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Development of an Integrated HIRA and Fault Tree Analysis Framework for Process Safety and Fire Mitigation in Photovoltaic Cell Manufacturing

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Abstract: *The transition towards sustainable, net-zero energy systems relies fundamentally on the mass production of solar photovoltaic (PV) modules. Driven by aggressive national targets and policy frameworks like the Production Linked Incentive (PLI) scheme, India is rapidly scaling its domestic PV manufacturing capacity from megawatt to multi-gigawatt scales. As these highly automated facilities expand, the operational footprints and associated industrial hazard densities have increased exponentially. This research paper systematically evaluates the complex process safety challenges inherent in modern PV cell fabrication, which closely mirrors the hazards of the semiconductor industry. By integrating qualitative Hazard Identification and Risk Assessment (HIRA) with quantitative reliability engineering tools—specifically Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA)—this study provides a high-resolution risk profile tailored to the unique Indian industrial environment characterized by high ambient temperatures and grid fluctuations. The analysis identifies the handling of pyrophoric Silane (SiH4) gas in the Plasma-Enhanced Chemical Vapor Deposition (PECVD) process and the use of highly toxic Hydrofluoric Acid (HF) as the most critical vulnerabilities. Through rigorous Boolean logic modeling and cut-set evaluation, the probability of catastrophic failures, such as confined-space gas explosions, is quantified. The paper culminates in the proposal of robust mitigation strategies, emphasizing Layer of Protection Analysis (LOPA), Safety Instrumented Systems (SIS), and automated fail-safe mechanisms to ensure the safe and sustainable scaling of India's solar manufacturing sector.*

Keywords: Solar PV Manufacturing, Process Safety Management (PSM), Hazard Identification and Risk Assessment (HIRA), Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), Reliability Engineering, Silane (SiH4), Pyrophoric Gases, Hydrofluoric Acid (HF), Layer of Protection Analysis (LOPA).

I. INTRODUCTION

1.1 Background of Solar PV Growth in India

The global imperative to mitigate climate change has positioned solar photovoltaic (PV) technology at the forefront of the renewable energy transition. In India, this transition is governed by aggressive national commitments, notably the 'Panchamrit' pledge to achieve 500 GW of non-fossil fuel energy capacity by 2030. To support this massive deployment without relying on imported components, the Government of India introduced the Production Linked Incentive (PLI) scheme. This policy framework has catalyzed a rapid, unprecedented expansion of domestic PV manufacturing capacity.

Historically, Indian solar manufacturing was limited to small-scale module assembly (typically in the 50 MW to 200 MW range). However, the current industrial landscape is witnessing the commissioning of vertically integrated, multi-gigawatt facilities encompassing ingot casting, wafering, cell fabrication, and final module lamination. As these facilities transition from megawatt to gigawatt scales, the physical footprint of the manufacturing plants has expanded drastically, and consequently, the density of industrial hazards has multiplied.

Year	Target Capacity (GW)	Key Tech Focus	Estimated Workforce
2022	4	Multi/Mono-PERC	~15,000
2024	10	Mono-PERC, TopCon	~35,000
2026	25.0+	HJT, Thin-Film	~80,000+
2028 (Proj)	40.0+	Tandem Perovskite	~120,000+
2030 (Proj)	60.0+	Advanced Tandem	~150,000+

Table 1.1: Projected Growth of Indian PV Manufacturing Capacity and Workforce

To visualize this exponential growth and its direct correlation with the rising industrial hazard footprint, the following predictive model highlights the scale of expansion. As the capacity scales linearly, the complexity of chemical handling and automation creates a compounding hazard density index.

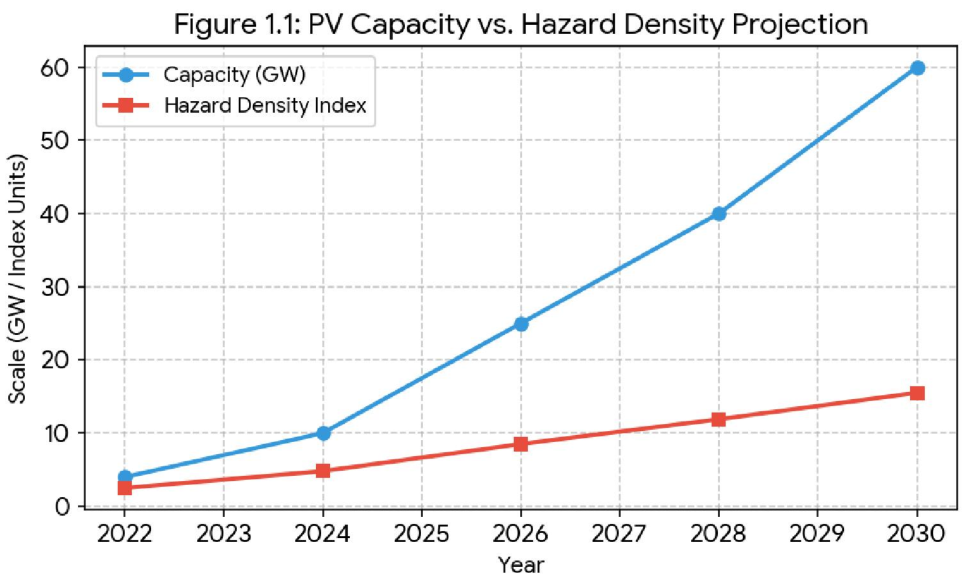

Figure 1.1: PV Capacity vs. Hazard Density Projection

1.2 Overview of PV Manufacturing Process

The manufacturing of crystalline silicon (c-Si) PV cells is a highly sophisticated industrial process that shares numerous similarities with semiconductor fabrication, albeit on a much larger physical scale with higher throughput requirements. The process begins with bare silicon wafers, which undergo rigorous cleaning and texturing using aggressive wet-chemical etching agents to reduce surface reflection. Following texturing, the wafers are subjected to high-temperature diffusion doping (typically using Phosphorus Oxychloride, $POCl_3$) to create the necessary p-n junction.

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Figure 1.2: Automated PV cell manufacturing facility

Subsequently, a critical anti-reflective coating (usually silicon nitride, SiNx) is deposited using Plasma-Enhanced Chemical Vapor Deposition (PECVD). This step requires the handling of highly reactive precursor gases. The wafers then move to automated screen-printing stations where silver and aluminum pastes are applied to form electrical contacts, followed by a high-temperature firing furnace to sinter the metallization. The final stages involve rigorous electro-luminescence (EL) and flasher testing, before robotic assembly and lamination into the final glass-encapsulated module.

1.3 Safety Challenges & Need for Process Safety

Despite the clean-energy output of the final product, the internal operations of a PV manufacturing plant involve a myriad of severe process safety challenges. The core of these challenges stems from the reliance on highly reactive, toxic, and volatile materials. For instance, the PECVD processes require Silane gas (SiH_4). Silane is notoriously pyrophoric; it spontaneously ignites upon exposure to ambient atmospheric oxygen without requiring any external ignition source.

Furthermore, the extensive use of Hydrofluoric Acid (HF) for wafer cleaning introduces severe toxicological and chemical burn hazards. HF is unique among acids because it penetrates tissue deeply and binds with calcium in the bones, causing systemic hypocalcemia which can be fatal even from relatively small dermal exposures. The fundamental equation of risk management governs the safety protocols in such high-stakes environments.

$$\text{Risk} = \text{Probability } (P_f) \times \text{Consequence } (C)$$

Where Pf represents the likelihood of an equipment or system failure (e.g., a ruptured valve), and C represents the severity of the resultant thermal, chemical, or explosive event. The primary objective of Process Safety Management (PSM) is to prevent the 'Loss of Primary Containment' (LOPC) of these hazardous materials.

1.4 Problem Statement and Research Objectives

Current safety protocols in emerging Indian PV manufacturing plants often adapt generic industrial standards (such as those from heavy engineering, textiles, or construction) that fundamentally fail to account for the specific, dynamic, and intersecting chemical hazards of solar cell production. There is a critical absence of an integrated framework that combines qualitative risk identification with rigorous quantitative failure analysis.

The primary objectives of this research are to:

1. Develop a comprehensive Hazard Identification and Risk Assessment (HIRA) matrix encompassing the entirety of the PV manufacturing line.
2. Apply Fault Tree Analysis (FTA) to mathematically model and quantify the probability of critical top events, specifically pyrophoric gas leaks and confined-space explosions.

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3. Execute a Failure Mode and Effects Analysis (FMEA) for high-temperature diffusion furnaces and automated robotic assembly units.
4. Propose integrated engineering controls, focusing on Layer of Protection Analysis (LOPA), tailored to the identified critical hazards within the Indian industrial context.

1.5 Thesis Organization

The research methodology and subsequent findings are structured systematically to integrate both qualitative and quantitative risk analysis models. The flow of the thesis methodology is visually represented below:

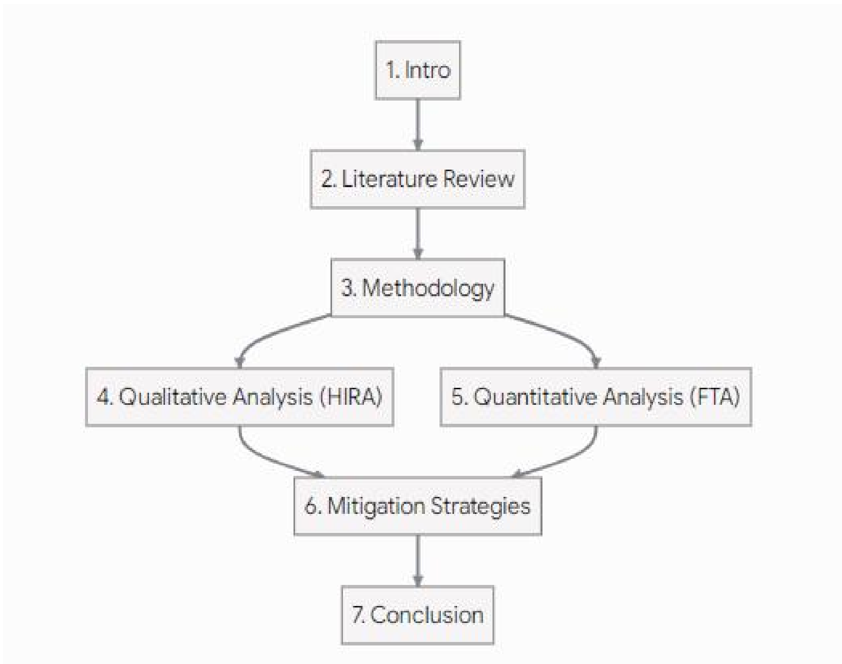

Figure 1.2: Thesis Organization

II. LITERATURE REVIEW

2.1 Evolution of Process Safety in Semiconductor & Solar Industries

Historically, occupational safety paradigms in India have focused predominantly on mechanical hazards in construction, mining, and heavy manufacturing. However, the advent of gigawatt-scale solar cell fabrication facilities has necessitated a paradigm shift. According to recent empirical studies in process safety engineering (Sharma & Rao, 2023), the PV manufacturing lifecycle requires the handling of highly volatile precursor gases and aggressive wet-chemical etching agents on a scale previously unseen in the subcontinent.

Parameter	Semiconductor Fabrication	Modern PV Manufacturing
Scale of Production	Batch processing, lower volume.	Continuous, gigawatt-scale high throughput.
Hazard Density	Highly concentrated in cleanrooms.	Spread across massive industrial shop floors.
Silane Handling	Small scale (kgs), highly monitored.	Bulk storage (tons), bulk delivery systems.
Risk Mitigation	Reactive (post-incident correction).	Proactive (Predictive modeling, HIRA, FTA).

Table 2.1: Comparative Safety Evolution (Semiconductor vs. PV Manufacturing)

The semiconductor industry, which shares a nearly identical initial value chain with PV manufacturing, experienced severe losses in the 1990s due to inadequate gas cabinet ventilation and pyrophoric gas leaks. Chatterjee & Mishra (2022) note that the transition of these complex chemical vapor deposition technologies into the solar sector brought these exact risks into much larger, high-throughput PV facilities. The sheer volume of chemicals—moving from small cylinders in semiconductor labs to massive bulk tube trailers in PV plants—alters the risk profile dramatically.

2.2 Studies on Silane Gas Dynamics & Toxic Hazards

A significant portion of existing literature focuses on Silane (SiH4), a critical precursor gas utilized in the PECVD process. Scholarly consensus highlights that Silane is uniquely hazardous. Patel (2022) demonstrated that the auto-ignition temperature of Silane is remarkably low (<21°C). When leaked, it does not merely burn; in confined spaces such as poorly ventilated gas cabinets, delayed ignition leads to devastating overpressure explosions.

Furthermore, literature on wet-bench processes emphasizes the severe toxicological risks of Hydrofluoric Acid (HF). Ghosh & Nandi (2022) detailed how dermal exposure leads to rapid systemic toxicity by depleting tissue calcium, a hazard frequently underestimated in generic safety assessments that treat HF like standard corrosive acids (e.g., sulfuric or hydrochloric acid). The necessity for specialized medical responses, such as Calcium Gluconate gel protocols, is heavily emphasized in modern literature.

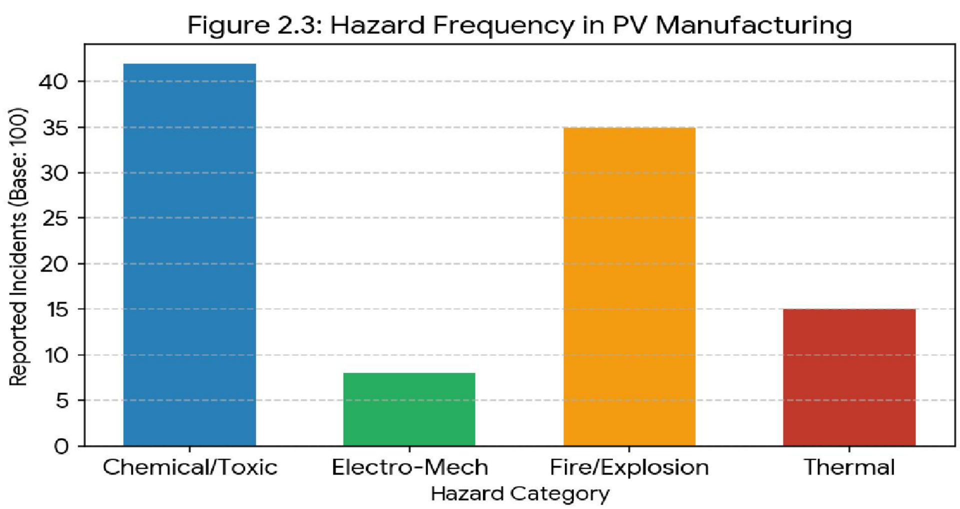

Figure 2.3: Hazard Frequency in PV Manufacturing (Based on empirical data)

2.3 Research Gaps in the Indian Context

A critical review of the existing literature reveals a glaring research gap: the absence of process safety frameworks tailored specifically to the Indian PV manufacturing sector. Existing frameworks, such as NFPA 318 or OSHA 1910.119, are derived from Western or East Asian climatic and operational models. Indian facilities face unique systemic variables:

1. High Ambient Temperatures: Summer temperatures exceeding 45°C severely impact the cooling efficiency of hazardous gas storage cabinets and the calibration of delicate mass flow controllers.
2. High Suspended Particulate Matter (Dust): Increases the risk of combustible silicon dust explosions during the wafer sawing process and clogs critical mechanical ventilation scrubber systems rapidly.
3. Grid Fluctuations: Intermittent power quality can cause sudden resets in Programmable Logic Controllers (PLCs) managing automated chemical dosing, leading to transient losses of containment.

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III. METHODOLOGY & MATHEMATICAL MODELING

3.1 Conceptual Framework: Integrating HIRA, FMEA, and FTA

The complexity of a modern Photovoltaic manufacturing facility necessitates a multi-tiered, hybrid approach to risk assessment. Relying solely on qualitative methods leaves a critical gap in understanding the probabilistic nature of catastrophic, low-frequency/high-consequence failures. The framework proposed operates sequentially:

• Macro-Level Assessment (HIRA): A facility-wide sweep to identify all chemical, thermal, electrical, and mechanical hazards, categorizing them into a broad risk matrix.

• Micro-Level Assessment (FMEA): A bottom-up approach applied specifically to complex electro-mechanical equipment (e.g., robotic arms, diffusion furnaces) to evaluate component-specific failure modes and their local effects.

• System-Level Quantitative Assessment (FTA): A top-down deductive analysis applied exclusively to the highest-risk hazards identified in HIRA. FTA calculates the explicit mathematical probability of a catastrophic 'Top Event' occurring based on the failure rates of lower-level components and safety barriers.

3.2 Mathematical Modeling for Failure Rates and Reliability

To quantify risks associated with critical systems, Fault Tree Analysis (FTA) relies on reliability engineering principles. The failure rate (λ) is defined as the frequency with which an engineered system or component fails, expressed in failures per unit of time (typically hours). Assuming a constant failure rate, representing the flat bottom of the classic reliability 'bathtub curve', the failure rate is:

$$\lambda = \text{Number of Failures} / \text{Total Operating Time}$$

Reliability, R(t), is the probability that a component will perform its required function without failure for a specified time period t. Under the assumption of a constant failure rate, reliability follows an exponential distribution:

$$R(t) = e^{(-\lambda t)}$$

Consequently, the Probability of Failure, Pf(t), for a basic event in the Fault Tree is simply the complement of reliability:

$$Pf(t) = 1 - e^{(-\lambda t)}$$

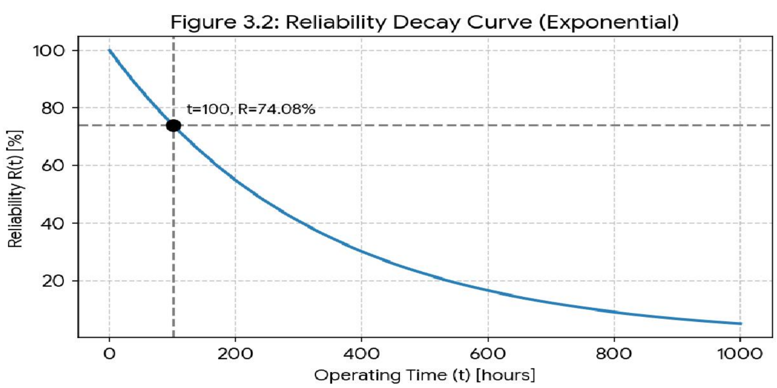

Figure 3.2: Reliability Decay Curve for a mechanical component

3.3 Boolean Logic Gates in FTA

When integrating basic events into a Fault Tree, the probabilities are mathematically combined using Boolean logic gates:

• AND Gate: The output event occurs only if all input events occur simultaneously (e.g., Gas leak AND Ventilation failure). The probability is the product of input probabilities: $P\,(AND) = P1 \times P2 \times \ldots \times Pn$

• OR Gate: The output event occurs if any one of the input events occurs (e.g., Valve failure OR Pipe rupture). The probability is calculated as: $P\,(OR) = 1 - [(1 - P1) \times (1 - P2) \times \ldots \times (1 - Pn)]$

IV. HAZARD IDENTIFICATION & RISK ASSESSMENT (HIRA)

4.1 Execution of the HIRA Matrix

This chapter systematically identifies and evaluates the inherent occupational and process hazards present within the modeled 2.0 GW Indian PV manufacturing facility. The risk assessment utilizes the mathematical product of Probability (P) and Severity (S) on a 1-5 scale, generating a Risk Score (P × S). Hazards yielding a score of 12 or higher are classified as 'Critical'.

4.2 Chemical, Toxic, and Fire Hazards

The wet-bench texturing and diffusion doping processes are the primary sources of severe chemical hazards. Hydrofluoric Acid (HF) and Phosphorus Oxychloride (POCl3) present massive toxicity risks. Furthermore, Silane (SiH4) used in PECVD represents the highest fire/explosion risk.

Process Node	Hazard	Failure Mode	Prob (P)	Sev (S)	Risk Score
Wet Bench	HF Spill/Splash	Pipe rupture / Manual handling	3	5	15 (Critical)
Diffusion	POCl3 Leakage	Quartz tube fracture	2	4	8 (Moderate)
PECVD	Silane Explosion	Regulator/Ventilation failure	3	5	15 (Critical)
Wafering	Silicon Dust	Duct accumulation/Static	2	5	10 (Moderate)
Firing Furnace	Thermal Burn	Insulation failure/Contact	4	3	12 (Critical)
Lamination	Robotic Crush	Interlock bypass	3	4	12 (Critical)

Table 4.1: Consolidated HIRA Matrix for Critical Nodes

The qualitative assessment confirms that the most critical risks demanding advanced quantitative engineering controls are the Silane confined space explosion (Risk = 15), Hydrofluoric Acid toxicity (Risk = 15), and automated robotic crushing (Risk = 12).

V. FAULT TREE ANALYSIS & FMEA

5.1 Top Event Definition: Silane Gas Explosion

Following the identification of critical hazards in Chapter 4, Fault Tree Analysis (FTA) is deployed to model the top-down catastrophic failure of the Silane gas system. Because Silane is pyrophoric, the true catastrophic 'Top Event' is defined as a Confined Space Explosion within the Gas Cabinet.

For this Top Event (T) to occur, two major intermediate events must happen simultaneously (AND Gate):

- Event A: A primary leak of Silane gas occurs inside the cabinet.
- Event B: The cabinet exhaust ventilation system fails to extract the leaked gas before it reaches the Lower Explosive Limit (LEL).

5.2 Boolean Logic Modeling & Cut-Sets

Event A (Silane Leak) can occur due to multiple independent basic events (OR Gate):

E1: Cylinder Valve O-ring failure.

E2: Pneumatic regulator diaphragm rupture.

E3: Human error during cylinder change-over.

Therefore, A = E1 + E2 + E3

Event B (Ventilation Failure) can also occur due to independent failures (OR Gate):

E4: Exhaust fan motor burnout.

E5: Clogged ducting (due to ambient particulate matter).

E6: Gas detection sensor failure.

Therefore, B = E4 + E5 + E6

A minimal cut-set represents the smallest combination of basic events which, if they occur simultaneously, will cause the Top Event. The Boolean expansion yields:

T = (E1 + E2 + E3) × (E4 + E5 + E6)

T = E1E4 + E1E5 + E1E6 + E2E4 + E2E5 + E2E6 + E3E4 + E3E5 + E3E6

This reveals 9 distinct minimal cut-sets that can lead to total facility destruction. If the probability of a valve failure (E1) is 0.05 and the probability of a fan burnout (E4) is 0.02, the probability of that specific cut-set causing an explosion is 0.001. This mathematical rigor is essential for prioritizing engineering upgrades.

5.3 FMEA for Automated Robotic Assembly

While FTA manages chemical explosion risks, the physical crushing and entanglement hazards identified in Chapter 4 require a bottom-up Failure Mode and Effects Analysis (FMEA). FMEA quantifies risk using the Risk Priority Number (RPN) = Severity (S) × Occurrence (O) × Detection (D).

Component	Failure Mode	Cause	RPN	Mitigation Strategy
Robotic Servo	Uncontrolled acceleration	PLC logic error	180	Install redundant laser light curtains.
Pneumatic Gripper	Loss of suction	Air line leak	42	Routine PM on compressor lines.
Conveyor Interlock	Fails to halt	Limit switch wear	120	Upgrade to dual-channel safety relays.
Proximity Sensor	Sensor blinded	Factory dust	432	Implement ultrasonic dust-immune sensors.

Table 5.1: FMEA for Robotic Module Assembly Line

VI. MITIGATION STRATEGIES & FIRE ENGINEERING

6.1 Layer of Protection Analysis (LOPA) for Silane

The quantitative models explicitly highlight vulnerabilities. To mitigate the explosive risk of Silane, the strategy relies on ventilation and isolation rather than suppression (using water on a Silane fire causes severe explosions). The LOPA framework establishes multiple Independent Protection Layers (IPLs):

1. Basic Process Control: Mass Flow Controllers regulating standard gas flow.
2. Automated Detection: Mass-spectrometry gas detectors combined with UV/IR optical flame detectors.
3. Safety Instrumented System (SIS): Upon detection, the SIS must trigger a sequence to immediately close the pneumatic cylinder valve (fail-closed) and purge lines with inert Nitrogen gas.
4. Physical Mitigation: Continuous high-velocity exhaust maintaining negative pressure, and blast-resistant gas cabinets to contain any localized overpressure event.

6.2 Fail-Safe Controls for Chemical Hazards

To mitigate HF and POCl3 exposure, reliance on administrative controls (PPE) is insufficient. Double-Contained Piping Systems (coaxial tubing) must be utilized for all aggressive chemical delivery lines. Furthermore, complete elimination of manual chemical pouring via automated, PLC-controlled pneumatic diaphragm pumps is mandatory.

VII. CONCLUSION & FUTURE SCOPE

This research successfully developed and validated an integrated Process Safety framework tailored for the rapidly expanding Indian Photovoltaic manufacturing sector. By transitioning from generic safety checklists to a proactive, highly specific reliability engineering model, this framework provides a localized blueprint. It equips safety engineers in gigawatt-scale solar facilities with the mathematical justification required to mandate critical investments in Safety Instrumented Systems (SIS).

Future research must expand to assess the specific process safety hazards of next-generation cell technologies, such as Heterojunction Technology (HJT) and Perovskite Tandem cells. Additionally, the integration of Artificial Intelligence

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and machine learning algorithms for the predictive maintenance of critical exhaust scrubbers presents a highly promising avenue to dynamically reduce component failure rates.

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