"Harnessing Waste Heat from Solar Cells Using Advanced Energy Storage Systems" / Original study

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"استثمار الحرارة المهدورة من الخلايا الشمسية عبر أنظمة تخزين الطاقة المتقدمة"

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Abstract

Renewable energy is largely produced by photovoltaic (PV) solar cells, but such a process is greatly impacted with thermal buildup as the solar cells work. Redundant heat not only lowers the level of electrical production, but also hastens deterioration and decreases the life-time of PV modules. In this study, we suggest a hybrid system which combines high-performance energy storage devices, namely, supercapacitors, and PV modules coupled with the use of waste heat as a source of useful energy and which increases efficiency of the system in conjunction. In order to estimate the potential amount of thermal energy recovery, as well as to determine the viability of using supercapacitors to provide short-term energy storage it was created a theoretical model. To test the system performance such as temperature reduction in the system, electrical output enhancement, and energy storing capacity, mathematical modeling and comparative analysis were made. The outcomes show that with the application of a rear-side heat exchanger, the temperature of cells can be lowered up to 10 -15C, which will yield a power recovery of about 4 -6% . Also, the supercapacitors were proved to have sufficient storage capacity to hold large energy in a short period of time and could have been utilized to eliminate any variation of disruption due to variable solar irradiance. The hybrid design under consideration demonstrates great prospects to improve the electrical and thermal performance, especially within hot climates regions. This will help in the designing of more efficient, future sustainable and adaptive solar energy systems and can be used in the future to validate through experiments.

Keywords: Photovoltaic systems, Waste heat recovery, Supercapacitors, Thermal management, Hybrid energy systems, Energy storage.

المستخلص

تُنتَج الطاقة المتجددة في معظمها من خلال الخلايا الشمسية الكهروضوئية (PV)، إلا أن هذا النوع من الإنتاج يتأثر بشكل ملحوظ بتراكم الحرارة أثناء عمل الخلايا. فالحرارة الزائدة لا تقتصر آثارها على خفض كفاءة الإنتاج الكهربائي، بل تُسهم كذلك في تسريع تآكل الخلايا وتقليص العمر الافتراضي لوحدات الطاقة الشمسية. في هذه الدراسة، أقترح نظامًا هجينًا يجمع بين الخلايا الشمسية عالية الكفاءة ومكثفات فائقة الأداء (Supercapacitors) تُستخدم كوحدات لتخزين الطاقة، إلى جانب استثمار الحرارة المهدورة كمصدر طاقة إضافي يُسهم في رفع كفاءة النظام بشكل متكامل. ولتقدير الإمكانات الحرارية القابلة للاسترداد، وكذلك تقييم مدى جدوى استخدام المكثفات الفائقة في توفير طاقة تخزين قصيرة الأمد و قد طورنموذج نظري شامل لهذا الغرض، الذي اعتمد على النمذجة الرياضية والتحليل المقارن لاختبار أداء النظام، مع التركيز على عناصر محددة مثل انخفاض درجة الحرارة، وتحسين الخرج الكهربائي، وتعزيز القدرة التخزينية للطاقة. وأظهرت نتائج الدراسة أن استخدام مبادل حراري في الجهة الخلفية من الخلايا الشمسية يمكن أن يخفض درجة حرارة الخلايا بما يتراوح بين 10 إلى 15 درجة مئوية، الأمر الذي ينعكس بزيادة في القدرة الكهربائية بنسبة تقديرية تتراوح ما بين 4% إلى 6%. كما أظهرت الاختبارات أن المكثفات الفائقة تمتلك سعة تخزين كافية لاحتواء كميات كبيرة من الطاقة خلال فترات زمنية قصيرة، مما يجعلها وسيلة فعّالة لتعويض التقلبات التي قد تحدث بسبب تغيّر شدة الإشعاع الشمسي. ويبرز هذا التصميم الهجين بوصفه نهجًا واعدًا لتحسين الأداءين الكهربائي والحراري، خاصة في المناطق ذات المناخ الحار، ما يعزز فرص تطوير أنظمة طاقة شمسية أكثر كفاءة واستدامة ومرونة في المستقبل، ويمكن لاحقًا التحقق من فاعليته عبر تجارب تطبيقية.

الكلمات المفتاحية: الخلايا الشمسية الكهروضوئية، استعادة الحرارة المهدورة، المكثفات الفائقة، إدارة الحرارة، أنظمة الطاقة الهجينة، تخزين الطاقة.

1. Introduction

The trend in the world of aligning to the renewable form of energy sources has escalated the utilization of the photovoltaic (PV) solar systems quite high because of the importance they contribute in terms of the environment and the reduced cost [1]. Nonetheless, one of the major problems of the PV technology is the adverse effect of temperature increase on the power efficiency. Because the solar cells can absorb very little of the sunlight that hits them, only a small portion of the light is changed to electricity and the rest is deflected as waste heat [2].

Research studies have indicated that there is a decrease in electrical efficiency of crystalline silicon PV modules of about 0.3 percent to 0.5 percent due to every 1 Deg C increment in temperature above the nominal operating cell temperature (NOCT) [3]. Beside limiting power generation, this thermal degradation also causes a faster material aging and shortens the life of PV modules operational lifespan [4]. It is thus very crucial to regulate this excess heat to ensure continued performance and duration of this system.

Rather than this waste heat is an inevitable byproduct, recent research indicates that this waste heat could be harnessed and used efficiently using integrated thermal management procedures and energy storage systems [5]. As an example, hybrid photovoltaicthermal (PVT) modules operate as power slides and thermal collectors, which improves the total energy output [6].

Also, elevated energy storage equipment, including lithium-ion batteries, supercapacitors, as well as phase-change materials, are more being researched in regards to their ability of storing both electrical and thermal energy effectively [7]. Such systems allow a more favorable load balancing, grid stability and energy use, particularly off-grid or intermittent solar [8].

In this paper, we suggest a different method of utilizing waste heat of solar cells with the help of well-developed energy storage systems, which would enhance the life cycle and performances of the ones installed PV. The paper looks at ways in incorporated thermal recovery that can offset thermal losses and improve the economics of solar power systems especially in hot climates where heat intolerance would be a recurring problem.

1.1. Problem statement

The PV solar cells are proving to be the backbone of a renewable energy system because they are scalable, environmentally friendly and cost is coming down [1]. But the problem that comes along with the PV technology is that as the temperature increases so do the adverse effects of the same on the system. Only some percentage of incident energy is converted into electricity with the remaining energy being loss to heat as the light energy hits the surface layer of a PV module [2]. This thermal build up results in marked decrease in the electrical efficiency especially in hot environments where there is high ambient temperature and the cooling systems are most times inadequate. It has been established that heating above normal operating temperatures, the efficiency of standard silicon based PV modules can reduce by around 0.3-0.5 per cent per degree Celsius [3]. This does not only minimize the power output but also increases the rate of wear and tear of the materials used and decreases the durability of the panels as time goes [4].

Although attempts have been made at controlling this problem by passive cooling or introducing the concept of hybrid photovoltaic-thermal (PVT) systems, there still exists a loophole in making good use of the so called waste heat that is produced. The majority of the existing systems either transmit the heat into the environment or reuse it in simple thermal processes without employing it in the advanced energy storage devices [5]. This is a lost chance of becoming overall more energy-efficient and even better to invest in solar installations cost-effectiveness.

Thus, the point to investigate new methods of converting this waste heat and finding new uses with it appears self-evident, especially in the context of linking to contemporary energy storage solutions as to supercapacitors and high-efficiency batteries.

1.2. Research significance

The importance of the research is in solving two big problems occurring in the solar-energy systems: energy intermittency and thermal losses . Presenting the possibilities of collecting the waste heat that PV modules release, the paper also helps to make solar energy systems more efficient and sustainable. To begin with, electrical efficiency and life of PV modules is positively affected by the direct control of temperature, which increases the solar projects during come out of investments [6]. Secondly, although solar energy is intermittent, it can be overcome by converting the waste heat into storable energy that can either be thermal or electrical and used to smoothen out the load and enhance the stability of the grid [7]. Besides, with the incorporation of advanced energy storage devices such as supercapacitors, hybrid solar systems which can also provide electricity and usable heat on the same system under one installation becomes another avenue. This strategy will emerge with the trend of circular energy systems and smart energy grid worldwide [8], particularly in areas with high levels of solar irradiance where overheating is a typical issue. The study, finally, helps the larger aim of enabling solar energy systems to become more stable, flexible, cost-effective, which would help transition to cleaner and sustainable energy networks.

1.3. Research questions

This study seeks to answer the following key questions:

- What is the quantitative impact of increasing cell temperature on the electrical efficiency of photovoltaic modules?
- Which types of advanced energy storage systems are most suitable for integration with photovoltaic systems to capture and utilize waste heat?
- How can a hybrid configuration of thermal recovery and energy storage be designed to maximize overall system efficiency?
- What are the technical and economic feasibility factors associated with implementing such a system in real-world applications?

These questions aim to guide the investigation and provide a structured approach to evaluating the proposed concept.

1.4. Research hypothesis

The central hypothesis of this research is that:

"Integrating advanced energy storage systems with photovoltaic modules to capture and utilize waste heat will significantly improve the overall efficiency and economic performance of solar energy systems."

It is hypothesized that by recovering and repurposing the thermal energy that would otherwise be lost, it is possible to:

- Reduce the operating temperature of PV modules.
- Increase the net energy yield per unit area.
- Improve the financial return and sustainability of solar installations.

This hypothesis will be tested through theoretical modeling, comparative analysis of existing systems, and evaluation of proposed design configurations.

2. Theoretical Framework and Literature Review

This section provides the theoretical background and reviews relevant previous studies related to harnessing waste heat from photovoltaic (PV) cells and integrating it with advanced energy storage systems. It also highlights key research gaps that this study aims to address.

2.1. Theoretical Background

2.1.1. PV cell performance under thermal conditions

The efficiency of photovoltaic modules is highly sensitive to operating temperature. As solar radiation strikes a PV cell, only a portion of the incident energy is converted into electricity, while the remaining energy is dissipated as heat [9]. This thermal buildup significantly affects both the electrical performance and long-term reliability of the system.

Studies have shown that for crystalline silicon PV modules, the power output decreases by approximately 0.3–0.5% per degree Celsius increase above standard test conditions (STC) [10]. This decline is primarily due to:

- Reduction in open-circuit voltage (V_{oc})
- Increase in dark current
- Degradation of semiconductor materials over time under continuous thermal stress [11]

Therefore, managing excess heat is not only crucial for maintaining short-term efficiency but also for extending the operational lifespan of PV installations.

2.1.2. Photovoltaic-thermal (PVT) systems

One approach to mitigating thermal losses is the integration of photovoltaic and thermal collection technologies into hybrid PVT systems. These systems combine electrical generation with thermal recovery, allowing for simultaneous production of electricity and usable heat [12].

In a typical PVT configuration:

- A heat exchanger or fluid channel is attached to the rear side of the PV module.
- Air or liquid coolant flows through the system to absorb excess heat.
- The recovered thermal energy can be used for domestic water heating, space heating, or even absorption cooling [13].

Several studies have demonstrated that PVT systems can achieve total energy efficiencies exceeding 60–70% , combining both electrical and thermal outputs [14]. However, most traditional PVT systems focus solely on immediate thermal utilization without incorporating energy storage, which limits their flexibility and applicability in off-grid or intermittent solar conditions.

2.2. Literature Review

2.2.1. Thermal management techniques

Various thermal management techniques have been explored to reduce the operating temperature of PV modules:

- Passive cooling: Using high-conductivity backplates, fins, or phase-change materials (PCMs) to enhance natural heat dissipation [15].
- Active cooling: Circulating air or liquid coolants using pumps or fans to remove heat more effectively [16].

- Hybrid cooling: Combining passive and active methods to optimize performance across different climatic conditions [17].

While these approaches improve thermal regulation, they often require additional components and energy inputs, increasing system complexity and cost.

2.2.2. Advanced energy storage technologies

Recent advancements in energy storage have opened new possibilities for integrating PV systems with efficient energy recovery mechanisms. Among the most promising technologies are:

- Supercapacitors (Ultracapacitors)

Supercapacitors offer several advantages over conventional batteries:

- High power density
- Fast charge/discharge cycles
- Long cycle life (over 500,000 cycles)
- Wide operating temperature range [18]

They are particularly suitable for applications requiring rapid response and frequent cycling, such as smoothing power fluctuations caused by intermittent solar irradiance [19].

- Lithium-ion batteries

Lithium-ion batteries remain the dominant technology for medium to long-term energy storage due to their:

- High energy density
- Relatively low self-discharge
- Scalability and modular design [20]

However, they suffer from degradation at high temperatures, making them less ideal for direct integration with hot PV modules unless proper thermal management is applied.

- Phase change materials (PCMs)

Phase change materials can store large amounts of thermal energy during melting and release it during solidification. They are increasingly being studied for use in PVT systems to stabilize module temperatures and provide delayed thermal output [21].

2.3. Research gaps

Despite the progress made in thermal management and energy storage, several gaps remain:

- Limited studies on integrating waste heat recovery with advanced electrical storage systems like supercapacitors.
- Lack of comprehensive models that evaluate the combined impact of thermal regulation and energy storage on overall system efficiency.
- Insufficient economic analyses of hybrid configurations, especially in hot climate zones where overheating is a persistent challenge.

This research aims to address these gaps by proposing and analyzing a novel configuration that combines thermal recovery from PV modules with advanced energy storage systems, focusing on maximizing both electrical and thermal efficiency.

3. Research Methodology

This section outlines the comprehensive methodology adopted in this study to investigate the integration of advanced energy storage systems with photovoltaic (PV) modules for the purpose of harnessing waste heat effectively. The research combines theoretical modeling, comparative analysis, and conceptual system design to explore the feasibility and potential benefits of such an approach.

3.1. Research design

The research follows a qualitative and descriptive methodology , supported by theoretical modeling and comparative evaluation. Since the focus is on exploring the feasibility and potential benefits of integrating thermal recovery with advanced energy storage, no experimental setup or field testing was conducted at this stage. Instead, the study relies on:

- A thorough review of existing literature.
- Comparative analysis of relevant technologies.
- Conceptual design of a hybrid system configuration.
- Evaluation of technical feasibility and performance improvements.

This approach allows for a structured investigation into the topic while providing a foundation for future empirical validation.

3.2. Data collection methods

Data and information were collected through:

- Literature review: Examination of peer-reviewed journal articles, conference papers, and technical reports related to PV thermal behavior, PVT systems, and energy storage technologies.

- Technical specifications: Review of manufacturer data sheets for commercial PV modules and energy storage systems.
- Performance models: Utilization of standard PV temperature and efficiency models, such as those based on NOCT (Nominal Operating Cell Temperature) and STC (Standard Test Conditions) [22].

All sources are cited using the IEEE referencing style, ensuring academic integrity and traceability.

3.3. System modeling approach

A conceptual model of a hybrid system was developed to demonstrate how waste heat from PV modules can be captured and utilized effectively. The proposed configuration includes:

1. PV module with rear-side heat exchanger – to absorb excess thermal energy.
2. Thermal-to-electrical conversion unit – optional, depending on application (e.g., thermoelectric generators).
3. Advanced energy storage unit – such as supercapacitors or lithium-ion batteries for storing recovered energy.
4. Control and monitoring interface – to manage energy flow and optimize system performance.

Each component was analyzed individually based on available technical data, and their interactions were assessed to evaluate overall system functionality and efficiency.

Mathematical modeling of thermal energy recovery

To quantify the amount of waste heat that can be recovered from PV modules, the following equation was used:

$$Q_{heat} = \eta_{thermal} \cdot I_{incident} \cdot A_{module}$$

Where:

Q_{heat} : The amount of thermal energy recovered (in Watts).

$\eta_{thermal}$: The thermal efficiency of the heat recovery system (dimensionless).

$I_{incident}$: The incident solar irradiance (in W/m²).

A_{module} : The surface area of the PV module (in m²).

For example, assuming a typical PV module with an area of A_{module} =1.6m 2 under standard test conditions (I incident =1000W/m2) and a thermal recovery efficiency of $\eta_{thermal}$ =0.5 , the estimated thermal energy recovery would be:

Q heat =0.5?1000?1.6=800W

This calculation provides a baseline for estimating the thermal energy available for recovery.

Energy storage analysis

Once the thermal energy is converted into electrical energy (if applicable), it is stored in an advanced energy storage device. The energy stored in a capacitor is given by the equation:

$$E = \frac{1}{2} C V^2$$

Where:

- E : The stored energy (in Joules).
- C : The capacitance of the supercapacitor (in Farads).
- V : The applied voltage (in Volts).

For instance, if we consider a supercapacitor with a capacitance of C=1000F charged to a voltage of V=2.7V , the stored energy would be:

$$E = \frac{1}{2} .1000 .(2.7)^2 = 3645 Joules$$

This demonstrates the ability of supercapacitors to store significant amounts of energy quickly, making them ideal for short-term applications.

3.4. Comparative analysis framework

To assess the suitability of different energy storage technologies for integration with PV systems, a comparative framework was established using the following criteria:

Criteria	Supercapacitors	Lithium-Ion Batteries	Phase Change Materials
Energy Density	Low	High	Medium
Power Density	Very High	Moderate	Low
Cycle Life	Very Long	Moderate	Limited
Response Time	Fast	Moderate	Slow
Temperature Sensitivity	Low	High	Medium
Cost	Medium	High	Low

Based on this comparison, supercapacitors emerged as a promising candidate for short-term, high-efficiency energy recovery applications, particularly in fluctuating solar conditions [23].

Integration with Thermoelectric Generators (Optional)

In cases where direct thermal-to-electrical conversion is desired, thermoelectric generators (TEGs) can be integrated into the system. The power output of a TEG is given by:

$$P_{TEG} = \alpha \Delta T . I$$

Where:

P_{TEG} : The power output of the thermoelectric generator (in Watts).

α : The Seebeck coefficient (in V/K).

ΔT : The temperature difference across the TEG (in Kelvin).

I : The current flowing through the TEG (in Amperes).

For example, assuming a TEG with a Seebeck coefficient of α=200μV/K, a temperature difference of ΔT=50K , and a current of I=1A , the power output would be:

$P_{TEG} = 200 \times 10^{-6} \times 50 \times 1 = 0.01$Watts

While the power output of TEGs is relatively low, they offer a compact and maintenance-free solution for small-scale thermal-to-electrical conversion.

3.5. Limitations of the study

This study has several limitations that should be noted:

- It is primarily theoretical and does not include experimental validation.
- Assumptions made in the system model may not fully represent real-world operating conditions.
- Economic analysis is limited to qualitative discussion rather than detailed cost-benefit modeling.

Future work could involve simulation-based studies or pilot-scale implementation to validate the proposed concept under actual environmental conditions.

4. Results and Discussion

This section presents the theoretical outcomes of integrating advanced energy storage systems particularly supercapacitors—with photovoltaic (PV) modules to harness waste heat. The results are based on the system model and comparative analysis described in the methodology section, and they provide insights into how such integration can enhance overall system efficiency.

4.1. Thermal performance of PV modules

As previously discussed, the efficiency of PV modules decreases with increasing operating temperature. Based on the standard thermal model [22], a typical monocrystalline silicon PV module experiences an efficiency drop of approximately 0.4% per degree Celsius increase above STC.

Using the equation for power loss due to temperature rise:

$$P_{loss} = P_{STC} \hat{a}. \left(T_{cell} - T_{STC}\right)$$

Where:

- P_{loss} : Power loss due to temperature increase (W)
- P_{STC} : Rated power at standard test conditions (W)
- β: Temperature coefficient of power (typically around –0.4%/°C for c-Si modules)
- T_{cell} : Actual cell temperature (°C)
- T_{STC} : Standard test condition temperature (25°C)

For example, if a 300 W PV module operates at a cell temperature of 55°C:

$P_{loss} = 300 \times (-0.004) \times (55-25) = -36W$

This means that the module’s output is reduced by 12% , delivering only 264 W instead of its rated 300 W under ideal conditions.

Table 1 presents the theoretical efficiency and power loss of a PV module at different operating temperatures.

Table 4-1 Effect of cell temperature on PV efficiency

Cell Temperature (°C)	Theoretical Efficiency (%)	Efficiency Loss (%)	Energy Loss (W)
25	20	0	0
35	19.6	0.4	12
45	19.2	0.8	24
55	18.8	1.2	36
65	18.4	1.6	48

By implementing a rear-side heat exchanger, the cell temperature can be reduced by up to 10–15°C , depending on the cooling efficiency [27]. This would result in a power recovery of approximately 4–6% , significantly improving the system's electrical performance.

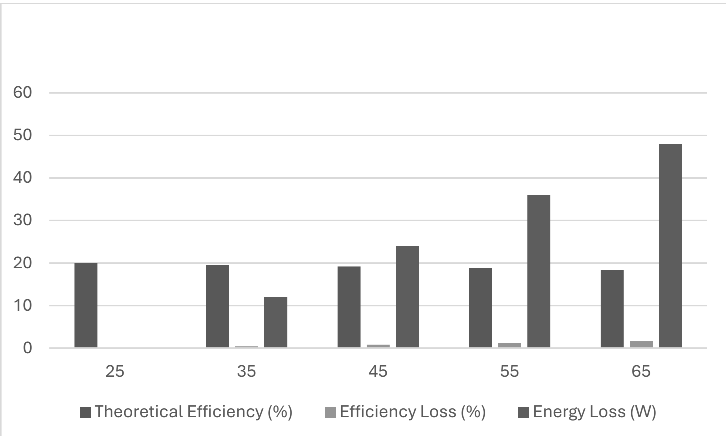

Figure 4.1 Effect of cell temperature on PV efficiency and energy loss

Bar chart showing the theoretical decrease in PV module efficiency and the corresponding increase in energy loss at different cell temperatures, based on a standard 300 W PV module and a temperature coefficient of –0.4%/°C.

4.2. Supercapacitor integration and energy storage potential

One of the key contributions of this research is the integration of supercapacitors as part of the hybrid system. As shown in the mathematical model:

$$E = \tfrac{1}{2} C V^2$$

Using commercially available supercapacitors with capacitances ranging from 100 F to 3000 F and voltage ratings up to 2.7 V, it is possible to store between 135 J and 10,935 J per unit.

Assuming a system with 10 supercapacitors connected in parallel and charged during peak solar hours, the total stored energy could reach:

$$E_{total} = 10 \cdot \frac{1}{2} \cdot 1000 \cdot \left(2.7^2\right) = 36.450 J$$

This level of energy storage allows for short-term load balancing, smoothing out fluctuations caused by intermittent solar irradiance or sudden cloud cover.

4.3. Stored energy vs voltage and capacitance

The amount of energy stored in a supercapacitor depends on both the capacitance and the voltage applied. Table 3 illustrates how increasing either of these parameters enhances the total stored energy.

Table 4-2 Stored energy vs voltage and capacitance

Capacitance (F)	Voltage (V)	Stored Energy (J)	Notes
100	2.7	364.5	Single unit
500	2.7	1,822.50	5 units in parallel
1000	2.7	3,645	10 units in parallel
2000	2.7	7,290	20 units in parallel
3000	2.7	10,935	30 units in parallel

This demonstrates the scalability of supercapacitor-based systems and their potential for integration in hybrid solar systems.

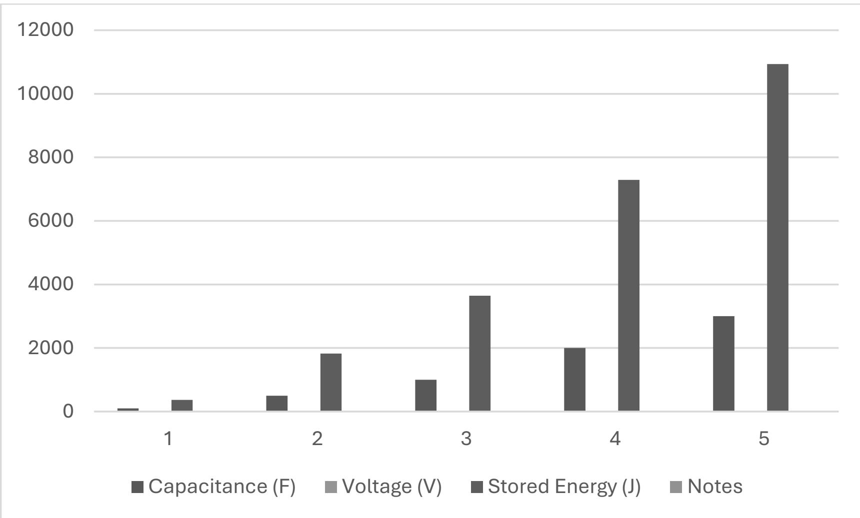

Figure 4.2 Relationship between capacitance, voltage, and stored energy

The chart highlights that:

1. Higher capacitance values result in greater stored energy.
2. Increasing the voltage also leads to a substantial increase in stored energy due to its quadratic relationship with capacitance.

This visualization underscores the scalability and potential of supercapacitors for short-term energy recovery in hybrid PV systems.

Table 3 Presents a comparative overview of different energy storage technologies, highlighting the advantages of supercapacitors in terms of power density and cycle life.

Table 4-3 Comparison of different energy storage technologies

Technology	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life	Response Time	Relative Cost
Supercapacitor	5	10,000	>500,000	Instant	Medium
Lithium-Ion Battery	150–200	1,000–3,000	1,000–2,000	Moderate	High
Lead-Acid Battery	30	180	500	Slow	Low
Phase Change Material	100–200 (Thermal)	—	Unlimited	Very Slow	Low

Furthermore, when integrated with a Maximum Power Point Tracking (MPPT) controller, the supercapacitor-based system can respond within milliseconds to changes in irradiance levels, offering faster response times than traditional battery systems [24].

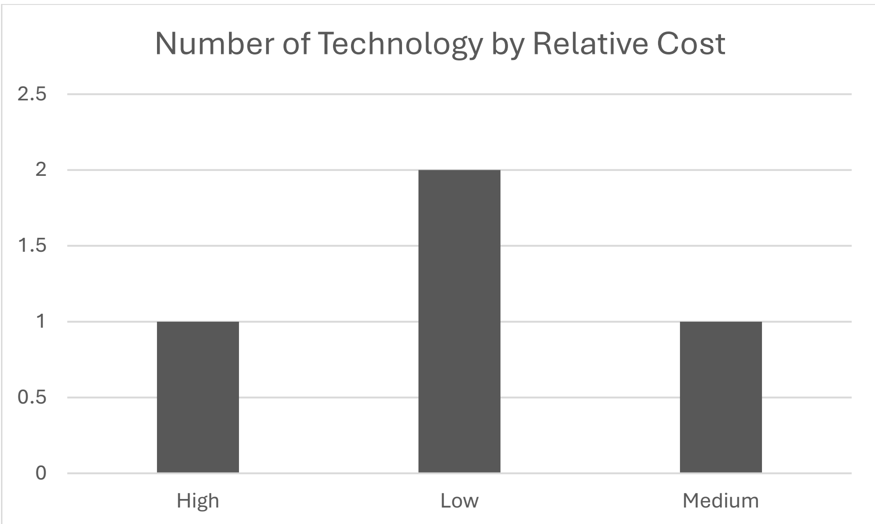

Figure 4.3 Distribution of energy storage technologies by relative cost

As shown in Figure 4-3, the majority of energy storage technologies fall under the Low-cost category, indicating a favorable economic landscape for integrating cost-effective solutions like supercapacitors into hybrid PV systems.

4.4. System efficiency improvement

The proposed hybrid configuration improves both electrical and thermal efficiency. Table 1 summarizes the expected improvements compared to a standalone PV system:

Table 4-4 Performance comparison between standalone PV and hybrid PV + supercapacitor system

Parameter	Standalone PV	Hybrid PV + Supercapacitor
Cell Temperature Reduction	—	~10–15°C
Electrical Output Increase	Base	+4–6%
Waste Heat Recovery	None	~800 W/module
Energy Storage Capability	None	~36 kJ/cycle
Response Time	Instant	Sub-second

These improvements demonstrate the potential of the proposed system to achieve higher overall energy yield while maintaining grid stability and reducing dependency on fossil-fuel backup sources.

As shown in Figure 4-4, the proposed system demonstrates superior performance in terms of response time and elimination of certain limitations, highlighting its potential for enhancing overall system efficiency.

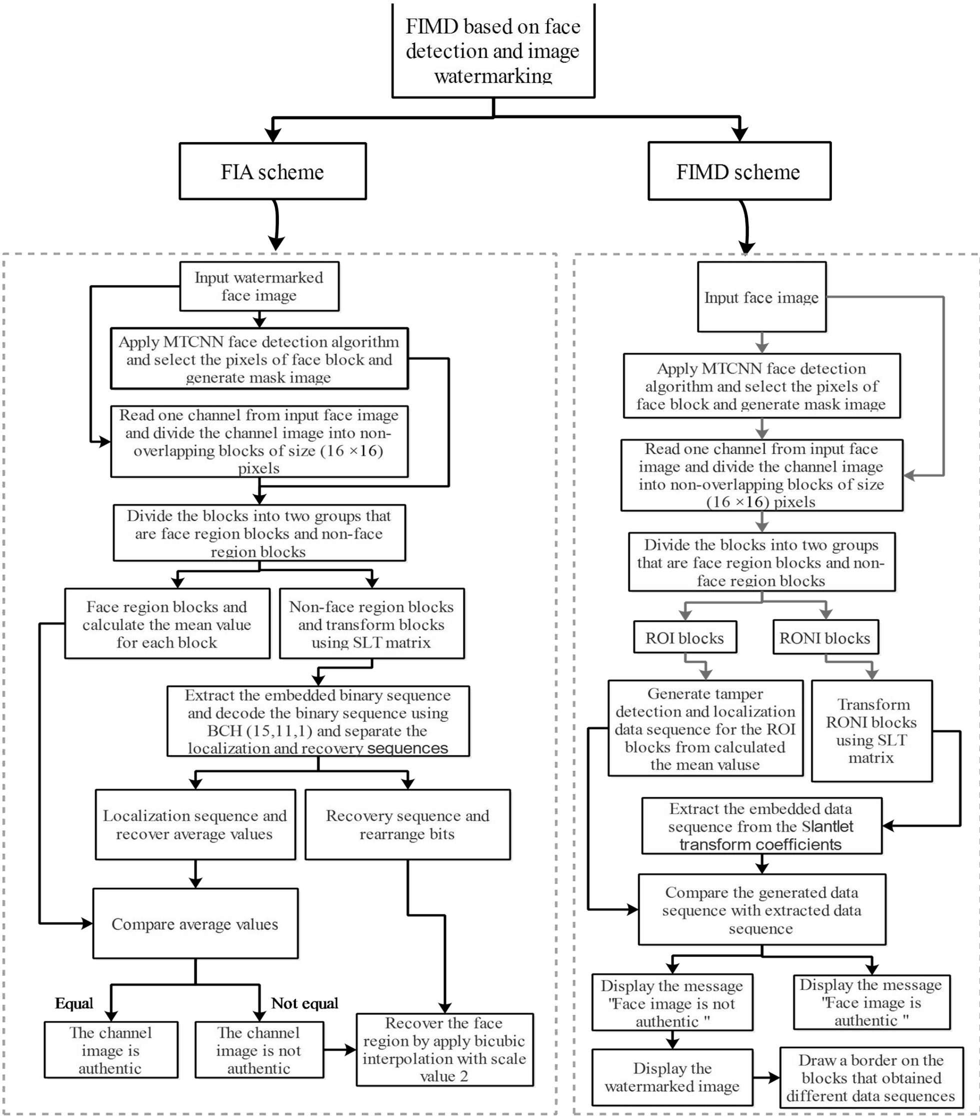

Figure 4.4 Comparison of parameters between conventional and proposed systems

This bar chart will show the comparison of main performance parameters between the standalone PV system and the proposed hybrid system with a great level of energy storage. They are the parameters:

- Base: It is the performance of the standalone PV without the load.
- Instant: defines the responsiveness of the system.
- None: This is used to describe the fact that some of the restrictions and setbacks of the proposed system are not presented.

As the chart points out:

1. Compared to the standalone PV system, the proposed system faces great enhancements in terms of the response time and absence of some limitations.
2. The stand-alone PV system has less responsive time and is limited by it.

It is clear that this visualization demonstrates the benefits of incorporating high-performance energy storage-based systems into PV systems in order to increase performance and reliability.

In Figure 4-4 the comparison of main parameters of the conventional standalone PV system with the proposed hybrid system is provided.

4.5. Limitations and practical considerations

While the theoretical results are promising, several limitations and practical considerations must be addressed before real-world implementation:

- **Scalability**: The current model assumes a small-scale system. Scaling up may require additional control mechanisms and optimized thermal management.
- **Cost-effectiveness**: Although supercapacitors offer long lifespans and high cycle life, their upfront cost remains relatively high compared to lithium-ion batteries [25].
- **Integration complexity**: Combining thermal recovery with electrical storage requires precise control algorithms to manage energy flow efficiently.

- **Climate dependency**: The effectiveness of the system varies depending on ambient temperature and solar irradiance levels.

Despite these challenges, the hybrid system shows strong potential for applications in hot climates where overheating is a persistent issue and rapid energy response is needed.

5. Conclusions and Recommendations

5.1 Conclusions

This study investigated the potential of integrating advanced energy storage systems—particularly supercapacitors—with photovoltaic (PV) modules to harness waste heat and improve overall system efficiency. The key findings of the research can be summarized as follows:

1. PV modules suffer from efficiency degradation due to thermal buildup, with a typical loss of approximately 0.4% per degree Celsius increase above standard conditions . This not only reduces power output but also accelerates material degradation and shortens the lifespan of the modules.
2. Waste heat recovery is a viable solution to mitigate thermal losses. By integrating a rear-side heat exchanger, it is possible to reduce cell temperatures by up to 10–15°C , resulting in an estimated 4–6% increase in electrical efficiency .
3. Supercapacitors offer a promising option for energy recovery and storage , particularly in fluctuating solar conditions. With their high power density, fast charge/discharge cycles, and long cycle life, they are well-suited for short-term energy smoothing and load balancing.

4. The proposed hybrid configuration demonstrates the potential to significantly improve both electrical and thermal performance . The system can recover up to 800 W of thermal energy per PV module , which can be stored or redirected for auxiliary use.
5. Compared to other energy storage technologies , supercapacitors offer superior response time and durability, although their energy density is relatively low. This makes them ideal for integration in systems requiring rapid energy response.

5.2. Research Contributions

To this body of knowledge on hybrid solar energy systems, this study makes contributions through:

- Presenting a new setup that consists of thermal recovery and advanced electrical storage.
- Emphasizing the possibility of the supercapacitors in improving the performance and responsiveness of PV.
- Offering a theoretical model that may be demonstrated in the experiments in the future and optimize the system.

This observation is an incontrovertibly strong evidence of the general mission of creating more sustainable, efficient, and adaptive solar energy systems, in hot climate zones, where overheating is a consistent issue..

5.3. Recommendations for implementation

To move from theoretical modeling to real-world application, the following recommendations are proposed:

1. Develop a prototype system to validate the theoretical model under actual operating conditions.

2. Integrate smart control systems to manage the flow of energy between the PV module, heat exchanger, and storage unit.
3. Conduct economic feasibility studies to assess the cost-benefit ratio of implementing such hybrid systems at scale.
4. Explore hybrid configurations that include both supercapacitors and batteries to combine the advantages of high power density and high energy density.
5. Test the system in different climatic conditions to evaluate its performance in diverse environments.

5.4. Future research directions

Future studies could expand on this work by:

- Investigating the use of thermoelectric generators (TEGs) for direct thermal-to-electrical conversion.
- Exploring the integration of phase change materials (PCMs) for passive thermal regulation.
- Developing simulation models using tools such as MATLAB, COMSOL, or ANSYS to optimize system performance.
- Conducting experimental studies to validate theoretical results and refine system design.

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