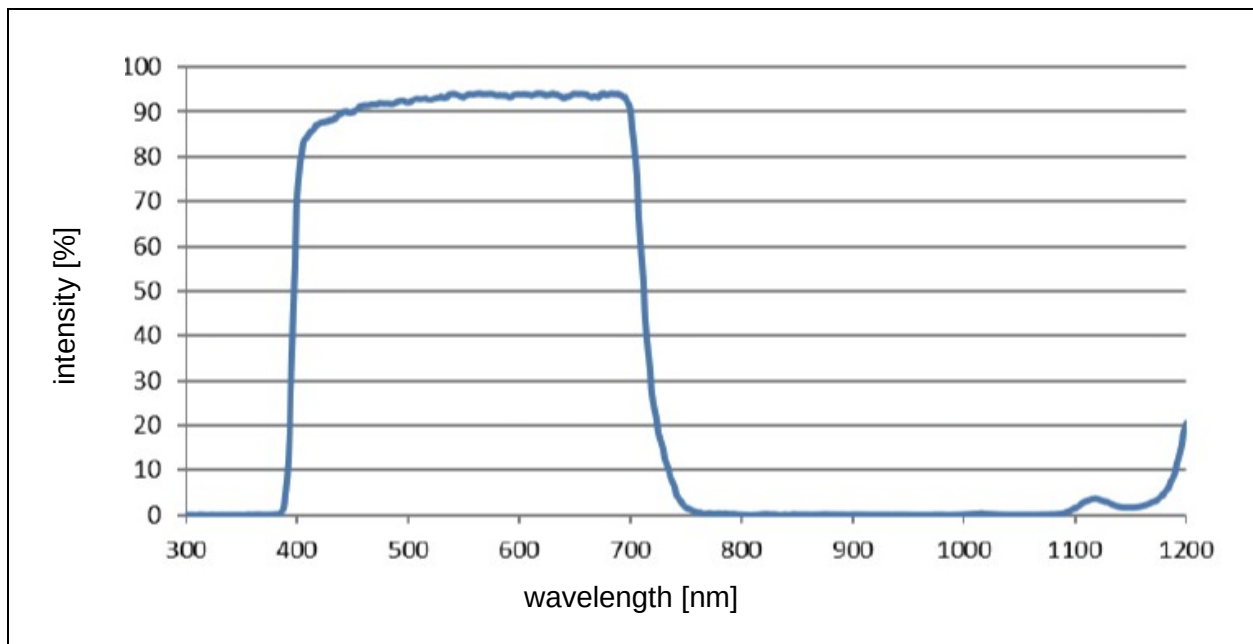


Figure 29: Hot Mirror Spectral Properties.

Source: www.laser2000.co.uk

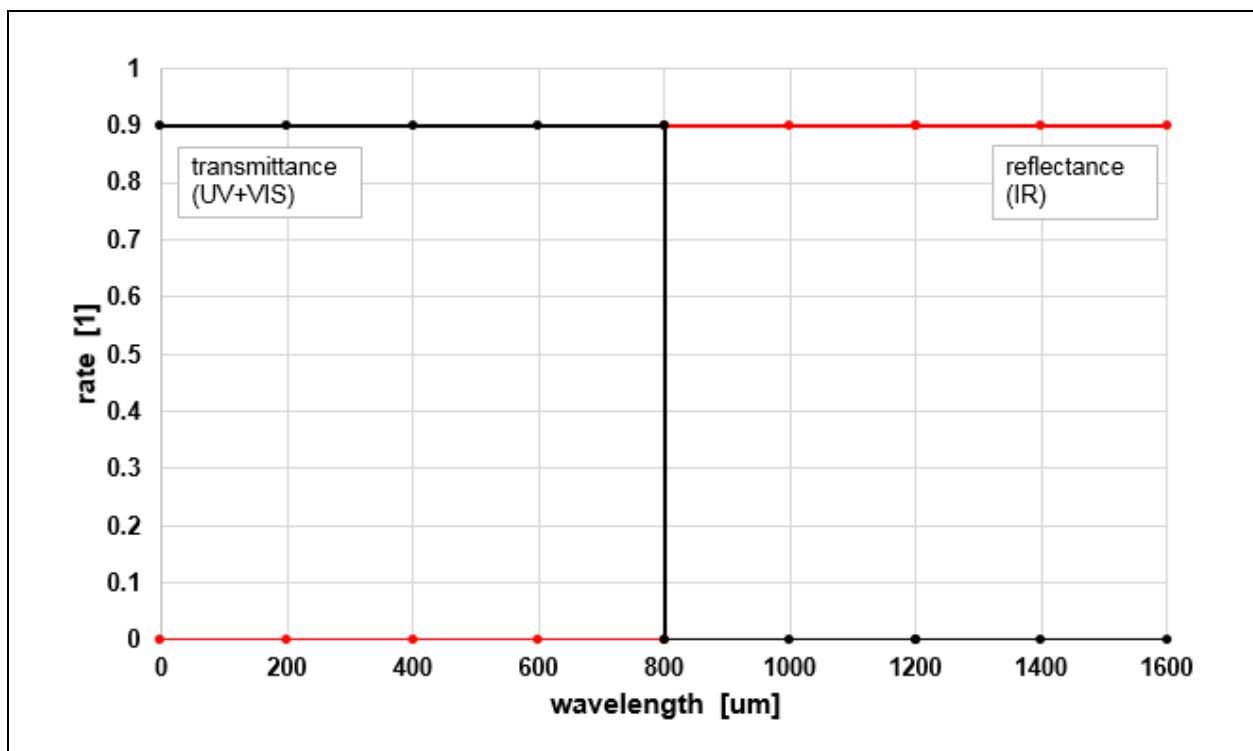


Figure 30: Hot Mirror's Spectral Approximations

Source: **Author**

6.3.3 Parabolically shaped Hot Mirror surface and its position

The hot mirror surface has a parabolic-shaped circular surface, which allows it to reflect the incoming rays parallel towards the thermal receiver device. Both parabolic “reflectors” need to

be adjusted in such a manner that both focal points have the same position, and the reflected rays are also identical.

In order to determine the focal length (f_{HotM}) of the hot mirror surface, an assumption is made; therefore, a beam is emitted from the thermal receiver device toward the hot mirror surface. The reflection of this hot mirror surface point needs to reach position ($X_{\text{rim}} / Y_{\text{rim}}$) which was used for the focal length analysis of the dish concentrator.

The reflection points at the hot mirror surface:

($X_{\text{HotM}} / Y_{\text{HotM}}$) when Y_{HotM} is one half of the thermal receiver device

Furthermore, an assumption is made in order to rotate by 180 degrees vertically the geometry, defined so far according to Figure 27. Due to the focal length of the hot mirror surface being of interest, this assumption can be made.

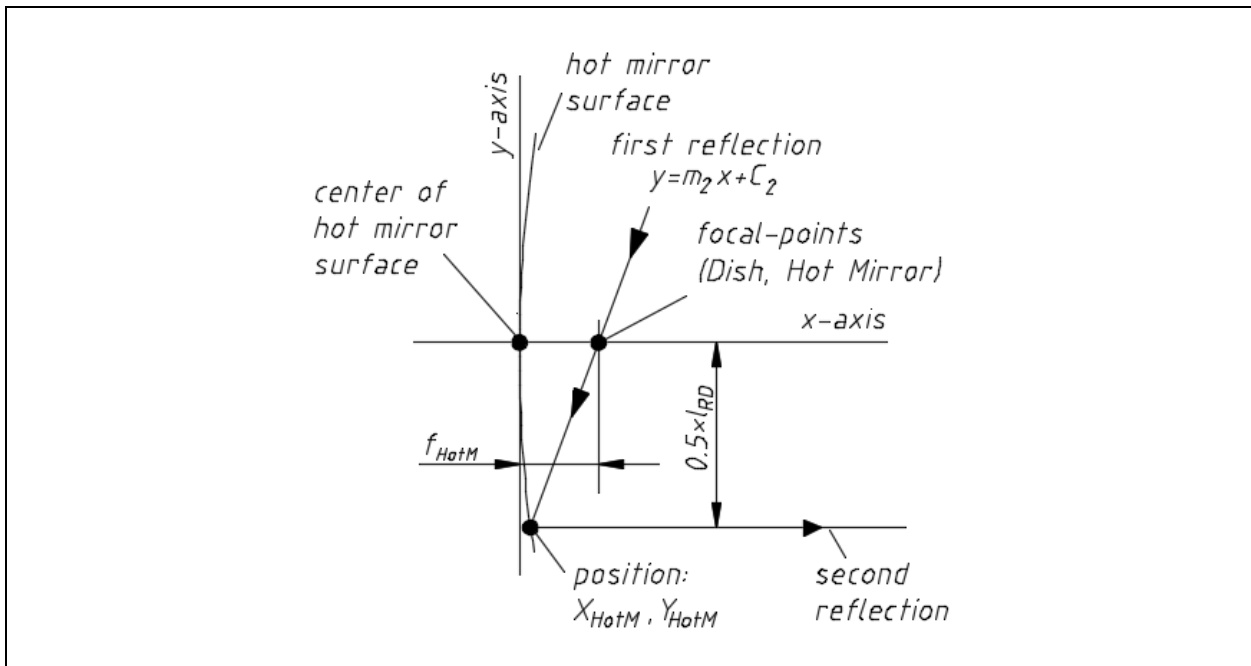


Figure 31: Hot Mirror Transmission / Reflection Data.

Source: (Edmund Optics Inc. Europe)

Two equations emerge, the first is based on the slope (m_1); however, to use m_1 in this assumption, it has to be multiplied by -1.

$$m_2 = -m_1 = \frac{0 - (0.5 \cdot l_{RD})}{f_{\text{HotM}} - X_{\text{HotM}}} \quad \text{Eq. 27}$$

$$m_2 = \frac{(0.5 \cdot l_{RD})}{f_{\text{HotM}} + X_{\text{HotM}}} \quad \text{Eq. 28}$$

Simplified and rearranged:

$$0.5 \cdot l_{RD} = m_1 \cdot f_{HotM} + m_1 \cdot X_{HotM} \quad \text{Eq. 29}$$

And second, the surface-based:

$$X_{HotM} = \left[\frac{(0.5 \cdot l_{RD})^2}{4 \cdot f_{HotM}} \right] \quad \text{Eq. 30}$$

$$0 = m_1 \cdot f_{HotM} + m_1 \cdot \left[\frac{(0.5 \cdot l_{RD})^2}{4 \cdot f_{HotM}} \right] - 0.5 \cdot l_{RD} \quad \text{Eq. 31}$$

Rearranged to a polynomial of the second order:

$$0 = (4 \cdot m_1) \cdot f_{\text{HotM}}^2 - (2 \cdot l_{\text{RD}}) \cdot f_{\text{HotM}} + \left[\frac{m_1}{4} \cdot l_{\text{RD}}^2 \right] \quad \text{Eq. 32}$$

The polynomial of the second order has two solutions:

$$x_{1/2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad \text{Eq. 33}$$

$$f_{\text{HotM}/1} = \frac{(2 \cdot l_{\text{RD}}) + \sqrt{(2 \cdot l_{\text{RD}})^2 - (4 \cdot m_1^2 \cdot l_{\text{RD}}^2)}}{8 \cdot m_1} \quad \text{Eq. 34}$$

The solution for $f_{\text{HotM}/1}$ was confirmed with an iterative solution, which represents the focal length (f_{HotM}) of the parabolic shape of the hot mirror surface.

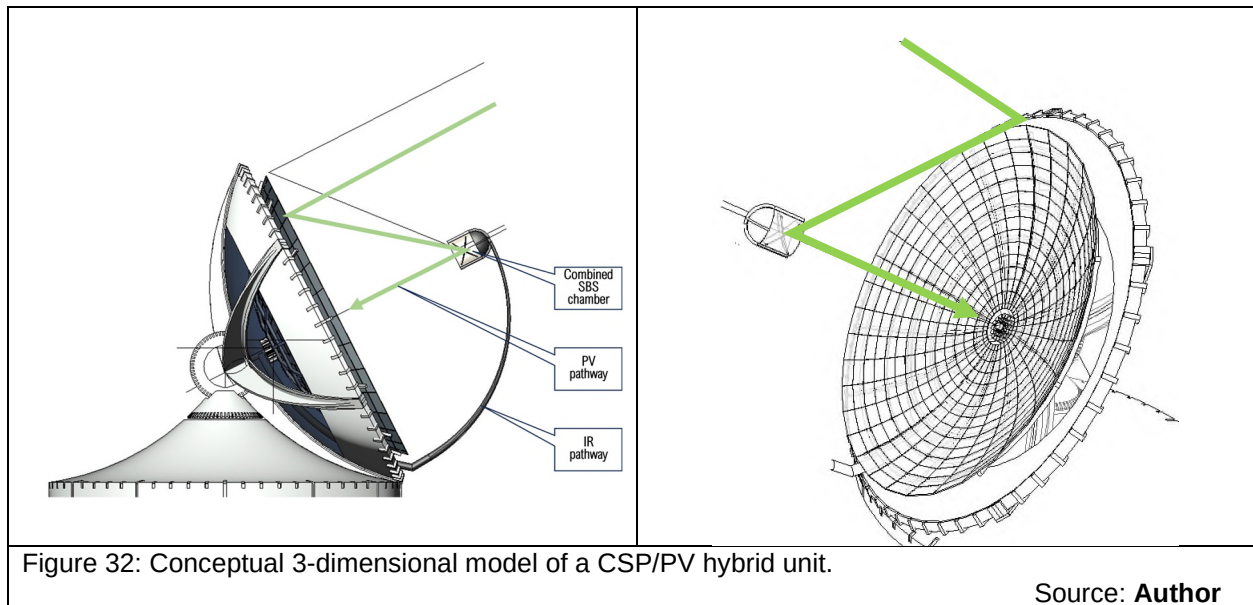
The location of the parabolic shape centre ($\text{pos}_{\text{HotM}}, 0$) is along the x-axis with the coordinates (pos_{HotM}), which is calculated as follows:

$$\text{pos}_{\text{HotM}} = f_{\text{Dish}} + f_{\text{HotM}} \quad \text{Eq. 35}$$

The total efficiency (Eq. 10) was calculated based on the power density of the relevant wavelength band. However, when compared to traditional technologies, the total efficiency is expected to be significantly higher due to the losses of unused energy from the total solar spectrum.

7 Business Model Innovation

The System's Value Proposition



7.1 Innovative Summary

This system is innovative both in design and cost. Spectrum beam-splitting in a single dish produces electricity and process heat from a single aperture, as shown in Figure 27, thereby improving energy yield. Cost-wise, local fabrication and low, predictable OPEX make the solution competitive with PV-only mini-grids while avoiding diesel/biomass fuel chains and providing valuable heat. This chapter offers a detailed business model innovation, with a section that addresses the issues of scalability and economic feasibility for resource-constrained rural settings in Nigeria.

7.1.1 The Demonstrator Theme

Designed to maximize both energy production and educational impact, the CSP/PV hybrid system serves as a cornerstone of Owodaiye Farms' operational strategy. With its theme park feature, it provides an interactive learning experience where visitors can observe energy generation in real time. Educational programs can illustrate the principles of energy flow and thermodynamics, specifically targeting school groups for field trips and workshops.

7.1.2 Community–Scale Regeneration

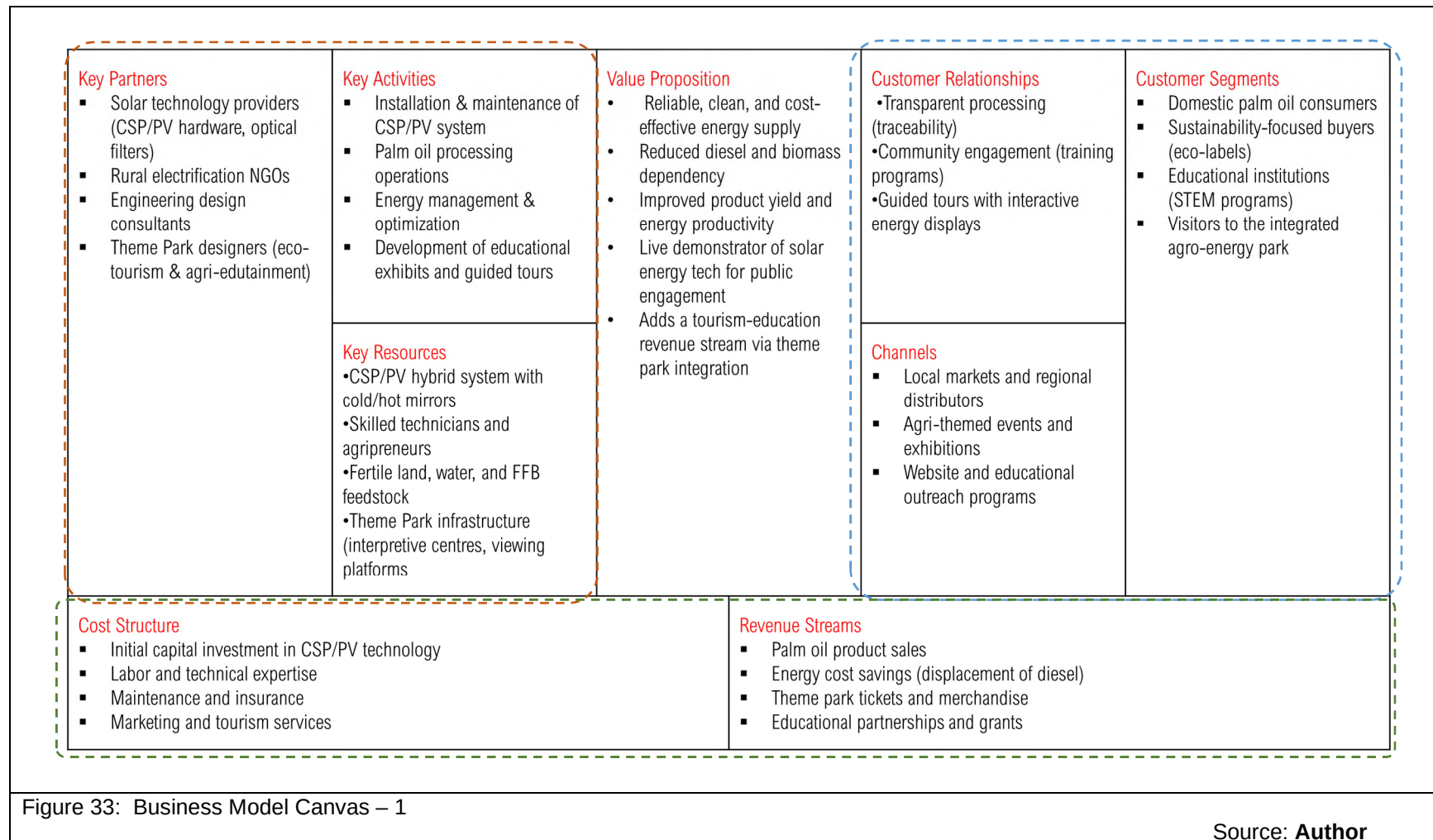
The core business model innovation lies in reimagining the solar collector not only as a source of energy but also as a community-scale demonstrator, showcasing how renewable energy systems can speed up economic development, sustainability education, and neighbourhood regeneration.

7.1.3 Spectrum-Splitting System as a Value Driver

The system design utilizes a hot mirror (at 0° AOI) to reflect infrared (IR) radiation toward a thermal receiver while transmitting visible light toward a downstream cold mirror (at 45° AOI), which then reflects visible wavelengths into a PV cell. This precise beam-splitting configuration preserves the PV cell's efficiency by thermally decoupling it from the IR spectrum, thus preventing overheating, a significant challenge in tropical climates. [130].

This optical innovation directly supports the business model by ensuring:

1. Increased and more consistent electrical yield
2. Usable thermal energy for agro-processing (e.g., sterilization and drying)
3. Simplified cooling infrastructure
4. Modular and replicable design for neighborhood clusters.



Based on the nine building blocks of the business model canvas in Fig. 29 [131]. The customer is at the core of any business model, and this is depicted by the three building blocks: customer segments, customer relationships, and channels. The rest of this section focuses on the collaborative impact that the customer and the innovator have on the growth of this business.

7.2 Business Model Canvas (with Energy Integration Opportunities)

7.2.1 Keying in the Partners

Partners in solar technology provide essential CSP/PV hardware necessary for maximizing solar capture and energy conversion. Establishing partnerships with local and international solar firms can ensure access to advanced technology and offer ongoing support for operational maintenance and upgrades. Collaboration may also involve sharing best practices and innovations in solar energy deployment within the agricultural context of palm oil processing. [132].

7.2.2 Business Model Canvas Highlights

Table 8: Highlights of the Business Model Canvas

Key Components:	Description:
Value Proposition	Dual-energy output (electricity + heat) for palm oil processing and educational use
Customer Segments	Smallholder farmers, local cooperatives, and educational institutions
Channels	On-site demonstrator, extension programs, digital dashboards
Customer Relationships	Co-ownership models, local stewardship, and energy literacy workshops
Revenue Streams	Palm oil output sales, training fees, carbon credits, and potential feed-in tariffs
Key Resources	Hybrid CSP/PV unit, optical filters (hot/cold mirrors), PV modules, thermal receiver
Key Activities	System operation, maintenance, training, and agro-processing
Key Partnerships	Agricultural cooperatives, technical colleges, local government, and microfinance institutions
Cost Structure	Initial capital (mirrors, dish, PV), training, upkeep, mirror replacements, monitoring tech

7.2.3 Regenerative Impact at the Neighborhood Scale

The model aligns with the regenerative ethos of Owodaiye Farms, which was established as an integrated farming enterprise by embedding clean energy infrastructure into the agricultural fabric

of its community. This enables enduring initiatives such as gradual reduction and eventual eradication of the reliance on diesel generators and firewood; **job creation** in PV/CSP system maintenance and agribusiness; **Skill development** through community energy literacy programs; and **energy sovereignty** for farming clusters via localized microgrids

As discussed by Orosz et al. (2016), spectrum-splitting hybrid systems have the potential to improve total solar utilization beyond 50% when combining electricity and heat capture. [133].

In a rural Nigerian context, this translates into greater energy resilience and productive capacity. In other words, the hybrid offers more than just palm oil processing; it provides a power solution for the immediate community, a rural area that has previously endured immense hardship due to the inadequate power supply from an almost non-existent national grid.

7.3 The Agri-Energy Theme Park – unique selling point (USP)

A key innovation lies in the transformation of the CSP/PV hybrid array into a live demonstrator system within an energy-themed attraction at Owodaiye Farms. This exhibit would:

- Visualize solar spectrum splitting: Real-time demos showing light being divided for PV and thermal use
- Interactive displays: Visitors can track energy flows from the sun through the system to process
- Educational signage: Explains the science and sustainability benefits
- Hands-on learning: School programs and engineering student internships

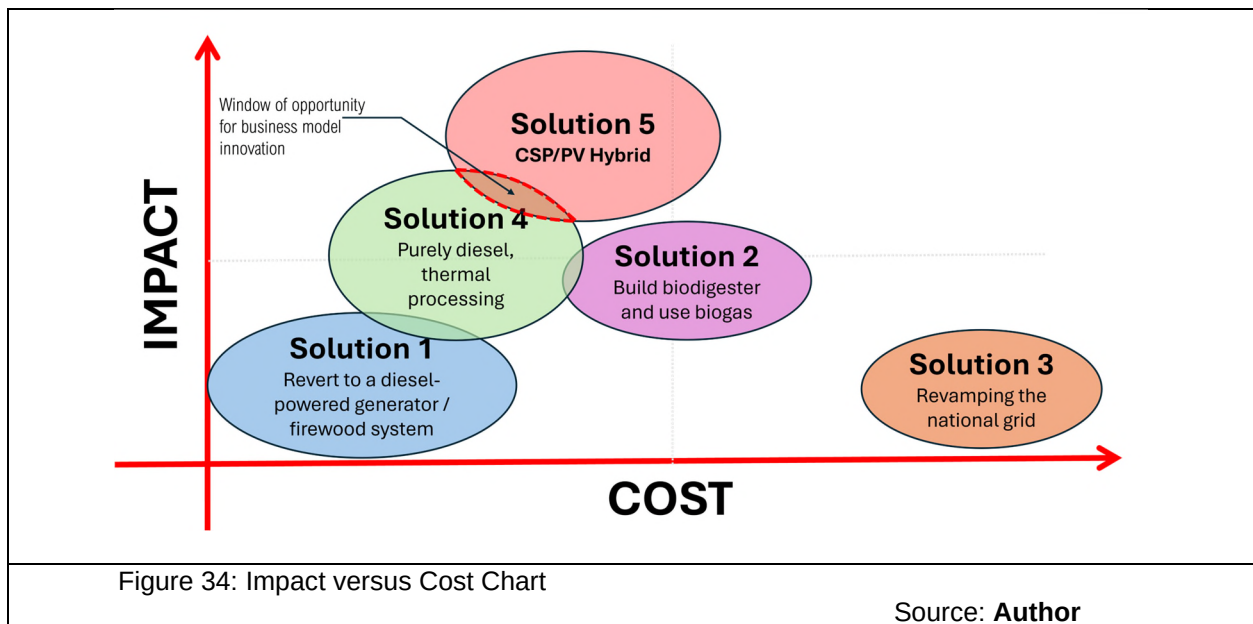
This adds a tourism and education layer to the business model, increasing visibility, community support, and revenue diversification.

7.3.1 Strategic Impact

Integrating energy and tourism enhances the farm's resilience by:

- Creating multi-stream income
- Reducing reliance on unsustainable fuels
- Positioning Owodaiye Farms as a flagship for decentralized solar innovation in agro-processing
- Promoting awareness and technology diffusion in rural Nigeria

7.4 Cost Modelling and Economic Feasibility



A full cost modelling would be beyond the scope of this work, but decent cost estimations and projections based on relatable projects are proposed [134]. These have been made, bearing in mind the deployment and scalability of the CSP/PV hybrid system in resource-constrained contexts such as rural Nigeria. Although precise costs require pilot deployments, preliminary assessments, as shown in Figure 28, show that the system is technically and economically feasible when compared with existing energy options [135] [136]. This section envisions a two-stage scaling strategy of technical optimization followed by economic adaptation for rural deployment. This work investigates a concentrated solar power / photovoltaic (CSP/PV) hybrid that uses spectrum beam-splitting: a parabolic dish concentrates sunlight, hot and cold mirrors divide the spectrum, and the system simultaneously produces electricity and process heat.

7.4.1 Cost Modelling and Benchmarks

Capital expenditure (CAPEX) for the proposed spectrum beam-splitting CSP/PV dish hybrid was estimated using a bottom-up methodology. The bill of materials for a 3 m parabolic dish and receiver assembly was defined, with cost benchmarks taken from a small-scale CSP and concentrator PV deployments in Sub-Saharan Africa [134] [137] and global renewable cost surveys [60] [61]. The Nigeria-specific PV/BOS pricing was from the Rural Electrification Agency and the Nigerian Electricity Regulatory Commission [138] [139].

Optics and drive systems dominate early-unit costs [140], while local fabrication of structural components can reduce CAPEX by 20–25 % relative to full importation. The resulting category shares and unit costs support an early-commercial mid-point CAPEX estimate of about USD 7,000/kW_e (range USD 5,000–9,000/kW_e).

7.4.2 Scaling Strategy and Roadmap

A visual scaling roadmap diagram is shown below in Figure 35, which integrates both the technical phases (TRL progression) and economic factors (CAPEX, OPEX, payback periods, and farmer affordability tiers). Assumptions are anchored to small-scale CSP/CPV rural electrification literature [134] [137].

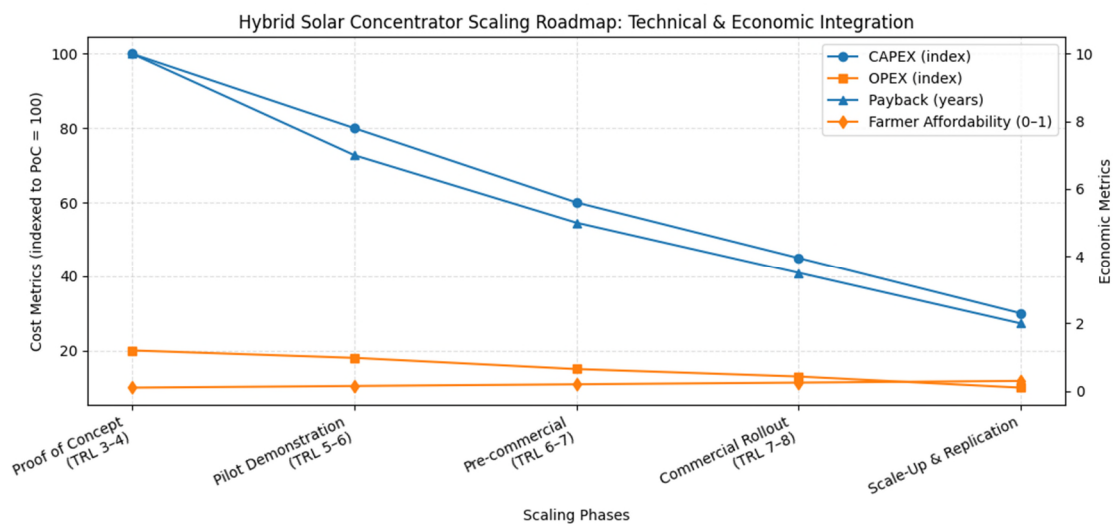


Figure 35: Evolution of indexed CAPEX/OPEX, payback period, and farmer affordability across TRL stages for the CSP/PV beam-splitting dish. Source: Author

Assumptions are anchored to small-scale CSP/CPV rural electrification literature [134] [137]. CAPEX narrowed to $\approx$ USD 5,000–9,000 per kW via subsystem cost decomposition and anticipated local-fabrication effects; values are indicative for TRL staging.

7.4.3 Data behind the chart

CAPEX index starts at 100 Proof of Concept (PoC) and declines with TRL. This corresponds to a **narrowed estimate of $\approx$ USD 5,000–9,000 per kW** at the early commercial stage, derived from **subsystem decomposition** and **analogous CPV/small-CSP rural literature** [134] [137].

7.4.4 Hardware (direct) costs

Subsystem	Basis of Estimate & Rationale	Indicative Cost (USD/kW _e)	Key Sources
Optics – Concentrator Mirrors	Imported rear-silvered glass mirrors (~40–60 USD/m ²) with local framing; 3 m dish ≈7 m ² . Early prototype cost scaled.	700–1,200	[60][134]
Spectral Splitters (Cold/Hot Mirrors)	Dichroic coatings; lab-scale quotes 100–250 USD/m ² plus protective mounts/alignment.	300–600	[117]
Dish Structure & 2-Axis Drive	Steel space frame with slew drives and actuators; local fabrication but imported drives.	800–1,300	[134], [137]
Receiver & Heat Exchanger	Medium-temp (200–300 °C) receiver tubes + insulation & HEX (~40–80 USD/m ²).	450–750	[33] [137]
Thermal Storage	Hot-water/oil tanks + valves, 30–80 USD/kWh _{th} scaled for 1–3 h.	350–750	[61]
PV Modules & Mounts	Nigeria PV ~0.35–0.45 USD/W _p + BOS 0.1–0.2 USD/W _p ; small visible-band array.	600–1,050	[141] [60]
Power Electronics	MPPTs/inverters ~0.15–0.3 USD/W _p at low volume imports.	300–500	[138]
Balance-of-Plant (BoP)	Cables, earthing, foundations; ~8–10 % of CAPEX in Nigerian mini-grids.	350–650	[141]
Controls & Instrumentation	PLC/SCADA, tracking sensors, metering ~3–6 %.	180–390	[134], [137]

Indirect / Soft Costs

Subsystem	Basis of Estimate & Rationale	Indicative Cost (USD/kW _e)	Key Sources
Engineering & Project Mgmt.	Design, QA/QC, owner's engineer; ~5–7 % typical in first-of-a-kind CSP/CPV.	240–450	[134], [137]
Installation & Commissioning	Civil works, assembly, testing, rural labour & crane hire ~6–10 %.	350–650	[141]
Transport & Logistics	Port-to-site haulage, insurance; rural last-mile premium ~3–6 %.	180–390	[60]
Duties/Taxes/Permits	Import duty/VAT if exemptions absent (0–5 %).	0–300	[142]
Contingency	FX + scope + field variance; higher for first-of-a-kind (7–12 %).	420–780	[61] [60]

Summing the hardware and soft cost categories yields an early-commercial CAPEX estimate of approximately USD 5,000–9,000 per kW_e, with a mid-point near USD 7,000/kW_e. This range is consistent with **small CPV and CSP rural electrification projects** [134], [137] and aligns with global benchmarks for early-stage solar thermal and PV balance-of-system pricing [60] [61]. As replication progresses, learning effects, local manufacturing of structural/receiver elements, and policy incentives (import duty waivers, VAT exemptions, pioneer tax holidays) are expected to drive costs towards USD 5,000–6,000/kW_e.

7.5 Policy and Market Alignment

The design supports Nigeria's **Renewable Energy & Energy Efficiency Policy (NREEEP)** and the **Rural Electrification Strategy and Implementation Plan (RESIP)**. Anchor agro-processors qualify for **Rural Electrification Agency Performance-Based Grants (PBG)**. Low OPEX and dual heat/power output align with **mini-grid and productive-use programmes** [63].

7.5.1 Policy Fit and Investment Incentives.

The proposed spectrum-splitting CSP/PV hybrid aligns well with Nigeria's Renewable Energy Master Plan (REMP) and the National Renewable Energy and Energy Efficiency Policy (NREEEP), both of which emphasize decentralized, solar-powered energy for agriculture and productive use in rural communities [143] [144]. By providing thermal energy for palm oil processing and electricity for auxiliary equipment, the system supports the Rural Electrification Agency's (REA) Mini-Grid and Productive Use programs, which aim to boost local agro-industry [145].

7.5.2 Investment Benefits and Incentives

Investors can benefit from a range of established incentives: import duty waivers and VAT exemptions on solar components under the Customs and Excise Tariff (Consolidation) Act [142]; pioneer status incentives managed by the Nigerian Investment Promotion Commission (NIPC), offering corporate income tax holidays of up to five years for renewable energy projects [146]; and favourable mini-grid feed-in tariffs along with cost-reflective tariffs under the Nigerian Electricity Regulatory Commission (NERC) Mini-Grid Regulation [147]. Moreover, projects like this can access green finance—such as Nigeria's Sovereign Green Bond — and international carbon credit markets for avoided diesel use, further enhancing investment returns. These

combined fiscal and policy measures bolster the economic rationale for local manufacturing and early deployment of the hybrid dish concentrator.

7.6 Empowering Youth for Sustainable Business Continuity.

One of the most pressing challenges in Nigeria's renewable-energy and agro-processing sectors is ensuring that businesses remain viable across generations while creating meaningful livelihoods for the country's **youthful population — over 60 % under the age of 25** and with youth unemployment historically above 30% [148]. Demonstrator projects such as the proposed **CSP/PV hybrid energy hub at Owodaiye Farms** can act as living laboratories where aspiring engineers, artisans, and farm entrepreneurs learn advanced solar fabrication, system integration, and productive-use energy management [149].

This vision of innovation as an intergenerational legacy resonates with global sustainability thinking and with the early environmental leadership of **King Charles III (then Prince Charles)**, who, under the influence of his father [150], and as early as 1970 [151], urged society to adopt sustainable practices and anticipate the long-term impact of industrial pollution. His foresight underscores the importance of **proactive stewardship** — passing on resilient, environmentally responsible enterprises to future generations.

8 Conclusion and Future Work

8.1 The Research Background

The deplorable power supply situation in Nigeria, particularly for rural communities, has been a significant obstacle to its development, especially for a region blessed with an abundance of DNI. It is important to note that energy, defined in physics, is the ability to do work [152]. The lack of it, especially at this scale, can only be concluded as an assault on a people's ability to work, and nowhere is this truer than with the rural farming community at Owodaiye Farms. Its palm oil processing factory has struggled through the decades, barely breaking even, let alone making enough profit for any form of reinvestment in this immensely profitable industry.

It is against this background that the opportunity to deploy perhaps the most innovative CSP/PV hybrid solution has come to light. This, of course, refers to the integration of spectrum beam-splitting SBS technology to attend to the dual thermal and electrical demands of palm oil processing.

8.2 Palm Oil Processing and Its Unique Energy Requirements

The study looked at the processing of palm oil, which involves significant energy demands, characterized by a ratio indicating a predominant reliance on thermal energy over electrical energy, typically averaging around 95% to 5% respectively. This stark contrast in energy demand primarily stems from the nature of palm oil processing, which includes steps such as sterilization and extraction that require substantial thermal input. This disparity initially posed a dual challenge – one of viability and feasibility. In this context, the use of biomass, the most generic system for thermal energy generation for palm oil processing, emerged as a sustainable contender. [153], particularly its capability of addressing both the thermal energy requirements and the reduction of waste associated with palm oil processing.

Biomass derived from oil palm processing—especially from residues such as empty fruit bunches, palm kernel shells, and fibers—represents a substantial resource for energy production. These materials can be converted into biofuels or used directly in thermal systems, thereby offsetting the thermal energy demand. [101]. The utilization of biomass as an energy source not only provides a route for waste valorization but also contributes to lowering greenhouse gas emissions associated with conventional energy sources. [154]. It has been estimated that significant energy

potential can be harnessed from palm oil mill residues, potentially providing a considerable amount of electricity through various thermochemical processes. [155].

8.2.1 The Case for CSP/PV Hybridisation

The unique situation at Owodaiye, where no biomass digester existed, necessitated a fundamental, and almost tailor-made, attention to its energy needs. One innovative approach to improving sustainability in palm oil processing was the integration of concentrated solar power (CSP) with photovoltaic (PV) systems. Such hybrid systems are helpful not only for their complementary energy characteristics—CSP provides thermal energy while PV caters to electrical needs—but also for enhancing overall energy efficiency and reliability. [44]. This singularly spelled out the aims and objectives for this study.

8.3 Summary of Contributions

This Engineering Doctorate (EngD) research has successfully demonstrated the design, development, and proof-of-concept validation of a hybrid solar energy system that integrates Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies through spectrum beam splitting (SBS). By incorporating hot and cold mirrors to achieve spectral separation, the hybrid system maximizes energy utilization by directing infrared (IR) radiation to thermal receivers and visible light to photovoltaic cells. This innovation directly addresses the unique energy challenges faced by palm oil processing farms in Southwest Nigeria, particularly at Owodaiye Farms, which served as the study site and deployment model.

The study is structured across several technical domains: solar resource assessment, optical system modelling, thermal-electric energy ratio evaluation, component sizing, experimental validation, and business model innovation. Laboratory results confirmed that combining hot and cold mirrors in a hybrid configuration significantly improved electrical yield (peaking at 19.5 mA at 28.5°C), validating the effectiveness of spectrum separation under equidistant alignment and controlled optical angles. The engineering model projected system-wide efficiencies of over 30%, which is a notable achievement in the tropical energy context.

Furthermore, the project explored the hybrid system's business model potential as a community-scale demonstrator and educational tool, proposing scalable deployment through modular kits and partnerships with agricultural cooperatives and educational institutions.

8.4 Engineering and Sustainability Impact

The hybrid CSP/PV system developed in this work represents a unique convergence of optical physics, renewable energy engineering, and agro-industrial sustainability. It has addressed issues such as **dual-output generation**, a concept that efficiently produces both electricity and process heat from solar input, matching the thermal-electricity demand profile of palm oil processing (95:5 ratio). **Thermal decoupling** prevents PV overheating by separating IR radiation early, maintaining higher PV performance. **System modularity** offers the opportunity for distributed deployment across farm clusters in off-grid or semi-grid rural areas.

Climate resilience has helped with reduced dependence on firewood and diesel, promoting decarbonization and biodiversity preservation. Local empowerment has positioned Owodaiye Farms as a knowledge-transfer hub for surrounding farming communities, aligned with Nigeria's renewable energy access goals.

8.4.1 Limitations of the Study

Despite these advances, several limitations remain. These include **material degradation**, where the long-term performance of optical filters in humid and dusty tropical environments requires further testing. **Scalability**: While a 3m dish configuration was validated as a preliminary design pathway, the full system behavior under higher power presents a case for prototyping. **Energy storage** has not been explored, and these are solutions that are essential for nighttime or cloudy-day operation.

8.5 Future Work and Development Pathways

Several research and development opportunities arise from this work:

8.5.1 Crude Sunlight Refinery Development

One of the most promising ideas emerging from this study is the evolution of the hybrid CSP/PV dish into a "Crude Sunlight Refinery". Just as crude oil is refined into multiple products (variations), based on a similar filtering of its components at various temperature levels, this system could be developed further to extract multiple energy dividends from full-spectrum solar input. Some of which would include the likes of:

Table 11: Possible Derivatives from a Crude Sunlight Refinery Endeavour

Property:	Type / Value:
Visible light	Electricity (via CPV)
Near IR	medium-temperature thermal (for steam generation)
Far IR	low-grade heat (for drying, fermentation, sterilization)
UV	photochemical applications (e.g., solar disinfection, photocatalysis)

This vision would require advanced optical coatings, adaptive mirror technologies, and perhaps multispectral receivers integrated into a unified facility. It would be a game-changer for off-grid industrialization in Africa.

8.5.2 Role of Semi-Metals (Metalloids) in CSP/PV Optimisation

The nature of these elements, including Silicon, Barium, and Germanium, along with their inherent semiconductor (or innate beam splitting) properties, holds great potential for dissipating energy under CSP conditions. Their molecular structures are designed so that when exposed to concentrated sunlight, they display behaviours that produce sustainable energy levels yet remain largely untapped.

8.6 Final Remarks

This EngD project has delivered a significant contribution to the innovative concept of solar energy systems for agro-industrial use in the Global South. Based on experimental work in science and initiated by a real-world need, the hybrid spectrum-splitting CSP/PV system demonstrates that interdisciplinary solutions can emerge from essential, local challenges.

The demonstrator at Owodaiye Farms offers more than just energy savings; it tells a new narrative of solar empowerment, regenerative farming, and rural transformation. Future work will continue this trajectory, aiming to transform sunlight—in its purest, "crude" form—into the lifeblood of local economies.

This work is, therefore, dedicated to the vision of sustainable development through engineering, pioneering foresight and ingenuity, local collaboration, and the sun's limitless potential.

9 References

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Appendix A



14 May 2025

Dear Mr Banjoko ,

Reference: CURES/25141/2025

Project ID: 28637

Title: Design of a Proof-of-Concept Hybrid Solar Concentrator System
Utilising Spectrum beam Splitting Technology to generate sustainable heat and
electricity, for palm oil processing farms in Nigeria

Thank you for your application to the Cranfield University Research
Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/25141/2025 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B:

Table 3.1: It highlights the daily average solar radiation available at the location of interest.
[89] [92]

Month:	representative day of the month	tmy ERA5 (2007-2022)		tmy SARA6 (2007-2023)		month ERA5 (2020-2023)		month SARA6 (2020-2023)	
		DNI [kWh/d m ²]	amb Temp [°C]	DNI [kWh/d m ²]	amb Temp [°C]	DNI [kWh/d m ²]	amb Temp [°C]	DNI [kWh/d m ²]	amb Temp [°C]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
January	17	154.7	30.47	191.0	30.44	191.88	27.85	163.7	27.85
February	16	182.9	31.82	157.7	31.39	165.44	28.38	138.5	28.38
March	16	173.2	31.13	115.9	29.27	131.66	28.03	98.6	28.03
April	15	152.5	28.61	171.7	28.61	119.04	27.83	114.9	27.83
May	15	91.9	28.72	115.3	26.29	108.55	27.18	120.6	27.18
June	11	5.6	24.94	37.7	24.94	77.41	25.70	86.3	25.70
July	17	81.9	25.59	102.6	25.59	83.48	25.08	69.8	25.08
August	16	114.3	25.65	23.0	25.61	76.95	24.85	64.4	24.85
September	15	31.0	25.26	58.5	25.77	72.28	25.20	71.8	25.20
October	15	89.9	27.27	65.3	27.27	97.36	26.15	108.6	26.15
November	14	157.2	28.58	161.1	28.39	131.74	27.03	139.4	27.03
December	10	152.2	29.03	210.4	28.43	175.36	27.25	168.2	27.25

Note: The DNI values are daily data, modelled on the mentioned day.

column (2) [92]

Remaining data: [89]

model typical meteorological year (**tmy**)

all ambient temperatures are averaged by the use of **only** daylight values (DNI > 0)