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Original Research Article

Lessons from China's Three-Decade Distributed Photovoltaic Development for Yemen

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ABSTRACT

Translating global distributed photovoltaic successes to Yemen's fragile and conflict-affected context remains a critical challenge. This study develops a strategic roadmap by adapting lessons from China's three-decade market evolution, informed by comparative experiences from Germany, Japan, and the United States within a conflict-sensitive analytical framework. This research hypothesises that phased policy measures, community-based models, and international partnerships can assist in overcome systemic constraints in fragile environments. Through policy analysis, historical case studies, and barrier mapping, results demonstrate that phased pilot initiatives reduce investment risks, while stakeholder involvement enhances project sustainability. Adaptive tariff structures, scalable deployment models, and local involvement emerge as prerequisites for resilience in unstable settings. The study concludes with a conflict-sensitive, adaptive framework for the phased deployment of distributed photovoltaics in Yemen. This framework prioritizes approaches that synergistically advance reliable energy access, community resilience, and sustainable photovoltaics adoption. By integrating energy planning with local development imperatives, the proposed strategy offers a transferable model for fostering robust and sustainable energy systems in similarly crisis-affected regions.

KEYWORDS

Distributed Photovoltaics, Renewable energy transition, Policy frameworks, Sustainability, Residential Solar, Feed-in Tariff, China, Yemen.

INTRODUCTION

The global low-carbon energy transition is accelerating, with distributed solar photovoltaic (PV) technology emerging as a cornerstone for achieving both climate mitigation and sustainable development objectives. By 2025, global cumulative PV installations surpassed 2.2 TW [1], driven by steep declines in component costs, continual technological advances, and the progressive refinement of enabling policy frameworks. Within this trajectory, China's contribution is unparalleled: national capacity surpassed 1 TW, constituting the largest concentration of PV deployment within a single country [1].

Despite this promising global trajectory, a stark divide persists. Fragile and Conflict-Affected States (FCAS) remain largely excluded from this transition; a challenge exemplified by the Republic of Yemen[2]. Even prior to the conflict, Yemen's centralised energy system

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[2] The Republic of Yemen, located at the southwestern tip of the Arabian Peninsula, bordered by Saudi Arabia to the north, the Red Sea to the west, the Gulf of Aden and the Arabian Sea to the south, and Oman to the east. As of 2022, Yemen's population was estimated at approximately 30.5 million, according to Central Statistical Organization (CSO) of Yemen, Available at: https://www.cso.gov.ye/.

was fragile, with the state-owned utility accounting for approximately 95% of generation from aging fossil fuel plants, generating a total installed capacity of just 1.5 GW [2]. Grid connectivity reached only 52% of the population, and rural communities, comprising nearly two-thirds of residents, were particularly underserved, with fewer than a quarter having access to the national grid [3]. Furthermore, per capita electricity consumption stood at a mere 217 kWh, which is less than one-sixth of the regional average [4].

The escalation of armed conflict in 2015 triggered the near-total collapse of an already fragile electricity system. Extensive damage to critical power infrastructures coupled with severe fuel shortages, caused available grid capacity to plummet from 1.5 GW to less than 300 MW [4]. By 2023, only 17% of households nationwide reported access to the public electricity grid, with rural electrification diminishing to a mere 10% [5]. Major urban centers experience daily outages lasting up to 20 hours, while many rural areas suffer complete grid failure [4]. In this context, off-grid solar PV systems have emerged a coping mechanism. Energy consumers increasingly rely on unregulated solar markets to provide essential energy services across both urban and rural settings [6]. Nonetheless, this growth has been characterized by a lack of coordination and fragmentation, presenting challenges related to equipment quality, limited technical support, and the absence of coherent regulatory frameworks and financing mechanisms necessary to effectively integrate distributed PV deployment into the national recovery strategy [7].

Research on distributed PV systems has evolved along two largely distinct scholarly strands, which remain largely disconnected. The first focuses on PV deployment in stable contexts, offering detailed insights into the policy and market mechanisms that enable large-scale adoption. In China, for instance, Bai *et al.* [8] trace how the sequencing of feed-in tariffs, industrial subsidies, and national programs shaped the sector's growth trajectory. Complementing this policy-level analysis, Zang *et al.* [9] document how distributed PV subsidies can crowd out utility-scale investment, while Yang *et al.* [10] demonstrates how subsidy withdrawal undermined the financial performance of PV enterprises. Studies of the Solar-energy Poverty Alleviation Program further highlight limits of top-down design: Więckowski [11] and Shengqing *et al.* [12] reveal a consistent gap between strong central policy and weak local implementation, characterized by administrative and operational bottlenecks.

Complementary research beyond China emphasizes distinct enabling conditions. In Germany market-based incentives coupled with robust citizen-energy models have fostered high levels of community participation and ownership [13]. In the United States, regulatory reforms and technical standardization for grid integration, such as streamlined interconnection procedures and compatibility requirements, have been instrumental in accommodating high penetrations of distributed PV [14]. Japan exemplifies policy experimentation and adaptive governance, reflected in iterative adjustments to renewable energy frameworks, encouragement of municipal-led initiatives, and the piloting of resilience-oriented grids [15]. Collectively, this strand of research identifies institutional stability, fiscal predictability, and robust technical capacity are critical enablers of successful PV deployment. However, it largely assumes socio-political and economic conditions rarely present in FCAS, limiting their direct applicability in such contexts.

A second strand of research addresses PV adoption specifically in FCAS environments. In the Yemeni context, studies have effectively documented the country's exceptional solar potential [16], and empirically mapped the rapid, market-driven uptake of off-grid systems [17]. This research underscores the capacity of decentralised PV to provide essential services under acute crisis but also reveals its severe limitations: uncoordinated adoption results in equipment quality issues, inequitable access, and significant sustainability challenges [6].

A critical disconnect persists between these two research traditions. The first provides lessons on scaling PV but fails to address adaptation for contexts of conflict and institutional fragility. The second documents local adaptation but lacks systematic frameworks for translating global best practices into actionable, conflict-sensitive policy models. This gap forces policymakers in Yemen and similar FCAS into a stark choice between uncoordinated, unsustainable market solutions and inapplicable models designed for stable states.

This study aims to bridge this divide by investigating which policy instruments and implementation strategies from China's distributed PV evolution can be feasibly adapted to Yemen. Using a mixed-method framework, combining cross-country policy benchmarking, conflict-sensitive transferability analysis, and sectoral barrier mapping, this research develops a practical, phased roadmap for distributed PV deployment. The ultimate goal is to prioritize interventions that enhance energy reliability, support community resilience, and integrate distributed PV into a coherent national recovery strategy for Yemen and similarly affected fragile states.

METHODS

This study employs a mixed-methods comparative framework to analyses China's distributed solar PV development (1990-2025) while assessing its applicability to Yemen. The methodology integrates policy analysis, historical case studies, and cross-country, benchmarking to provide a multi-dimensional understanding of distributed PV deployment in fragile contexts. As illustrated in **Figure 1**, the methodological approach consists of the following components:

1. Literature Review: A systematic review of academic publications, policy documents, and technical reports was conducted to map the evolution of distributed PV in China, with a focus on policy instruments, business models, and market outcomes.
2. Phase-based Policy Analysis: China's distributed PV development was examined across five distinct phases (1990–2025). This analysis focused on identifying critical policy interventions, market dynamics, and implementation challenges inherent to each phase.
3. Cross-country Benchmarking: International best practices were compared with China's experience to extract transferable lessons. The analysis highlighted contextual factors that shape the success or failure of distributed PV policies across diverse national contexts.
4. Yemen Case Assessment**:** Yemen's electricity sector was assessed through a review of national reports, donor documents, and academic studies. The analysis focused on pre-conflict conditions, the impacts of ongoing conflict, the rise of decentralised solar solutions, and the main regulatory, financial, and infrastructural barriers to distributed PV deployment.
5. Barrier Identification and Strategic Roadmap: The study identified the financial, regulatory, and technical obstacles inhibiting distributed PV adoption in Yemen. Based on the comparative findings, a phased, context-specific roadmap was developed, outlining actionable recommendations for Yemen and similar fragile states.

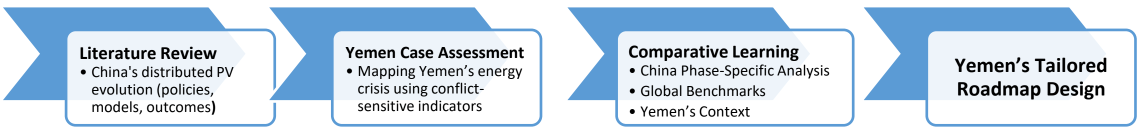

Figure 1. Research methodology

This study is organised as follows: Section 2 provides an overview of the current status of China's distributed PV market. Section 3 examines Yemen's electricity sector, focusing on the pre-conflict landscape, the impacts of the ongoing war, and the rise of decentralised solar systems as a coping mechanism. Section 4 breaks down the evolution of China's distributed PV development into five distinct phases, identifying key policy interventions, challenges, market dynamics, and concludes with tailored recommendations for Yemen drawn from each phase.

Section 5 synthesises the key findings and presents a phased roadmap for Yemen's distributed PV development to support a sustainable energy transition. Finally, Section 6 provides concluding remarks and discusses the study's limitations and directions for future research.

OVERVIEW OF CHINA'S DISTRIBUTED PV MARKET STATUS

China's expansion of solar PV has historically focused on large-scale, centralised power plants, which accounted for over 80% of total installations until 2016 [18]. However, this trend shifted significantly in 2017, when distributed solar PV achieved a 37% share of the total solar PV market, with installations reaching 53.1 GW [19]. As illustrated in Figure 2 below, this trend continued to evolve, and by 2021 distributed PV accounted for 29.3 GW (53.4%) of China's new solar PV additions, including a record 21.6 GW from residential systems, which represented nearly 40% of total additions for the year.

By the end of 2024, China's cumulative installed solar capacity reached 885.68 GW, with 374.78 GW coming from distributed PV systems [18]. Distributed PV generation, particularly in residential applications, has become a key driver of China's energy transition, with 145.15 GW of capacity installed on household rooftops [18].

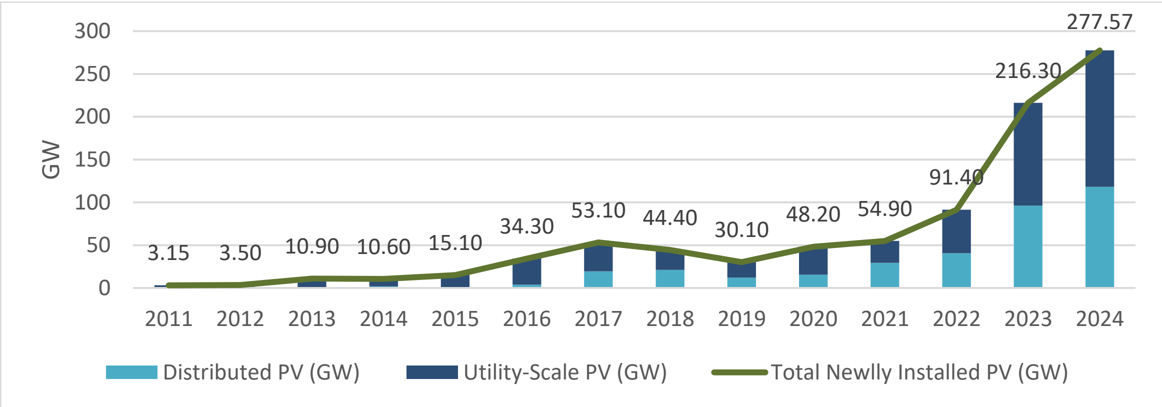

Figure 2. China's annual solar PV capacity additions (2011–2024): Utility-Scale vs. Distributed systems. Source: [18], [20]

As depicted in Figure 2, China added 277.57 GW of new solar capacity in 2024, comprising 159.39 GW (57.4%) from centralised solar power stations and 118.18 GW (42.5%) from distributed solar systems, including 29.55 GW from residential rooftops [21]. This new added capacity of distributed PV represents a 23% year-on-year increase from 2023, when 96.29 GW of distributed capacity was added [18]. According to official statistics from the National Energy Administration (NEA), a further 212 GW of solar capacity was installed in the first half of 2025 [22], bringing the cumulative installed capacity to 1.08 TW [23].

China's experience in distributed solar development can be categorised into five stages, as illustrated in Figure 3. Each stage is marked by specific challenges, policy interventions, and market dynamics, as summarised below:

- <u>Phase 1: Industry and Technology Development (1990s – 2005)</u>
  Early efforts focused on R&D and off-grid applications. Government initiatives (e.g., 863/973 Programmes) supported PV manufacturing, while rural electrification projects laid the foundations for market. Domestic growth was limited by financial incentives, expertise constraints, and high costs.
- <u>Phase 2: Policy Development and Market Formation (2005 – 2008)</u>
  Inspired by Germany's success with feed-in tariffs, the Renewable Energy Law of 2005 established a national policy framework, introducing grid access mandates and

cost-sharing mechanisms. However, weak enforcement and tariff uncertainties slowed distributed PV adoption.

- Phase 3: Utility-Scale Market Growth (2009 – 2015)
  This phase marked a significant shift towards large-scale solar deployment; Policy reforms (e.g., Golden Sun Program, nationwide FiTs), drove centralised PV expansion, while distributed PV lagged due to regulatory and grid integration challenges.
- Phase 4: Subsidy-Based Growth of Distributed PV (2016 – 2018)
  The 13th Five-Year Plan prioritised distributed PV, setting ambitious targets and launching initiatives like the Solar Energy Poverty Alleviation Program. Despite rapid growth, uneven regional development and delayed subsidies remained challenges.
- Phase 5: Transition to Grid Parity and Market Maturity (2018 – Present)
  China shifted toward market-driven growth, phasing out subsidies, and introducing mechanisms such as peer-to-peer energy trading and bulk-buying programmes. In 2024, distributed PV accounted for 42.5% of new capacity, driven primarily by residential installations.

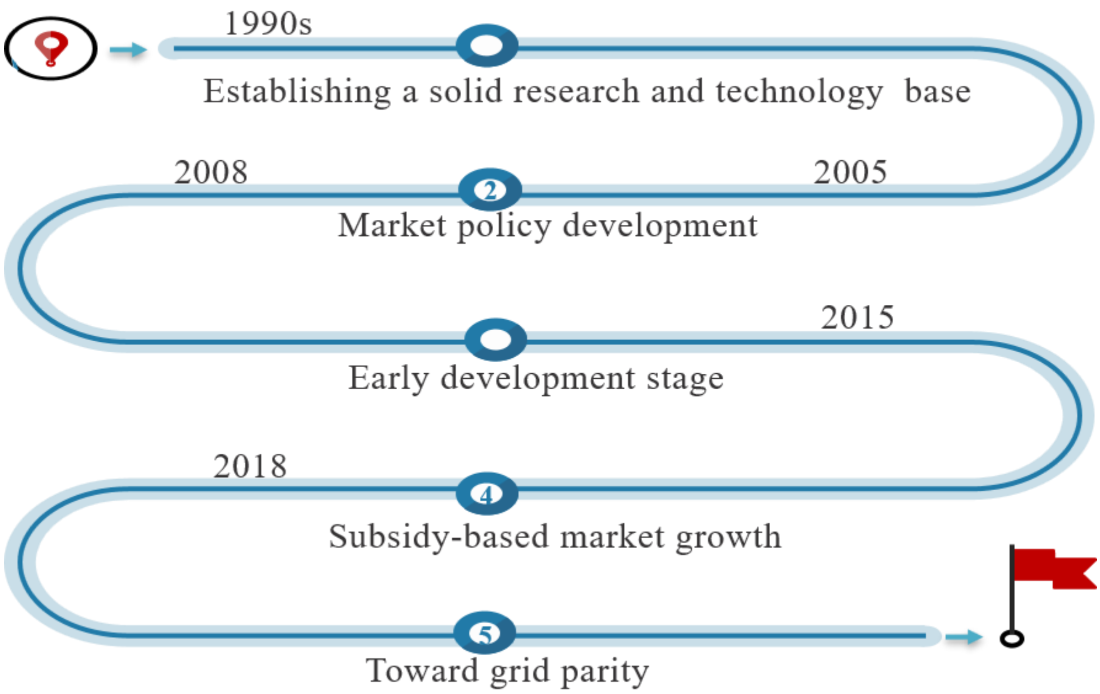

Figure 3. China's stages of the development of distributed PV

YEMEN ELECTRICITY SECTOR OVERVIEW

Yemen's electricity sector has historically faced institutional inefficiencies, infrastructural deficiencies, and overdependence on fossil fuels. Political instability and chronic underinvestment have compounded these issues, resulting in an unreliable power supply with severe urban-rural access disparities. The 2015 escalation of armed conflict devastated the sector, causing extensive grid damage, fuel shortages, and operational collapse. Consequently, off-grid PV systems have emerged as an unregulated but critical alternative. This section examines the sector's pre-conflict conditions, wartime degradation, and the adaptive shift toward solar energy.

Pre-Conflict Electricity Infrastructure (Pre-2015)

The Public Electricity Corporation (PEC), a state-owned entity under the Ministry of Electricity and Energy (MoEE), oversaw the vertically integrated electricity sector. PEC had struggled to meet the growing electricity demand [24]. The sector was constrained by aging infrastructure, fossil fuel dependency (95% of generation), inefficient governance, and underinvestment [3]. By 2014, installed capacity totaled 1.5 GW, primarily from heavy fuel oil (HFO) and diesel plants operating below optimal efficiency [4]. The national grid reached only 52% of the population, starkly below the MENA regional average of 93% [25]. Rural areas, home to 60% of Yemenis[3], were particularly affected, with only 23% having grid access [26].

In 2014, per capita electricity consumption stood at 188 kWh, compared to a MENA regional average of 2,790 kWh [27]. Residential users accounted for 62% of grid consumption, followed by commercial/institutional sectors (15%). Industrial activity was minimal: only 2,000 of 2 million grid subscribers were small-to-medium industries, with larger enterprises relying entirely on private diesel generators. The fragile power grid infrastructure, coupled with years of conflict-related destruction, looting, and vandalism, had left citizens grappling with frequent load-shedding, lasting several hours per day[4].

Conflict Impact (2015 – Present)

The escalation of armed conflict in 2015 severely exacerbated Yemen's electricity crisis; a World Bank assessment in 2020 indicated that approximately half of the electricity infrastructure across 15 cities had sustained damage, with 70% of assessed generation plants partially compromised. Additionally, 33% of distribution substations and 40% of transmission substations were either partially or completely destroyed [4]. The political instability along with fuel shortages due to geopolitical tensions in several regions further hindered access to these facilities, complicating maintenance and operation efforts, and the Public Electricity Corporation (PEC) lost its ability to provide even minimal services.

Yemen's energy crisis indicators (**Table 1**) reflect stark declines in the available generation capacity, which plummeted to less than 300 MW, a significant drop from the pre-conflict capacity of 1,500 MW. This collapse in capacity resulted in widespread load-shedding and blackouts, with urban areas enduring up to 20 hours of daily outages, while some regions faced complete grid failures. Households' relied primarily on alternative sources for lighting [4]. By 2023, the Multiple Indicator Cluster Survey (MICS) reported that only 17.3% of households nationwide had access to electricity from the public grid [5]. Access disparities between urban and rural areas remain pronounced, with urban households experiencing a 31.6% grid penetration rate compared to just 10.6% in rural regions [5].

The conflict severely exacerbated pre-existing systemic weaknesses in Yemen's electricity sector, creating critical governance, economic and logistical barriers to energy recovery. This institutional fragmentation paralysed any remaining policy development or enforcement capacity, with the PEC losing most of its oversight functions, compounding pre-conflict regulatory stagnation that had already left renewable energy strategies outdated by nearly a decade [28]. This left solar PV markets completely unregulated, with no grid codes established to standardize distributed PV integration or equipment quality standards, creating

[3] As of 2020 Yemen's rural population was 18,519,540, based on the world Bank, https://documents1.worldbank.org/curated/en/155661668808873760/pdf/Yemen-Second-Phase-of-the-Emergency-Electricity-Access-Project.pdf

[4] When electricity demand exceeds generation capacity, grid voltage and frequency decline below critical operational thresholds, operators enact predefined network segments load-shedding or brown outs to restore supply-demand equilibrium. Insufficient or delayed load shedding exacerbates imbalance, destabilizing grid synchronization, leading to uncontrolled widespread blackouts.

an environment where substandard equipment proliferated and installation practices remained unsupervised [28].

Table 1. Yemen's electricity sector crisis indicators, 2014 vs. 2023

Indicator	Pre-Conflict (2014)	Post-Conflict (2023)
Grid Access		
National Rate	52%	17.3%
Rural Rate	23%	10.6%
Per capita Consumption	188 kWh	226 kWh[5]
Infrastructure		
Generation Capacity	1.5 GW	0.307 GW (-80%)
T&D Losses	39.9%	45–60% (grid fragmentation)
Public Grid	Centralised government control	Fragmented
Solar PV Adoption		
Solar PV as Primary Lighting	Minimal (<5% households)	Urban 59%; Rural 79%
PV System Lifespan	N/A	2–3 years[6]
Institutional Capacity		
Regulatory Framework	Weak but functional	Fragmented; Outdated
Grid standards	No RE standards enforcement	Absent (no PV grid-codes)
Economic/Logistical		
Financial Incentives	Limited access to finance; no incentives.	Persistent constraints.[7]
Supply chain stability	Functional	3–4 months delays; trade restrictions; geopolitical crises

Off-Grid Solar PV as a Coping Mechanism

In response to the unreliable public electricity supply and limited fuel availability since 2015, there has been a notable increase in the adoption of off-grid solar PV systems. The total installed capacity of solar PV systems in Yemen lacks comprehensive documentation. However, a market assessment conducted by the Regional Center for Renewable Energy and Energy Efficiency (RCREEE) estimated that, as of November 2016, stand-alone small solar systems provided electricity to approximately 75% of the urban population and 50% of the rural population in selected governorates [29]. Investments in the residential solar PV sector were estimated to exceed 1 billion USD over the previous five-year period [29]. As shown in Figure 4 below, by 2022 , Solar PV has become the primary source of electricity for lighting across urban, semi-urban, and rural areas, with 79% of rural households relying on solar PV systems as their main lighting source; compared to 68% in semi-urban and 59% in urban areas [30]. Notably, northern districts demonstrate the

[5] Based on PEC-Sana'a 2022 annual report, the per capita electricity consumption for grid-connected consumers under PEC's supervision was recorded at 240, 226 kWh in 2020 and 2021 respectively

[6] Affordability remains a significant barrier for vulnerable households. As a result, the majority of consumers choose inexpensive, substandard systems that frequently fail within months. Based on [6] the majority of solar PV systems installed before 2018 are now non-operational.

[7] Yemen's prolonged economic crisis has led to significant macroeconomic instability, marked by a sharp contraction in GDP, hyperinflation, and a steep depreciation of the Yemeni rial. From an average exchange rate of 215 YER/USD in 2014, the rial has depreciated to between 533 YER/USD and 2,288 YER/USD in other regions by March 2025. This volatility has eroded purchasing power, increased the cost of imports, and hindered investment in energy infrastructure.

highest adoption rates, with governorates such as Al-Bayda (87.4%), Sana'a (86.1%), Dhamar (83.5%), and Ibb (82.3%) [5].

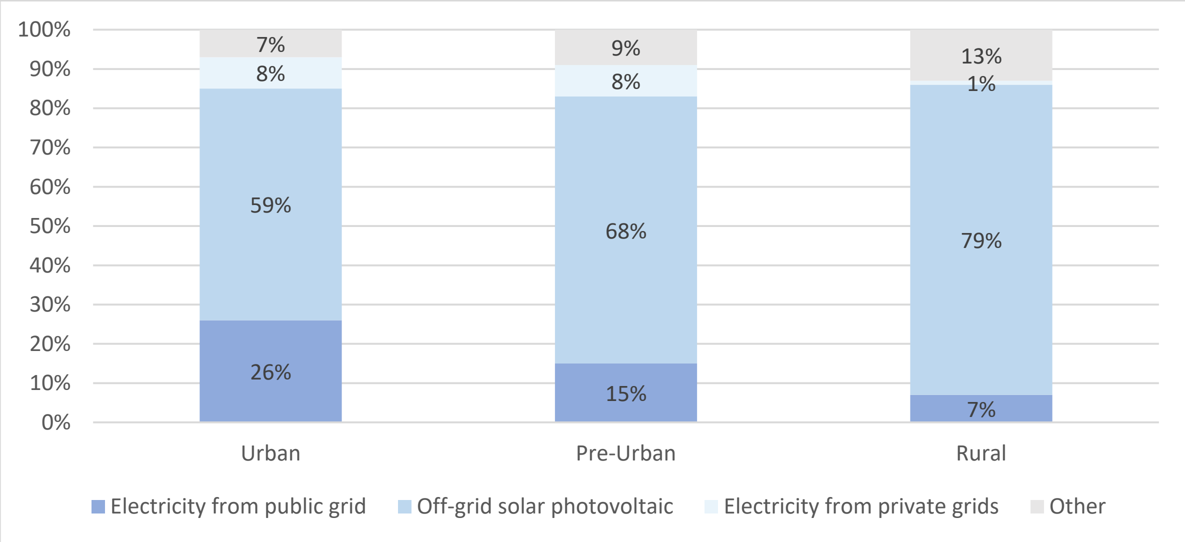

Figure 4. Households' main sources of electricity for lighting, Yemen 2020. Source: [30], [31]

This surge of off-grid solar systems reflects a practical response rather than a motivated strategy. In contrast, the utilisation of grid-connected PV technology has been notably absent in the country's generation mix. Evaluating the potential of such technology is essential, considering the current state of the national power grid, which traditionally supports a one-way power flow. Furthermore, the obstacles and challenges to introducing such technology have not been comprehensively assessed.

The absence of an enabling institutional environment and technical standards to regulate the integration of grid-connected solar PV presents significant barriers. Addressing these issues is crucial before adopting this technology on a broader scale.

CHINA'S DISTRIBUTED PV DEVELOPMENT PHASES & LESSONS

The following section explores the five distinct phases of China's distributed PV development, emphasising the challenges, policy interventions, and market dynamics that shaped its evolution. Each phase concludes with cross-contextual analysis, linking China's experiences to Yemen's potential challenges and opportunities.

Phase (1): Industry and Technology Development (1990s – 2005)

During the 1990s, the development of China's solar PV market faced considerable challenges, including high production costs, capital shortages, insufficient R&D funding, and a lack of supportive market formation from the government [32]. The domestic venture capital exhibited little interest in the PV sector [33]. Consequently, the application of PV modules was largely limited to small-scale uses, such as signal stations for communication, negative pole protection in petroleum pipelines, and weather forecasting stations [33].

Institutional and Policy Foundations Oversight of RE development fell under China's rural energy departments at various administrative levels [33]. Notably, in 1994, RE was formally recognised as an independent energy subsector and a cornerstone of China's national development agenda, as part of the "Agenda 21"[33]. By 1998, approximately 100,000 personnel were engaged in renewable energy agencies at the central government level, focusing on activities encompassing: management, R&D, training, equipment certification, and regulatory compliance, with a particular emphasis on rural energy applications [34].

The initial deployment of solar PV in China was primarily focused on rural electrification [35]. Driven by the Brightness Program 1996, the program sought to alleviate poverty and provide electricity to 23 million individuals in remote regions, with an objective to deliver 100 watt of capacity per person through the utilisation of renewable resources such as solar PV and wind energy [36]. Funding was sourced from user contributions, local and central government allocations, and foreign grants [37]. This initiative resulted in the installation of approximately 1.78 million household systems, 2,000 village systems, and 200 station systems, while establishing a framework for national and local government financing mechanisms as well as Implementing technical training systems [37].

<u>Market Formation Efforts</u> By 2000, Chinese government began to shift its focus to demand-side policies to build the solar PV power market [38]. This transition involved enhancing the quality and reliability of PV products to penetrate foreign markets and fostering government interest through domestic demonstration programmes [39]. The Tenth Five-Year Plan (2001-2005) underscored the importance of new and renewable energies, emphasizing PV commercialization in rural areas [40]. However, the plan lacked specific developmental targets, and the financial incentive framework for renewable energy remained underdeveloped [41]. Existing incentives consisted of subsidies, tax incentives, and customs duties [42]. These measures laid the groundwork for more comprehensive quantity- and price-based support mechanisms in later years.

The introduction of FiTs and Renewable Portfolio Standards in countries such as Germany, Italy, the USA, and Spain during the 1990s and 2000s spurred global demand for solar PV modules, creating an opportunity for China to capitalise on this market growth [39].

In 2002, the Township Electrification Program (TEP) was instituted to commercialise renewable energy technologies in isolated areas where PV and wind power represented economically viable alternatives to traditional grid extensions [34]. By its completion in 2003, the program had electrified over 1,000 townships, benefiting nearly one million people, with a substantial government subsidy of 240 million USD allocated for equipment costs [43]. This phase of the project highlighted essential lessons in capacity building, including system design, load management, and the establishment of reliable battery systems, which became integral to subsequent project's phase [34].

<u>R&D Investment and Industrial Growth</u> Government policies actively promoted PV industry growth through R&D support, knowledge development, manufacturing localization, and set technology and market development goals [44]. Government R&D appropriations increased dramatically from 11 billion USD in 2001 to 26 billion USD in 2006. raising the share of R&D in total government expenditure from 3.7% to 4.2% [41]. Key publicly-funded R&D initiatives included [41]:

- The 863 Program (State High-Tech Development Plan): Focused on simulated advanced technology development, including PV.
- The 973 Program (National Basic Research Program): Focused on basic science research to complement the 863 Program.

Both programmes were funded and managed by the Ministry of Science and Technology (MOST), with additional support from provincial and municipal governments [41]. Despite the lack of world-leading achievements in this phase, the establishment of robust research institutions played a crucial role in acquiring knowledge, overcoming technical challenges, and equipping decision-makers with essential information for informed policy-making [8].

The 2004 amendment of Germany's Renewable Energy Sources Act (EEG), which guaranteed fixed tariffs for renewable electricity, further stimulated demand for PV products and attracted Chinese companies to the PV manufacturing sector [42].

By the mid-2000s, China has emerged as a global leader in PV cell production, surpassing Western production capabilities [45]. This remarkable growth was facilitated by technology transfers, access to European markets, and favorable resource costs. However, the domestic PV market experienced slow growth, with only 70 MW of cumulative PV capacity by 2005, attributed to the absence of a national long-term plan, a lack of comprehensive legislative frameworks, limited expertise in renewable energy, and insufficient financial incentives [8]. Meanwhile, the policy practice in Europe became the example of China. Chinese government began adapting solar PV policies to domestic conditions[8].

Phase (1): Yemen's Context and Lessons

Yemen's current stage of solar PV development closely resembles China's early phase in the 1990s. As depicted in Table 2, while China's early phase was marked by weak manufacturing capacity, limited R&D investment, and a lack of cohesive policy frameworks, Yemen faces additional complexities due to its ongoing conflict, economic instability, and fragile institutional capacity. These unique challenges necessitate tailored strategies that build on China's lessons while addressing Yemen's specific context, as summarised in below.

Table 2. Phase (1): Yemen's context, lessons, and strategic pathways

Priority Area	Insights from China's Experience	Yemen's Current Challenges	Strategic Actions for Yemen	Expected Outcomes
Rural Electrification	Early adaptive rural electrification programmes (e.g., Brightness Program) enabled off-grid PV deployment in rural areas.	Severe rural energy poverty exacerbated by conflict, logistics, and security constraints.	Adapt scalable, off-grid PV projects using existing frameworks. Leverage current institutional capacities to coordinate rural electrification efforts.	Improved electricity access in rural areas. Foundation for decentralised PV development and enhanced social stability.
R&D and Technical Capacity	Targeted R&D investments (863/973 Programmes) built local expertise. Comprehensive training programmes increased technical proficiency.	Limited indigenous R&D and technical expertise Outdated standards and weak quality control.	Initiate joint international-local R&D projects. Establish regional training centers and enforce updated technical standards.	Enhanced local innovation and improved installation quality.
Local Manufacturing & Supply Chain	Gradually developed a domestic manufacturing base and local supply chains for PV components.	Absence of local manufacturing leads to high import dependency and supply chain vulnerabilities. High soft costs (e.g., weak supply chains, and currency volatility) inflate solar PV equipment costs by 30–50% compared to regional averages.	Develop conflict-resilient supply chains (e.g., regional partnerships and strategic market plans) Encourage technology transfer partnerships (e.g., local assembly units and PV mounting structures).	Reduced import costs. Strengthened supply chain resilience and local employment.

Phase (2): Market policy development (2005 – 2008)

This phase of China's distributed solar PV development was characterized by efforts to overcome market, institutional, and legislative barriers hindering the large-scale deployment of solar PV [8]. During this period, Germany emerged as a global leader in renewable energy by implementing high FiTs, a comprehensive incentives package, and prioritising grid-connected solar PV systems [44]. These strategic measures not only accelerated Germany's energy transition but also inspired several European Union (EU) member states to adopt similar policies, leading to significant growth in solar PV deployment across the region [46].

Legislative Framework and Key Mechanisms Chinese national targets for all REs, along with associated R&D investments, are established through Five-Year Plans (FYPs). These plans serve as the fundamental policy instrument for setting targets, developing strategies, and implementing plans. As shown in Figure 5 distributed generation identified as a strategic area although no specific targets have been defined.

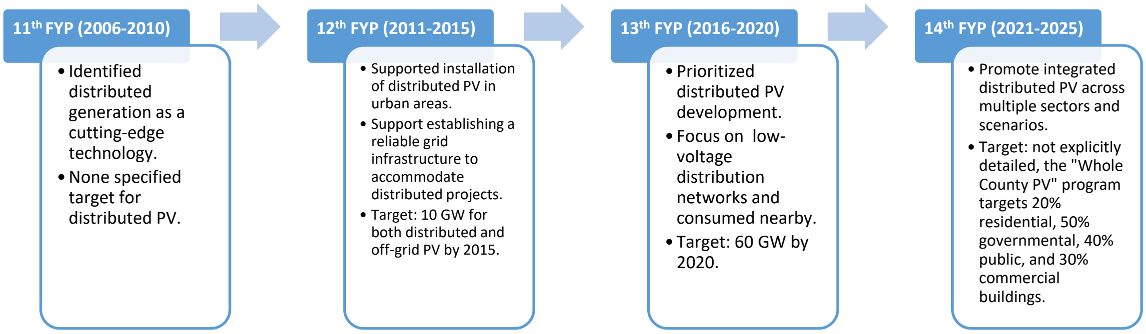

Figure 5. Distributed PV in China's five-year development plans (FYP). Source: [47] [48].

Following a comprehensive evaluation of global RE incentivization strategies, Chinese regulators favored the German solar PV measures [49]. Consequently, by the end of 2005, China enacted the Electricity Law, which established a national framework for renewable energy development [50]. This legislation introduced several key mechanisms to promote the deployment of renewable energy, including solar PV, as summarised in Table 3.

Table 3. Key mechanisms of China's 2005 renewable energy law and implementation challenges. Source: [50]–[52]

Mechanism	Policy Target	Implementation Challenges
Target Setting	Provides clear roadmap for RE deployment, guiding policy and investment decisions.	Lack of enforcement mechanisms led to inconsistent implementation across regions. Local governments often lacked the capacity or political will to meet national targets. Ambiguity in target timelines created investor uncertainty.
Grid Access Obligations	Ensured a market for renewable energy producers, reducing financial risks and encouraging investment.	Inadequate enforcement mechanisms resulted in delayed or avoided grid connections by utilities. Persistent payment delays undermined investor confidence. Outdated grid infrastructure limited RE integration.

Mechanism	Policy Target	Implementation Challenges
Pricing Mechanisms	Improved the financial viability of renewable energy projects by guaranteeing higher revenues for producers.	Lack of clarity in the FiT policy created investor uncertainty. Insufficient payments to offset high capital costs. Regional disparities in tariff implementation.
Cost-Sharing Mechanisms	Reduces financial burden on renewable energy developers, but led to higher electricity prices for consumers.	Raising concerns about affordability. Inefficient fund allocation and management. Disproportionate distribution of funds favored developed regions.
Market Prioritization	Accelerated the growth of the renewable energy sector by providing it with strategic importance in national energy planning.	Exclusion of distributed solar PV from policy frameworks. Overemphasis on large-scale projects marginalized decentralised systems.
Special Fund for RE Development	Provided critical financial support for innovation and infrastructure development, fostering technological advancement and industrial growth.	Limited funding and bureaucratic inefficiencies constrained project support. Regional imbalances in fund allocation.

In parallel, a favorable taxation policy was partially introduced to further incentivise RE development [52]. By 2008, the Chinese government proposed an income tax exemption for qualified enterprises during the first three years of operation, followed by a reduced income tax rate of 50% for the subsequent three years [53].

Solar PV development during this phase remained limited, with cumulative PV installations reaching only 140 MW by 2008 [45]. This slow progress was primarily attributed to the lack of clarity surrounding the FiT policy [52] and the lack of ambitious governmental goals for distributed PV in FYP plan [54].

It became evident that the 2005 electricity law's requirement for grid companies to purchase all renewable power without a comprehensive framework was not sufficient to ensure their full compliance in connecting and procuring grid-connected renewable power [51].

As summarised in Table 3, Several challenges became increasingly apparent during this period, including a lack of coordination in planning between central and local authorities, weakness and gap in encouragement framework, challenges in integrating projects into the grid, lengthy grid connection processes, and payment delays [52]. Moreover, distributed PV was absent from the country's policy and medium to long-term targets [54].

Phase (2): Yemen's Context and Lessons

Yemen's current policy landscape for REs mirrors China's second phase, where foundational frameworks were established but faced implementation challenges. However, Yemen's context is compounded by ongoing conflict, fragmented governance, and economic instability, which exacerbate barriers to policy enforcement and market formation. Table 4 translates China's lessons into context-specific strategies for Yemen

Table 4. Yemen's Context, Lessons, and Strategic Pathways

Priority Area	Insights from China's Experience	Yemen's Context	Strategic Actions for Yemen	Expected Outcomes
Regulatory Framework	Enacted national renewable energy laws. Gaps in enforcement & implementation clarity hindered impact.	Fragmented policies with weak enforcement. Limited institutional capacity and legal, and conflict. Donor-driven initiatives lack cohesion.	Develop a conflict-sensitive "Core Policy Package". Establish a Multi-Donor RE Coordination Unit.	Coherent, implementable minimum regulatory framework.
Market Signaling	Used financial incentives to signal opportunities. Ambiguous FiTs & insufficient tariffs stifled investment.	Inconsistent financial support and market signals due to political and economic instability.	Implement guaranteed offtake mechanisms: secure donor-backed payment guarantees.	De-risked early investments. Demonstrable success builds confidence.
Stakeholder Coordination	Central coordination among agencies/industry was crucial but inconsistent.	Deeply fragmented governance & lack of trust. Lack of coordination results in fragmented efforts.	Promote multi-stakeholder platforms to align policies with industry needs and improve sector governance.	Enhanced collaboration and smoother policy execution.
Public Awareness & Demand	Conducted nationwide campaigns to increase PV acceptance.	Severe poverty limits household investment. Low awareness of distributed PV. Current concerns limits engagement.	Launch public awareness programmes Demonstrate "Energy as Service" Models as visibility tools.	Increased community buy-in & perceived value. Creation of visible success stories. Scalable models for household access.

Phase (3): Utility-Scale market growth (2009 – 2015)

In response to the challenges hindering renewable energy development in earlier phases, China's 2009 amendments to the Renewable Energy Law aimed at enhancing the grid-connection framework, prioritising the purchase of electricity generated from renewable sources, streamlining the compensation for renewable energy, and strengthening central government oversight of provincial and local renewable energy development planning [55].

The 2009 law revisions played a crucial role in overcoming a major obstacle facing selling electricity to the national grid. However, the absence of profitability remained a critical factor in driving companies' interest in the PV electricity-generation market [56].

During this stage, China introduced a range of policies to support the distributed PV industry, transitioning from bidding systems to investment subsidies and eventually adopting a FiT mechanism, as illustrated in Figure 6.

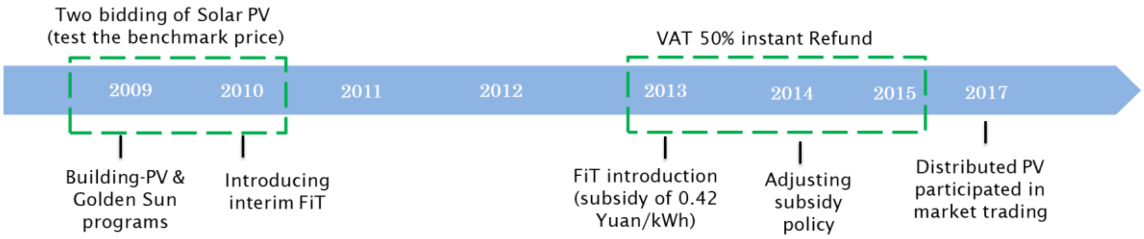

Figure 6. Policies adjustment, from investment subsidy to FiT. Source: [35], [45]

Pilot projects and international experience Pilot projects play a crucial role in evaluating emerging technologies and testing the appropriateness at the local level prior to their widespread adoption, drawing on international experiences from countries like Germany, Japan, and the United States, as mentioned in **Table 5**. These programmes represented a substantial effort to promote the growth of the PV market, aiming to acquire practical experience in PV system installation and stimulate investments in solar energy. The outcomes of these projects offered government officials invaluable experience, paving the way for policy improvement and the expansion of subsequent initiatives.

Table 5. Evolution of PV policies in Germany, Japan, and California

Country	Program	Key Features	Outcomes
German	1,000-Roof (1991-1995)	Focus on hands-on installation experience and promote PV consumers. 70% subsidy for household PV systems.	2,250 installations (5 MW). Helped create initial consumer market awareness.
	100,000-Roofs (1999–2003)	Low-interest loans. Fostering private sector involvement.	Catalyzed market PV adoption, driving the majority of growth during this period.
Japan	Sunshine Program (1974-1994)	Focused on R&D for renewable energy technologies.	PV tech development and market groundwork.
	Buy-back system (1992)	Purchased surplus PV power at fixed rates (early feed-in tariff).	Early grid-connected PV adoption.
	Solar Roofs (1994–2005)	50% initial subsidy (declining 10%/year). Low-interest loans and awareness campaigns	Market expansion.
	Monitoring Residential PV (1994–1996)	Aims to encourage the growth of the PV market Subsidy cover 50% of PV installation costs.	Improved data collection and market understanding. Supported early residential PV adoption.
	Development of the Infrastructure	Follow-up program to build infrastructure supporting residual PV systems. Increased funding substantially.	Enabled scaling of PV deployment.

Country	Program	Key Features	Outcomes
USA	California Renewable Portfolio Standard (2002)	Utilities required 20% renewable electricity by 2017.	Accelerated renewable deployment including solar PV
	California Solar Initiative CSI (2007-2016)	Declining upfront incentives. Targeted residential, commercial, government sectors. 2.167 billion USD budget.	Drove scale through market-based incentives.
	New York Sun Initiative (2012–present)	Targeted installation of 3.175 GW by 2023. Incentives for residential PV (≤25 kW) and commercial (≤750 kW). Additional support for low/moderate-income households (up to 6 kW).	PV growth and access for underserved communities. Progressing toward the 3+ GW target.

At this early China's PV market, two primary pilot solar subsidy programmes were issued in 2009. These programmes provided valuable insights for China, Building-Integrated PV (BIPV) Program and Golden Sun Demonstration Project, targeted the installation of 500 MW through these pilot projects within two to three years. The BIPV program, focused on accelerating the development of rooftop solar PV facilities, the program provided upfront subsidies for grid-connected rooftop and BIPV systems [57]. The second program, the Golden Sun Demonstration Project offered support for solar projects with capacities of 300 kW or larger, covering up to 50% of investment costs, including power transmission and distribution systems [58].

By mid of 2010, the Golden Sun had received proposals for approximately 300 projects, with a cumulative capacity of 640 MW [59]. However, the absence of proper regulations and oversight resulted in a substantial squandering of investment, as numerous solar companies engaged in deceptive tactics to obtain higher subsidies. This included providing false information to the government regarding material costs and the products quality. Therefore, the Ministry of Finance had to declare a significant withdrawal of subsidies, totaling over 10 billion Yuan in 2013 (approximately 1.6 million USD) [49].

<u>Feed-in tariffs and market incentives</u> In order to evaluate the benchmark price of domestic PV power generation, the National Energy Administration (NEA) has organized two rounds of public tenders for solar-powered projects in 2009 and 2010 [53]. The lower-than-expected bid prices discouraged energy companies and private solar equipment suppliers from investing, as project developers expected challenges in achieving profitability or securing a favorable investment return. In parallel, Chinese manufacturers sought improved domestic incentives as local PV equipment faced export reduction pressure due to European Union anti-dumping and anti-subsidy duties, which limited future market expansion in major European markets, previously significant buyers of Chinese solar panels [60].

In July 2011, the National Development and Reform Commission NDRC introduced a nationwide FiT policy to promote the development of solar PV. The policy divides solar projects into two following categories [61]:

- For projects approved before July 1, 2011, and operational before December 31, 2011, a unified tariff of 1.15 Yuan/per kWh (0.177 USD/kW).

- For projects approved after July 1, 2011, and projects approved before July 1, 2011, but not operational until December 31, 2011, the electricity price would be 1 Yuan/kWh (0.154 USD/kW).

The FiT mechanism standardized rates across locations and installation types, with intentional flexibility for future adjustments based on market and technology trends [61]. Additionally, a renewable power surcharge, analogous to Germany's EEG levy, was introduced to bridge the cost gap between renewables and coal power [51].

In August 2013, the NDRC further classified PV projects into distributed and centralised systems, guaranteeing FiTs for 20 years [58]. For the first time, distributed PV projects granted a standardized subsidy of 0.42 Yuan/kWh for the entire electricity produced (desulfurized coal benchmark price + 0.42 Yuan /kWh), for both self-consumed and exported to the grid distributed PV projects. Tariffs for new utility-scale PV installations were gradually reduced to reflect cost learning and enhance competitiveness, as shown in **Figure 8**.

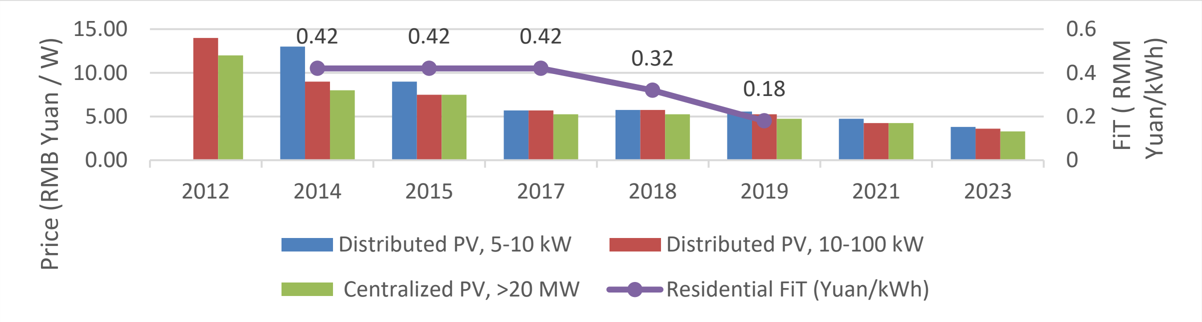

Figure 7. Turnkey photovoltaic systems price changes in China (2012-2020).
Source: [20], [47], [54], [56], [62]

In the context of August-2013 revisions, the centralised power generation was further divided into three regions based on solar resource distribution, tariffs for new utility-scale PV installations were gradually reduced over time to reflect the sector's learning curve and enhance competitiveness in the PV market, as illustrated in **Figure 8**. It forecasted that FiTs would experience a yearly reduction of at least 10% for projects with a capacity smaller than 20 GW. For projects exceeding 20 GW, it was forecast that indicated a more significant decline of 20% per year in FiTs [39]. Moreover, by the end of 2013, the government proposed a refund of 50% of the Value Added Tax (VAT) on self-consumed solar power (from 17% VAT to 8.5%) [53].

<u>Challenges and market outcomes</u> Despite these policy advancements, distributed energy growth lagged behind centralised utility-scale solar PV installations, due to various challenges, including unclear FiT policies, delayed technical standards, and complex permit procedures [57]. In parallel, the low electricity tariff for residential sector in several areas has a direct impact on the savings potential of residential solar installations compared to higher electricity prices for commercial and industrial facilities [56].

In order to streamline administrative procedures and grid connection management, by the beginning of 2015, provincial energy administrative departments have been granted the authority to approve utility-scale PV projects. For distributed PV generation of up to 6 MW for industrial and commercial self-consumption, only local government registration was required [63]. As demonstrated in **Figure 7**, the impact of these measures on distributed PV installations was not immediately evident as local governments needed time to establish and implement the necessary procedures [64].

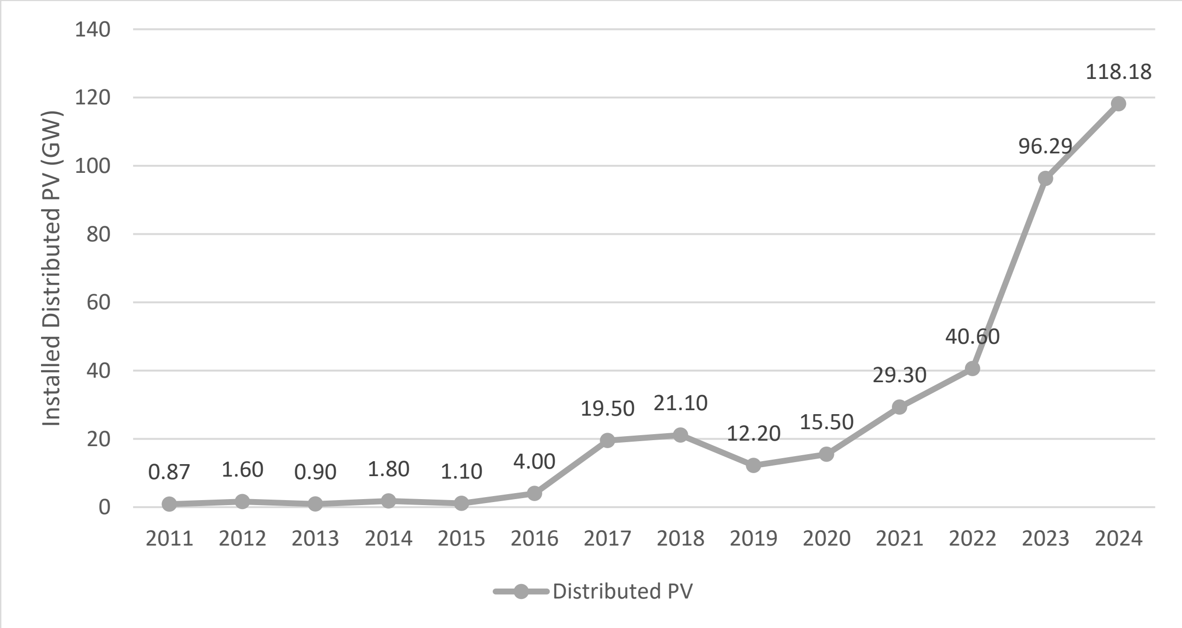

Figure 8. Distributed PV growth in China 2011-2024. Source: [18], [20], [21]

Larger-scale PV systems have consistently taken advantage of economies of scale, demonstrating a significant competitive edge in the few years following the introduction of the FiT paradigm. As illustrated in Figure 8, the cost of centralised PV systems, typically ranging from 10 to 20 MW, decreased by approximately 50% between 2011 and 2015.

Even during this phase of China's PV development, which saw significant growth in the utility-scale rather than distributed PV market, the use of pilot projects to stimulate investment and build local capacity emerged as a key lesson for preparing the market for the widespread adoption of distributed PV in emerging countries. Pilot projects not only provide practical experience but also help identify and address technical, financial, and regulatory challenges before scaling up. Moreover, while adopting international policies can offer valuable insights, it is crucial to carefully adapt these policies to address local challenges, such as insufficient grid infrastructure, weak enforcement mechanisms, and coordination gaps between central and local authorities. Policies must be tailored to the unique socio-economic and geographic context of each country to ensure effective implementation and long-term sustainability.

Phase (3): Yemen's Context and Lessons

During this phase of China's solar PV development, characterized by substantial growth in the utility-scale segment rather than the distributed PV market, pilot projects played a critical role in stimulating investment and enhancing local capacity. This approach not only provide practical experience but also help identify and address technical, financial, and regulatory challenges before for the widespread adoption. Furthermore, while international policy frameworks can offer valuable insights, it is crucial to carefully adapt these policies to address local-specific challenges local challenges as well as the unique socio-economic and geographic context of each country to ensure effective implementation and long-term sustainability.

This experience phase demonstrates that pilot programmes, adaptive tariffs, and community engagement are critical for scaling distributed PV. Yemen, however, should leverage these lessons to its fragile context, grid instability, and conflict dynamics, as summarised in below Table 6.

Table 6. Phase (3): Yemen's pilot implementation framework and strategic pathways

Priority Area	Insights from China's Experience	Yemen's Current Challenges	Strategic Actions	Expected Outcomes
Pilot Project Design	Golden Sun and BIPV tested scalability but faced significant challenges. International pilots provided adaptable models.	No conflict-sensitive demonstration projects. Lack of monitoring capacity.	Deploy context-specific pilot projects. Third-party monitoring with international partnerships.	Paving the way for larger scale deployment; Documented.
Tariff & Compensation	Created diverse financing models for project funding, including public-private partnerships; Improvements.	Hyperinflation makes fixed tariffs unsustainable. No payment infrastructure in conflict zones.	Indexed Tariffs: Link compensation to hard currency (USD) or commodity baskets. Utilize smart and advanced payment techniques.	Inflation-resilient investor returns. Accessible revenue collection.
Community Engagement	Limited residential engagement slowed distributed adoption.	Security risks deter; low awareness	Community Ownership Structures: Develop cooperative models with revenue-sharing. Train local technicians for O&M.	Enhanced project sustainability & vandalism deterrence. Local capacity building.
Grid Integration and Technical Refinement	Developed advanced grid connection standards and storage solutions.	Grid instability, weak grid management, and Outdated/ absent technical standards hinder PV integration	Develop grid codes and standards suit Yemen's condition. International partnerships for technical assistance. Pre-engineered solutions for rapid deployment.	Improved system reliability. Reliable power despite grid challenges.

Phase (4): Subsidy-based growth (2016-2018)

The Chinese 12th FYP set relatively modest distributed PV target, aiming for only 10 GW of various distributed technologies by 2015 [54]. As depicted in Figure 5, the lack of ambitious governmental goals for distributed PV in earlier plans significantly hindered its growth.

Ambitious Targets and Regulatory Streamlining The 13th Five-Year Plan (2016 – 2020) marked a significant turning point for Chinese distributed PV, setting an ambitious target of 60 GW for distributed PV by 2020. This target notably surpassed the 45 GW goal set for centralised PV systems during the same period [48]. The significant shift in governmental policy demonstrated a strong emphasis on prioritizing distributed PV during upcoming period. Under this favorable distributed PV landscape, complementary initiatives included [48]:

- Establish 100 distributed PV application demonstration zones by 2020.
- Equip 80% of newly constructed rooftops and 50% of existing rooftops with a grid-connected PV system.

In 2016, the government introduced revisions to streamline the management of PV power projects. Utility-scale PV projects now require local approval, whereas distributed PV systems only need to undergo local filing. These measures have been implemented gradually, and certain provinces and regions are planning to further decentralize the level of filing function for distributed PV systems to lower levels such as districts and cities [62].

Integration with Poverty Alleviation The 13th FYP integrated the distributed PV with a poverty alleviation effort through investment in RETs [48]. The Solar Energy Poverty Alleviation Program (2014 – 2020), was designed to harness renewable energy's potential to uplift underprivileged regions. The program specifically targeted high-poverty counties and rural villages by deploying small-scale solar projects with capacities ranging from 100 kW to 300 kW [48].

The project employs a variety of support mechanisms, including financial grants, subsidized low-interest loans, and contributions from state-owned enterprises and government agencies. Additionally, FiTs provided by both central and local governments play a crucial role in the project's financial framework [65].

The program significantly improved living standards for poor households by enabling them to sell electricity generated from PV systems to power utilities, increase the annual income of impoverished households by approximately 3,000 Yuan (approximately 400 USD) through the installation of 3 kW solar PV systems [66]. Additionally, profits from village-level or multi-village solar PV power stations funded local employment opportunities. Over the six-year period, initiative successfully installed 26.49 GW of solar PV systems, benefiting 4.18 million households across 1,472 counties and 138,091 villages [66].

The program's implementation encountered significant governance and operational obstacles that constrained its effectiveness. Institutional fragmentation, characterized by overlapping mandates and weak intergovernmental coordination, limited consistent policy execution. Outcomes varied widely across regions due to differences in local governance capacity. Operational challenges, including unclear administrative responsibilities and non-compliance by some private contractors, further impeded project delivery. Additional complications such as inequitable profit-sharing, non-transparent income allocation, and inconsistent installation quality were observed. Although formal procedural targets were largely met, the focus on compliance over functional outcomes, combined with limited technical support and weak local oversight, prevented the realization of sustainable and equitable benefits [11].

Market Expansion and Outcomes As shown in **Figure 8**, the turnkey prices for typical PV projects, indicated a gradual increase in the attractiveness investment in distributed PV. Notably, in the case of small rooftop residential systems (5-10 kW), the prices have decreased by half, from approximately 13 Yuan/W in 2014 to around 6-6.5 Yuan/W by 2017 [47]. Similarly, small commercial systems (10-100 kW) prices have dropped by about one-third during the same period [20]. Despite these cost reductions, the distributed PV subsidy remained at 0.42 Yuan/kWh until the end of 2017, while FiT for centralised PV plants decreased significantly. This created a growing advantage for distributed PV over utility-scale projects, particularly for large enterprises with access to balance-sheet financing [54].

Driven by national goals, incentive policies, a profitable business model, cost reduction efforts, and improvements in management procedures. Distributed PV energy experienced rapid development in 2016 [67]. As shown in Figure 7, the new installed capacity of distributed PV reached 4 GW in 2016, compared to 1.1 GW in 2015. Commercial and industrial installations constituted the majority of the distributed PV capacity, accounting over 97% of the installed capacity. A significant transformation took place in 2017, with the installation of 19.5 GW of distributed solar PV capacity. This notable surge allowed distributed PV to achieve almost 37 percent share of the total solar PV installation accounted at 53.1 GW. Whereas household rooftop solar systems accounted for a small share of installed distributed PV capacity (0.6 GW) [64].

Phase (4): Yemen's Context and Lessons

China's subsidy-based growth phase (2016–2018) offers critical lessons for emerging economies like Yemen. Key takeaways include the importance of ambitious national targets, streamlined approval processes, cost reduction strategies, and integrated poverty alleviation programmes to drive distributed PV adoption. Yemen can benefit from adopting similar strategies, such as financial incentives, cost-sharing mechanisms, integrating renewable energy with poverty alleviation programmes, and community-based projects to address energy access challenges and improve livelihoods (Table 7).Policymakers should address challenges such as complex investment structures, profit distribution issues, and inadequate post-installation management and maintenance to ensure the long-term sustainability of distributed PV systems.

Table 7. Phase (3): Lessons, critical challenges, and mitigation for Yemen's distributed PV

Priority Area	Insights from China's Experience	Yemen's Context	Strategic Actions	Expected Outcomes
Subsidies & Financial Mechanisms	Aggressive, time-bound subsidies accelerated deployment Capital cost focused support.	Overreliance on donor funding and fragmented subsidies, compounded by extreme poverty, undermine sustainability.	Conflict-sensitive, performance. Tiered Grant Conversions: (e.g., Shift grants to concessional loans over specified period)	improved financial sustainability; Inflation-resilient incentives
Poverty Integration	Direct household income linkage. Multi-model approaches	High poverty levels; socio-economic disparities; internally displaced persons.	Integrate distributed PV projects with community-based initiatives and poverty alleviation programmes.	Measurable socio-economic improvement. Strengthened community resilience and trust.
Implementation Governance	Centralised fund management. Unified standards	Fragmented territories Weak institutions and poor coordination. Transparency, and accountability.	Third-party fund administration. Transparent funding mechanisms and multi-stakeholder coordination	Reduced corruption risks Accelerated deployment

Priority Area	Insights from China's Experience	Yemen's Context	Strategic Actions	Expected Outcomes
Demand Aggregation	Aggregating demand across municipaliti es to negotiate bulk purchases of solar equipment "Whole County PV model".	Lack of functioning and experienced municipal structures. Costs and logistical challenges.	Leverage Bulk Procurements. Partner with well-known global manufactures for discounted pricing on high-efficiency modules.	Lower equipment costs Access to conflict-affected zones

Phase (5): Transition to Grid Parity and Market Maturity (2018-now)

The economic performance of distributed PV has historically depended on supplementary government support. As subsidies decline, sustaining growth rates becomes increasingly challenging. The challenge is further compounded by the widening disparity between available subsidies and the accelerated decline in PV system costs. This phase underscores the critical role of strategic policy sequencing in maintaining growth during subsidy withdrawal.

From Subsidies to Market Mechanisms The gradually decrease in renewable energy subsidies creates uncertainty for investors who struggle to accurately predict the expected returns on their projects, to facilitate the transition from subsidized support to a self-sustaining distributed PV market, certain measures have been implemented:

- The initial phase of policies (2016-2017): Policy focused on promoting local implementation of market-based trading, including "leading runner" and special state-level initiatives, fully organized by local energy authorities. This approach is driven by the vision of the "energy internet," which aims to integrate the energy sector with digital technologies [68].
- The second phase (2017-2019): Emphasis shifted to enabling distributed PV operators' direct market participation. In 2017, the government introduced a pilot program for distributed energy trading that included three mechanisms for exchanging distributed energy: direct trade, entrusted sales, and sales to the grid [69]. The first model, peer-to-peer model, enables multi-bilateral trading between generators and consumers. The second model, entrusted sales, left the generated electricity trade up to the grid operator on behalf of the distributed PV generators. While sales to the grid model represents selling distributed PV power to grid utilities at a fixed tariff [68].

Formal Subsidy Phase-out and Market Restructuring y 2018, China took the official step of embarking on the path towards removing distributed PV installations subsidies [49]. This procedure was driven by the widening gap in renewable energy subsidy funds and rapid decline in investment costs for distributed PV [67]. Furthermore, the excessive installation in certain areas has resulted in overcapacity, leading to a re-prioritization of support, with a focus on construction of sufficient transmission infrastructure [69].

As illustrated in **Figure 8**, Chinese government has accelerated the removing subsidies process and implemented a stricter control on distributed PV financing budget. In the initial stage, the subsidy rate for distributed PV installations was reduced by 0.05 Yuan/kWh, decreasing to 0.37 Yuan/kWh for projects that commenced operation after January 1, 2018. By the end of May 2018, a further reduction of 0.05 Yuan/kWh was applied, bringing the subsidy down to 0.32 Yuan/kWh (approximately 0.049 USD /kWh). Additionally, these policy amendments introduced, for the first time, a cap on distributed PV capacity, limiting it to 10 GW.

The policy adjustments landscape since 2018 has created a sense of uncertainty in the distributed PV market, raising doubts regarding the ability to sustain the progress achieved in the previous year [49]. Despite these challenges, distributed PV installations reached 21.1 GW by the end of 2018, with 12.2 GW added in the first half of the year [54]. However, the growth was primarily driven by C&I projects, which accounted for 20.5 GW, while residential installations lagged at just 0.6 GW [70]. This disparity was exacerbated by the lack of solar installations on public buildings including, government buildings, universities, hospitals, and other facilities, despite the theoretical potential of over 1,000 GW of rooftop solar capacity in China [71].

In June 2021, NEA launched a new pilot initiative, the "Whole County PV Program," to promote the development of rooftop distributed PV projects nationwide [72]. The program aims to reduce the costs of distributed solar energy, particularly the soft costs associated with customer acquisition and contracting, through a tender or auction process. This process selects a single supplier and installer responsible for all rooftop solar installations within each participating county [73].

As part of the program, specific targets have been set to ensure widespread adoption: by the end of 2023, no less than 50% of existing government buildings, 40% of public buildings, 30% of commercial buildings, and 20% of rural buildings across 676 counties must be equipped with solar rooftop installations [72]. To achieve these goals, the program requires pilot county governments to take a leading role in developing implementation plans, collaborating closely with power grid companies and relevant investment firms [72]. Provincial energy authorities are tasked with compiling comprehensive pilot plans based on the proposals submitted by each county [74]. Counties that successfully achieve the specified targets by the end of 2023 will be granted full status as demonstration counties, serving as models for broader implementation [73].

In the context of distributed PV systems, the subsidy program for residential installations was officially extended until the end of 2021. However, the phase-out plan for subsidies became increasingly aggressive during this period, as detailed in **Figure 8**. In mid-2019, a significant reduction was implemented, lowering the subsidy rate to 0.18 Yuan/kWh for residential customers and 0.10 Yuan/kWh for commercial and industrial distributed PV systems. This downward trend continued, with the residential subsidy rate further declining to 0.08 Yuan/kWh in 2020 and 0.03 Yuan/kWh in 2021.

Since 2020, household PV has emerged as the primary driver of the distributed PV development. According to **Figure 2**, more than half of the new installed capacity originated from distributed PV in 2021. The residential PV market experiencing explosive growth, surpassing 50% for the first time in history. Household PV installations achieved an annual capacity of 21.6 GW, representing a year-on-year growth of 114%. This surge was fueled by reduced sensitivity to module prices, power outages, decarbonization pressures, and local government bulk-buying programmes [75].

The latest China's 14th Five-Year Plan for Renewable Energy (2021-2025) does not include specific targets for distributed PV generation capacity [76]. Instead, the plan focuses on the installation of distributed solar systems in various facilities such as government buildings, transportation hubs, schools, hospitals, and industrial parks, along other dual-use applications such as agrivoltaics and fishery agrivoltaics [76].

Phase (5): Yemen Context and Lessons

China's transition to grid parity -achieving cost competitiveness with conventional power sources- marked a pivotal shift from subsidy dependence to market-driven distributed PV growth. Demonstrates that gradual subsidy withdrawal, innovative business models, and infrastructure modernization are critical for achieving grid parity. Although, Yemen remains far from grid parity with no clear path to grid parity. China's transition toward grid parity offers critical lessons include the importance of gradual subsidy reductions, market-based trading mechanisms, and targeted policies to accelerate residential and commercial PV adoption.

STRATEGIC PATHWAYS FOR YEMEN'S DISTRIBUTED PV TRANSITION

Building on the phased evolution of China's distributed PV market and grounded in a contextual analysis of Yemen's energy and governance landscape, this section adapts the previously outlined lessons into a strategic roadmap tailored to Yemen's fragile, conflict-affected context and complex socio-political realities. As shown in Figure 9, the roadmap comprises four sequential phases, each aimed at building system capacity through policy reform, modular implementation, stakeholder engagement, and external collaboration. Designed for adaptability and resilience, the roadmap seeks to embed long-term sustainability into Yemen's decentralised energy future.

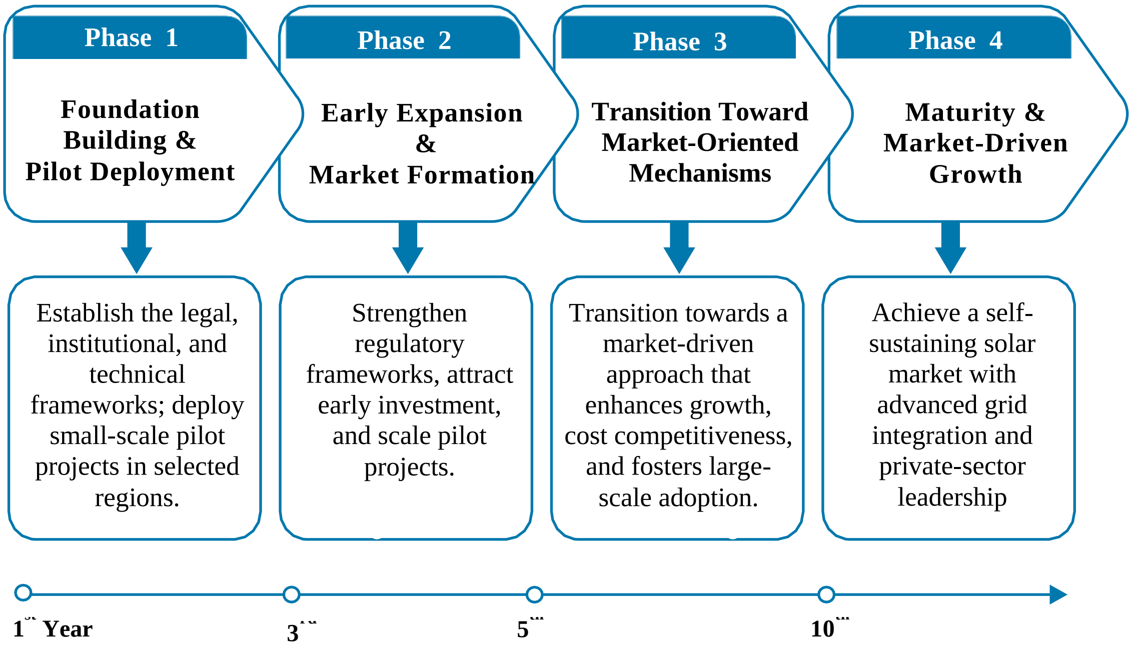

Figure 9. Phased Roadmap for Yemen's Distributed PV Development

CONCLUSIONS

China's distributed PV success extends beyond mere technical achievement, offering a powerful conceptual framework for phased market-building, dynamic policy adaptation, and strategic state-market interaction. While its model cannot be directly replicated in a fragile state, its core principles—predictable signals, iterative learning, and integrated socio-economic design—provide an essential foundation for Yemen to build a localized, scalable, and sustainable distributed PV sector. This study has translated China's three-decade evolution into a conflict-sensitive adaptation framework, positioning distributed PV not merely as an energy solution but as a potential catalyst for institutional innovation and community resilience in Yemen.

The analysis underscores that Yemen's energy transition must prioritize policy coherence and long-term stability to attract investment, drawing from China's use of performance-based incentives and public-private partnerships. Crucially, Yemen can adapt China's integrated approaches by linking distributed PV to rural development and humanitarian objectives, such as powering healthcare clinics and water pumps, thereby addressing energy poverty within a broader sustainable development framework. Market-based mechanisms, including aggregated procurement and community-led microgrid models, emerge as viable pathways to scale despite institutional constraints.

LIMITATIONS AND FUTURE RESEARCH

This section outlines the study's key limitations, outlines the methodological framework's applicability to other FCAS, and discuss directions for future research.

Limitations

The primary limitation of this research is its focused examination of Yemen as a single case study. While this approach enables deep contextual analysis, it necessarily limits the immediate generalizability of findings across all fragile and conflict-affected states (FCAS), each characterized by unique political economies, conflict dynamics, and resource endowments. Furthermore, this study is constrained by the limited availability of reliable, granular data on Yemen's informal solar market and energy consumption patterns, which restricted opportunities for detailed quantitative modeling and forecasting. Finally, the effectiveness of any proposed policy intervention remains contingent upon achieving minimum levels of political stability and institutional functionality, conditions that remain profoundly uncertain within Yemen's ongoing conflict context.

Transferable Framework

Despite these constraints, this study establishes a robust and transferable methodological framework for energy policy adaptation in fragile and conflict-affected states (FCAS). The core contribution of this study is the development and demonstration of a replicable analytical process. This involves deconstructing successful renewable energy models through phased policy analysis, conducting comparative benchmarking, performing context-specific barrier assessments, and formulating conflict-sensitive implementation roadmaps. This framework equips researchers and policymakers working in other fragile states with a structured approach to adapt global energy transition strategies to local challenges. As a result, this study significantly contributes to the broader fields of sustainable development, energy policy transfer, and post-conflict reconstruction.

Future Research Directions

This study identifies several critical avenues for future investigation:

- Comparative FCAS Analysis: Researchers should apply this methodological framework to other fragile states to enable cross-case comparisons. Such research would help distinguish between context-specific barriers and common challenges faced in the deployment of distributed renewable energy across multiple FCAS.
- Techno-Economic Modeling: Future work should focus on developing granular techno-economic models tailored to the contexts of FCAS. This entails building comprehensive datasets on component costs, household energy expenditures, and willingness-to-pay within informal solar markets to better assess financial viability and subsidy requirements.

- Innovative Finance and Governance Mechanisms: Exploration of novel financing mechanisms (such as blockchain-enabled aid payments and blended climate finance instruments) and governance models (including community energy cooperatives and public-private partnerships) is required to overcome the institutional and economic constraints documented in this study.

REFERENCES

1. G. Masson, A. Van Rechem, M. De l'Epine, and A. Jager-Waldau, "Snapshot of Global PV Markets 2025 Task 1 Strategic PV Analysis and Outreach PVPS," International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), France, Apr. 2025. https://doi.org/10.69766/PBHV9141.
2. International Energy Agency (IEA), "Electricity in Yemen," https://www.iea.org/countries/yemen/electricity, [Accessed: Oct. 29, 2025].
3. A. M. Almohamadi, "Priorities for the Recovery and Reform of the Electricity Sector in Yemen," DeepRoot Consulting, Yemen, May 2021, https://www.deeproot.consulting/en/publications/priorities-for-the-recovery-and-reform-of-the-electricity-sector-in-yemen, [Accessed: Oct. 29, 2025].
4. World Bank Group, "Yemen Dynamic Needs Assessment: Phase 3 (2020 Update)," World Bank Group, Washington DC, USA, 2020, http://documents.worldbank.org/curated/en/490981607970828629, [Accessed: Oct. 29, 2025].
5. Central Statistical Organization (CSO) and United Nations Children's Fund (UNICEF), "Yemen Multiple Indicator Cluster Survey 2022-2023, Survey Findings Report," United Nations Children's Fund, Yemen, 2023, https://www.unicef.org/yemen/documents/yemen-mics-multiple-indicator-cluster-survey, [Accessed: Oct. 29, 2025].
6. S. R. Ersoy, J. Terrapon-Pfaff, M. Dhamrin, and A. Baboraik, "Sustainable Transformation of Yemen's Energy System: Development of a Phase Model," Friedrich-Ebert-Stiftung, 2022, https://library.fes.de/pdf-files/bueros/jemen/19245.pdf, [Accessed: Oct. 29, 2025].
7. I. AL-Wesabi, F. Zhijian, C. P. Bosah, and H. Dong, "A review of Yemen's current energy situation, challenges, strategies, and prospects for using renewable energy systems," *Environ. Sci. Pollut. Res.*, vol. 29, no. 36, pp. 53907–53933, 2022, https://doi.org/10.1007/s11356-022-21369-6.
8. B. Bai, Z. Wang, and J. Chen, "Shaping the solar future: An analysis of policy evolution, prospects and implications in China's photovoltaic industry," *Energy Strateg. Rev.*, vol. 54, p. 101474, 2024, https://doi.org/10.1016/j.esr.2024.101474.
9. A. H. Zhang, S. M. Sirin, C. Fan, and M. Bu, "An analysis of the factors driving utility-scale solar PV investments in China: How effective was the feed-in tariff policy?," *Energy Policy*, vol. 167, p. 113044, 2022, https://doi.org/10.1016/j.enpol.2022.113044.
10. L. Yang, H. Hua, and J. Zhang, "The impact of phasing out subsidy for financial performance of photovoltaic enterprises: evidence from '531 new policy' on China's photovoltaic industry," *Front. Energy Res.*, vol. 12, p. 1486351, 2024, https://doi.org/10.3389/fenrg.2024.1486351.
11. M. Więckowski, "Greening the Red: How China Deploys Solar Energy to Beat Poverty," Lund University, Department of Sociology, 2025, https://lup.lub.lu.se/student-papers/search/publication/9194446, [Accessed: Oct. 29, 2025].
12. S. Xu, Q. Zhang, and L. Yang, "Policy evaluation and optimization for photovoltaic poverty alleviation projects in Anhui Province of China," *Sci. Rep.*, vol. 14, no. 1, p. 22402, 2024, https://doi.org/10.1038/s41598-024-73545-y.

13. J. Von Ditfurth and S. Rausch, "How cost-effective were subsidies for solar energy in Germany?," Discussion Paper, Centre for European Economic Research (ZEW), 2025. https://doi.org/10.2139/ssrn.5319040.
14. D. Baldwin, J. Kerby, D. Powell, R. Margolis, J. Zuboy, S. Siddiqui, E. Schweitzer, and T. McDermott, "Distributed Energy Resource Interconnection Roadmap," Pacific Northwest National Laboratory, Richland, WA, 2025, https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-35696.pdf, [Accessed: Oct. 29, 2025].
15. S. M. G. Dumlao and S. Ogata, "Japan's local consumption of solar energy: The role of energy demand in residential and small-scale solar projects," *Sol. Energy*, vol. 287, p. 113175, 2025, https://doi.org/10.1016/j.solener.2024.113175.
16. Lahmeyer International GmbH, *National Strategy for Renewable Energy and Energy Efficiency*. Ministry of Electricity and Energy, Sana'a, Yemen, 2009.
17. D. Ansari, C. Kemfert, and H. Al-Kuhlani, *Yemen's Solar Revolution: Developments,* Challenges, *Opportunities*, no. 142. Berlin, Germany: DIW Berlin, 2019.
18. NEA, "Status of Photovoltaic Power Construction in 2024 (In Chinese)," National Energy Administration, Beijing, China, 2025, https://www.nea.gov.cn/20250221/f04452701c914d51a89d0c0ea6f4acd1/c.html, [Accessed: Oct. 29, 2025].
19. L. Fang, X. Honghua, and D. Jinhong, "National Survey Report of PV Power Applications in China 2023," International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), 2024, https://iea-pvps.org/wp-content/uploads/2025/01/IEA-PVPS-Task-1-NSR-China-2023.pdf, [Accessed: Oct. 20, 2025].
20. L. Fang, X. Honghua, and Y. Yang, "National Survey Report of PV Power Applications in China 2020," International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), 2021, https://iea-pvps.org/wp-content/uploads/2021/09/NSR_China_2020.pdf, [Accessed: Oct. 29, 2025].
21. A. Jäger-Waldau, "Snapshot of photovoltaics− March 2025," *EPJ Photovoltaics*, vol. 16, p. 10, 2025, https://doi.org/10.1051/epjpv/2025012.
22. National Energy Administration (NEA), "The National Energy Administration held a press conference to introduce the grid-connected operation of renewable energy in the first half of the year (In Chinese)," 2025, https://www.nea.gov.cn/20250731/36b5b3b74d344325bb67f38b8e943c18/c.html, [Accessed: Oct. 22, 2025].
23. National Energy Administration (NEA), "The National Energy Administration released national power industry statistics for January-May 2025 (In Chinese)," 2025, https://www.nea.gov.cn/20250623/6a557ee5ad944062a6c01d6e8417474e/c.html, [Accessed: Oct. 29, 2025].
24. T. Sufian, C. ÖĞÜTÇÜ, and M. Barra, "Energy investment and business climate report for observer countries," Belgium, 2016, https://www.energycharter.org/fileadmin/DocumentsMedia/Occasional/Yemen_Investment_Report.pdf, [Accessed: Oct. 24, 2025].
25. World Bank, "Access to electricity (% of population) - Yemen, Rep," https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=YE, [Accessed: Oct. 29, 2025].
26. Central Statistics Organization (CSO), "Statistical Year Book, Chapter (10): Industry and Energy; Indicators of Production Quantities of Main Energy, Electricity and Water in the (Public Sector): 2012- 2016," Central Statistics Organization, Sana'a, Yemen, 2016.
27. World Bank, "Electric power consumption (kWh per capita)," 2025, https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?end=2013&start=2013&view=chart, [Accessed: Oct. 29, 2025].

28. K. Baragona, "Yemen Emergency Electricity Access Project-Phase II (P178347)," The World Bank, Washington DC, USA, 2022.
29. M. Mahmoud, R. Al-Shaibani, A. Almohamadi, K. Hashim, A. Cabanero, and K. Saeed, "Assessment of the status of solar PV in Yemen," World Bank Group, Washington, D.C, 2017, http://documents.worldbank.org/curated/en/284461511876486207, [Accessed: Oct. 20, 2025].
30. World Bank, "Yemen Poverty and Equity Assessment: Living in Dire Conditions," The World Bank, Washington DC, 2024, https://documents1.worldbank.org/curated/en/099030424081530447/pdf/P17919414df5860011a33814c87a62dce86.pdf, [Accessed: Oct. 29, 2025].
31. A. Aghajanian, "Mobile Phone Survey Monitoring Round II, 2023," World Bank and Development Data Group, 2023. https://doi.org/10.48529/JFYS-0N62.
32. A. H. Zhang and S. M. Sirin, "Overall review of distributed photovoltaic development in China: process, dynamic, and theories," *Glob. Sustain.*, vol. 7, p. e28, 2024, https://doi.org/10.1017/sus.2024.33.
33. C. De Gouvello, N. Berrah, L. Jufeng, and Y. Song, "China: 40-Year Experience in Renewable Energy Development-Policies, Achievements, and Lessons Learned," The World Bank, Washington, DC, 2021.
34. NREL, "Renewable Energy Policy in China: Financial Incentives," National Renewable Energy Laboratory, 2004, http://www.nrel.gov/docs/fy04osti/36045.pdf, [Accessed: Oct. 29, 2025].
35. X. Zhao, Y. Zeng, and D. Zhao, "Distributed solar photovoltaics in China: Policies and economic performance," *Energy*, vol. 88, pp. 572–583, 2015, https://doi.org/10.1016/j.energy.2015.05.084.
36. Y. Zhang, P. Xie, Y. Huang, C. Liao, and D. Zhao, "Evolution of Solar Photovoltaic Policies and Industry in China," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 651, no. 2, p. 22050, 2021, https://doi.org/10.1088/1755-1315/651/2/022050.
37. NREL, "Renewable Energy in China: Brightness Rural Electrification Program," National Renewable Energy Laboratory, Golden, Colorado, USA, 2004, https://docs.nrel.gov/docs/fy04osti/35790.pdf, [Accessed: Oct. 29, 2025].
38. J. Liu, "China's renewable energy law and policy: A critical review," *Renew. Sustain. Energy Rev.*, vol. 99, pp. 212–219, 2019, https://doi.org/10.1016/j.rser.2018.10.007.
39. A. Kumar, G. Vibhash, V. Singh, S. Singla, and P. Girdhar, "Rooftop Solar in India Looking back, Looking ahead," Price waterhouse Coopers (PwC), India, 2018, https://www.cif.org/sites/cif_enc/files/rooftop_solar_pv_in_india_ctf_pwc._v8pdf_0.pdf, [Accessed: Oct. 29, 2025].
40. National Renewable Energy Laboratory (NREL), "Renewable Energy Policy in China: Overview," . *NREL International Programs Fact Sheet*, no. October. 2004, https://www.nrel.gov/docs/fy04osti/35786.pdf, [Accessed: Oct. 29, 2025].
41. X. Tan and Z. Gang, "An Emerging Revolution: Clean Technology Research, Development and Innovation in China," World Resources Institute (WRI), Washington DC, 2009, https://pdf.wri.org/working_papers/an_emerging_revolution.pdf, [Accessed: Oct. 29, 2025].
42. P. Huang, S. O. Negro, M. P. Hekkert, and K. Bi, "How China became a leader in solar PV: An innovation system analysis," *Renew. Sustain. Energy Rev.*, vol. 64, pp. 777–789, 2016, https://doi.org/10.1016/j.rser.2016.06.061.
43. R. Nair, "Solar PV policies and their impacts in China and India," The Fletcher School of Law and Diplomacy, Tufts University, Medford, MA, USA, 2014, https://sustainabledevelopment.un.org/content/documents/5590Solar_PV_in_China_and India.pdf, [Accessed: Oct. 29, 2025].

44. H. Sun, Q. Zhi, Y. Wang, Q. Yao, and J. Su, "China's solar photovoltaic industry development: The status quo, problems and approaches," *Appl. Energy*, vol. 118, pp. 221–230, 2014, https://doi.org/10.1016/j.apenergy.2013.12.032.
45. L.-C. Ye, J. F. D. Rodrigues, and H. X. Lin, "Analysis of feed-in tariff policies for solar photovoltaic in China 2011–2016," *Appl. Energy*, vol. 203, pp. 496–505, 2017, https://doi.org/10.1016/j.apenergy.2017.06.037.
46. Y. Wang, G. Luo, and H. Kang, "Successes and failures of china's golden-sun program," in *2017 6th International Conference on Energy, Environment and Sustainable Development (ICEESD 2017)*, 2017, pp. 585–606, https://doi.org/10.2991/iceesd-17.2017.109.
47. L. Fang, X. Honghua, W. Sicheng, L. Hailing, and Y. Yang, "National Survey Report of PV Power Applications in China 2019," International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS), 2020, https://iea-pvps.org/wp-content/uploads/2020/09/NSR_China_2019.pdf, [Accessed: Oct. 20, 2025].
48. National Energy Administration (NEA), *China: 13th Five-Year Plan for Energy* Development *(In Chinese)*. National Energy Administration, Beijing, China, 2016.
49. H. Tan, "Solar Energy in China: The Past, Present, and Future," *China Focus*, 2021. https://chinafocus.ucsd.edu/2021/02/16/solar-energy-in-china-the-past-present-and-future/, [Accessed: Oct. 20, 2025].
50. National People's Congress of China, *Renewable Energy Law Of The People's* Republic *Of China Amended 2009 (In Chinese)*. National People's Congress, Beijing, China, 2009.
51. S. Schuman and A. Lin, "China's Renewable Energy Law and its impact on renewable power in China: Progress, challenges and recommendations for improving implementation," *Energy Policy*, vol. 51, pp. 89–109, 2012, https://doi.org/10.1016/j.enpol.2012.06.066.
52. Z. Peidong, Y. Yanli, S. Jin, Z. Yonghong, W. Lisheng, and L. Xinrong, "Opportunities and Challenges for Renewable Energy Policy in China," *Renew. Sustain. Energy Rev.*, vol. 13, no. 2, pp. 439–449, 2009, https://doi.org/10.1016/j.rser.2007.11.005.
53. X. G. Zhao, G. Wan, and Y. Yang, "The turning point of solar photovoltaic industry in China: Will it come?," *Renew. Sustain. Energy Rev.*, vol. 41, pp. 178–188, 2015, https://doi.org/10.1016/j.rser.2014.08.045.
54. E. Martinot, M. Hong, H. Runqing, Z. Mofan, and Y. Min, "Distributed energy in China: Review and perspective 2020-2025," *World Resour. Inst. Work. Pap.*, 2020, https://wri.org.cn/research/distributed-energy-china-2020-2025, [Accessed: Oct. 29, 2025].
55. Standing Committee of the National People's Congress, *Decision of the Standing Committee of the National People's Congress on Amending the Renewable Energy Law of the People's Republic of China (In Chinese)*. National People's Congress (PRC), Beijing, China, 2009.
56. A. Hove, Q. Wenyun, L. Qingyang, and L. Yuzhao, "Economics of Urban Distributed PV in China: Sino-German Energy Transition Project," Sino-German Energy Transition Project, Beijing, China, 2021, https://www.dena.de/fileadmin/dena/Dokumente/Projektportrait/Projektarchiv/Entrans/Economics_of_Urban_Distributed_PV_in_China_EN.pdf, [Accessed: Oct. 29, 2025].
57. M. Yao and X. Cai, "An Overview of the Photovoltaic Industry Status and Perspective in China," *IEEE Access*, vol. 7, pp. 181051–181060, 2019, https://doi.org/10.1109/ACCESS.2019.2959309.
58. W. Daoyuan, L. Yanxue, G. Qunyin, and G. Weijun, "Research on the Solar Photovoltaic (PV) Development in China," *Int. J. Ind. Electron. Electr. Eng.*, vol. 5, no. 12, Dec.-2017, pp. 325–332, 2017.

59. E. Martinot, "Renewable power for China: Past, present, and future," *Front. Energy* Power *Eng. China*, vol. 4, pp. 287–294, 2010, https://doi.org/10.1007/s11708-010-0120-z.
60. Y. S. Cheng, K. P. Tsang, and C. K. Woo, "Protectionism's adverse impact on renewable energy deployment: evidence from the European Union's import duties on China-made photovoltaic panels," *Energy Policy*, vol. 206, p. 114789, 2025, https://doi.org/10.1016/j.enpol.2025.114789.
61. National Energy Administration (NEA), *China: Notice No. 1594 of 2011 on Improving Solar PV Feed-in Tariff (In Chinese)*. National Energy Administration, Beijing, China, 2011.
62. L. Fang, X. Honghua, and W. Sicheng, "National Survey Report of PV Power Applications in CHINA 2016," International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS), 2017, https://iea-pvps.org/wp-content/uploads/2020/01/National_Survey_Report_of_PV_Power_Applications_in_China_-_2016.pdf, [Accessed: Oct. 29, 2025].
63. IRENA, "Renewable Energy Policies for Cities: Experiences in China, Uganda and Costa Rica," International Renewable Energy Agency, Abu Dhabi, 2021, https://www.infobuildenergia.it/wp-content/uploads/2021/05/IRENA_Policies_for_Cities_2021-V2.pdf, [Accessed: Oct. 29, 2025].
64. Y. Abdelilah, H. Bahar, T. Criswell, P. Bojek, F. Briens, J. Moorhouse, and L. M. Martinez, "Renewables 2022: Renewable Electricity," International Energy Agency (IEA), Paris, 2022, https://iea.blob.core.windows.net/assets/ada7af90-e280-46c4-a577-df2e4fb44254/Renewables2022.pdf, [Accessed: Oct. 29, 2025].
65. Z. Jin and D. S. Ialnazov, "Sustainability assessment of individual-level solar energy poverty alleviation program-A case on Jinzhai County, China," *Front. Sustain.*, vol. 3, p. 1072141, 2022, https://doi.org/10.3389/frsus.2022.1072141.
66. Z. Wang, J. Li, J. Liu, and C. Shuai, "Is the photovoltaic poverty alleviation project the best way for the poor to escape poverty? - a DEA and GRA analysis of different projects in rural China," *Energy Policy*, vol. 137, p. 111105, 2020, https://doi.org/10.1016/j.enpol.2019.111105.
67. M. Yuan, H. Miao, and M. Zhang, "Distributed Solar PV in China: Growth and Challenges," World Resources Institute, 2018, https://www.wri.org/insights/distributed-solar-pv-china-growth-and-challenges, [Accessed: Oct. 29, 2025].
68. H. Uhde and G. C. Malima, "Experimenting with local electricity markets in China–multilevel drivers and barriers in the sociotechnical regime," *Energy Res. Soc. Sci.*, vol. 69, p. 101577, 2020, https://doi.org/10.1016/j.erss.2020.101577.
69. H. Uhde, "Peer-to-peer electricity trading in China and the EU–A comparative evaluation of key policy documents," *Res. Glob.*, vol. 4, p. 100078, 2022, https://doi.org/10.1016/j.resglo.2021.100078.
70. G. Baiyu, "Rooftop solar to roll out on China's public buildings," Dialogue Earth, 2021, https://chinadialogue.net/en/energy/rooftop-solar-to-roll-out-on-chinas-public-buildings/, [Accessed: Oct. 29, 2025].
71. Bloomberg News, "China Rooftops Could Almost Match Size of Global Solar Industry," 2023. https://www.bloomberg.com/news/articles/2023-03-06/china-rooftops-could-almost-match-size-of-global-solar-energy-industry, [Accessed: Oct. 29, 2025].
72. NEA, *Notice of the General Affairs Department of the National Energy Administration on Submitting a Pilot Plan for the Development of Rooftop Distributed Photovoltaics in the County (In Chinese)*. Beijing: National Energy Administration, 2021.
73. A. Hove, "Synergies between China's whole county PV program and rural heating electrification," *WIREs Energy Environ.*, vol. 12, no. 5, 2023, https://doi.org/10.1002/wene.488.
74. NEA, "List of Pilot Projects for Rooftop Distributed Photovoltaic Development in Entire Counties (In Chinese)," National Energy Administration, China, 2021,

https://www.gov.cn/zhengce/zhengceku/2021-09/15/content_5637323.htm, [Accessed: Oct. 29, 2025].
75. D. Feldman, K. Dummit, J. Zuboy, and R. Margolis, "Spring 2023 Solar Industry Update," National Renewable Energy Laboratory (NREL), 2023. https://doi.org/10.2172/1974994.
76. NDRC, "Notice on Issuing the 14th Five-Year Plan for Renewable Energy Development (In Chinese)," National Development and Reform Commission, 2021, http://www.nea.gov.cn/2016-12/19/c_135916140.htm, [Accessed: Oct. 29, 2025].

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