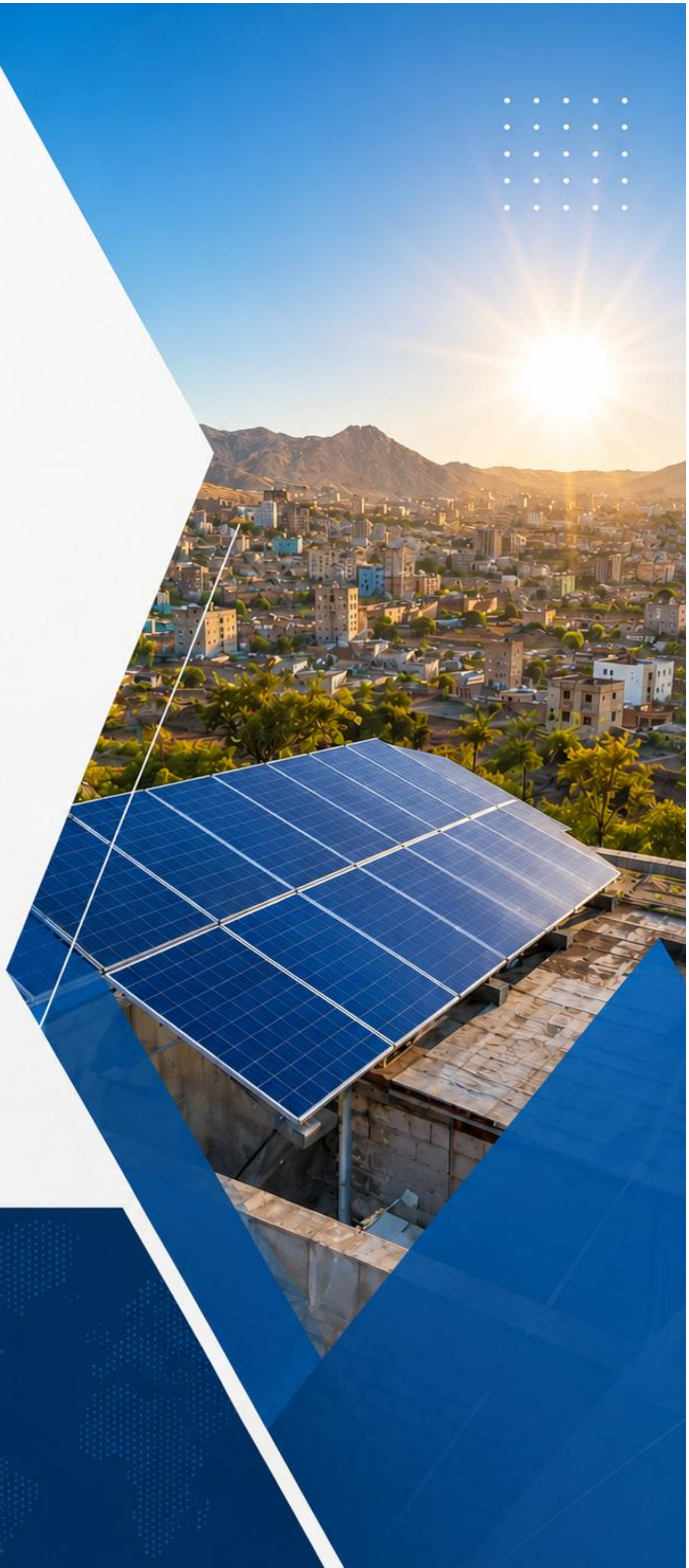
Adaa Foundation
مؤسسة أداء للدشقارات والدباحاث

Environmental Impact Assessment of Yemen's Electricity Transition:

From Public Grid to Decentralized Solar Power (2014–Present)

A Desk-Based Research Study Using Remote Sensing and Secondary Data Triangulation



Decentralized Solar Transition | Environmental Impacts | Groundwater & Natural Resources | Evidence for Sustainable Decisions

FINAL REPORT

Prepared by:
Hamzah AlGunaid

July 2026

Adaa Foundation
مؤسسة أداء للدراسات والابحاث

ENVIRONMENTAL IMPACT ASSESSMENT — FINAL REPORT

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Prepared for

Adaa Foundation for Consultancy and Studies

Final Report — English Version
July 2026

Contents

ENVIRONMENTAL IMPACT ASSESSMENT / ADAA FOUNDATION

Yemen's Solar Transition: *A Decade in Data*

From public grid collapse to decentralized solar power — what twelve years of satellite evidence actually show, 2013–2024.

8 satellite datasets | 16 secondary sources | 22 governorates | Zero-budget research initiative

82%
Collapse in national energy-use intensity, 2014–2016

410 MW
National solar capacity in 2024, up from 60 MW in 2015

~0.6M t
Estimated CO_2 avoided per year by 2024 (indicative)

2040s
Projected first wave of panel end-of-life disposal

Twelve Years, Three Phases

How the transition actually unfolded, from collapse to partial, uneven recovery

2014
Grid infrastructure sabotaged; national power plant collapses in March 2015

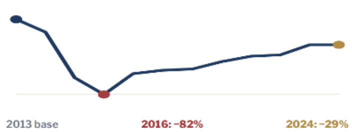
2015 – 2017
Grid access falls to about 10%. Mass emergency household solar adoption — an estimated USD 1–2 billion invested

2018 – 2022
Consolidation. Household growth slows to about 3.4% per year; institutional solar programmes begin (hospitals, water utilities)

2023 – 2024
First utility-scale entry — the 120 MW Aden Solar Plant, Yemen's largest single installation

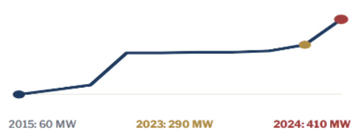
Energy-Use Intensity

Satellite nighttime-light radiance, national mean, 2013–2024



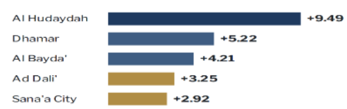
Solar Capacity

Installed MW nationally, 2015–2024



Agricultural Land Growth

Cropland expansion, 2016–2024, leading governorates (percentage points of land area)



National average: +1.4 pp

M

KEY FINDING — MA'RIB CASE STUDY

Yemen's solar boom was driven almost entirely by **necessity, not marketing**. Ma'rib — the one governorate that kept cheap local diesel throughout the conflict, via its own oil and gas resources — shows no meaningful solar-driven agricultural expansion, despite equal economic logic. Where the fuel crisis didn't force the switch, adoption simply didn't happen at comparable scale.

Beyond Energy: The Fuller Picture

Vegetation, air quality, and institutional response — measured, not assumed

VEGETATION / GREEN LAND

+24.5%

National vegetation greenness (NDVI) rose 2013–2024, broad-based across most governorates — consistent with, though not proof of, solar-enabled irrigation expansion.

AIR QUALITY — REPORTED NON-FINDING

No change

Satellite-measured NO_2 (+3%) and CO (+4.2%) show no detectable improvement, 2019–2024 — reported honestly as a real result, not omitted.

INSTITUTIONAL RESPONSE

76+ / 152

Health facilities solarized (World Bank) and public facilities solarized under UNDP's ERRY programme since 2023 — project-level, not nationally representative.

Groundwater Depletion

Cheap solar pumping removed the cost brake that once limited irrigation. Satellite gravimetry shows a **renewed water-storage decline from 2021–2024**, timing-consistent with fastest solar growth — documented, plausible, still unquantified at governorate scale.

Coming E-Waste Wave

Panels from the 2015–2017 adoption wave reach end-of-life around **2040–2042** — no disposal framework exists yet. Lithium batteries entered the market in 2024, with documented counterfeit-quality problems shortening real-world lifespan.

Air Quality — No Signal

Two independent pollutants (NO_2, CO) both show flat-to-rising trends, not decline. **No satellite-detectable local air-quality benefit** coincides with the solar transition in this period — a genuine, reported result.

Five-Year Outlook
2029 capacity scenarios, MW

LOW	BASELINE	HIGH
442	617	895

Methodology: Free satellite data (VIIRS, GRACE-FO, Sentinel-2/5P, MODIS, Dynamic World) cross-validated against 16 secondary sources, using a two-stream triangulation protocol. All estimates are labelled by evidence confidence; findings that didn't confirm expectations are reported as such.

Adaa Foundation
for Consultancy and Studies — July 2026

Executive Summary

Between 2014 and 2016, Yemen's public electricity grid collapsed under the pressure of armed conflict, falling from a pre-conflict baseline estimated at 36–67 percent of the population (depending on source and definition) to approximately 10 percent on-grid access by 2016–2017. In the absence of a functioning national utility, households, farms, and institutions turned to decentralized solar power at a scale with few global precedents. This report presents the findings of a twelve-year, desk-based environmental impact assessment of that transition, built entirely from satellite remote sensing and secondary data, conducted as a self-initiated, non-budgeted research effort by Adaa Foundation.

The assessment finds that energy-use intensity, measured through satellite nighttime-light data, collapsed by 60–82 percent between 2014 and 2016 and has since only partially recovered, remaining, as of 2024, well below pre-conflict levels nationally. National solar capacity grew from approximately 60 MW in 2015 to 410 MW in 2024, with the majority of that late growth attributable to a single 120 MW utility-scale plant near Aden rather than broad-based household expansion, which has grown far more slowly (approximately 3.4 percent per year) since 2019.

Solar's environmental co-benefits are real but are estimated, not directly measured: avoided greenhouse gas emissions are modeled at roughly 450,000–710,000 tonnes of CO_2 per year as of 2024, up from an estimated 66,000–104,000 tonnes/year in 2015. Two environmental risks accompany this benefit and remain under-monitored at the national level: cheap solar-powered irrigation pumping is plausibly accelerating pre-existing groundwater depletion (a renewed decline is visible in satellite gravimetry data from 2021 onward), and the panels installed during the 2015–2017 emergency-adoption wave will begin reaching end-of-life around 2040–2042, for which no disposal or recycling framework currently exists. Satellite-measured air quality (NO_2 and CO) shows no detectable improvement over 2019–2024, a genuine and reported non-finding.

The report closes with a five-year outlook built on explicitly separated growth assumptions, a formal significance rating of each identified impact, and a set of concrete, actionable recommendations, including the finding that solar's low running cost alone has not been sufficient to drive adoption absent a fuel crisis, evidenced by Ma'rib governorate, which retained cheap local diesel throughout the conflict and shows no meaningful solar-driven agricultural expansion despite equal economic incentive.

1. Background and Rationale

Yemen's public electricity grid, already covering an estimated 36 to 67 percent of the population before 2014 depending on the source and definition consulted, deteriorated sharply following the onset of armed conflict. Sabotage of transmission infrastructure in 2014 and the collapse of the country's largest power plant in March 2015 reduced on-grid access to approximately 10 percent by the end of 2016. In the absence of a functioning public utility, households and institutions turned to decentralized solar power, with solar becoming the dominant household electricity source in a majority of governorates within two to three years.

More than a decade later, this shift had not been assessed as an environmental transition in its own right. Existing literature documents the emergency-substitution period (2015–2017) in detail but treats the subsequent decade largely as a stable end-state, leaving its environmental trajectory, emissions, land use, groundwater interaction, and the approaching end-of-life disposal of first-generation panels, largely unexamined at the national level. This assessment was designed to close that gap using only free, openly accessible data: a well-documented, conflict-driven energy transition, occurring over a sufficiently long timeframe to support meaningful trend analysis, in a context where continuous satellite data exists precisely because ground-based institutional monitoring collapsed.

2. Research Objectives and Questions

Primary objective: to assess, through remote sensing and secondary data trend analysis, the environmental implications of Yemen's shift from public grid electricity to decentralized solar power between the pre-2014 baseline and the present.

- How has energy-use intensity changed nationally and by governorate between 2012 and the present, and what does this reveal about the relative roles of grid electricity, generator use, and solar power over time?
- What is the observable spatial footprint and growth trajectory of utility-scale solar installations?
- What secondary evidence exists regarding avoided fossil-fuel consumption and associated emissions attributable to the shift to solar power?
- What documented environmental risks have accompanied the transition, particularly groundwater depletion and the emerging concern of photovoltaic end-of-life waste, and how well are these currently monitored or quantified?
- Where do existing secondary data sources agree, and where do they diverge or rely on outdated surveys presented as current?

3. Scope and Methodology

3.1 Temporal, Spatial, and Thematic Scope

The study covers 2012–present, with 2014 as the conflict-onset marker separating three analytical phases: Phase 0 (pre-2014 baseline), Phase 1 (2015–2017, collapse and improvisation), and Phase 2 (2018–present, consolidation). Spatial coverage is national, disaggregated to Yemen's 22 governorates wherever data permits. Thematic scope includes energy-use trends, solar capacity and avoided emissions, groundwater interaction, and photovoltaic end-of-life waste. Air quality was added mid-study once a viable satellite proxy (Sentinel-5P) was identified. Explicitly excluded throughout: primary household surveys, economic or livelihood impact analysis, and health outcome assessment, these are deliberate boundary decisions, not oversights.

3.2 Data Sources

Eight satellite and remote-sensing datasets were used, all free and requiring at most a one-time institutional account registration: VIIRS nighttime-lights (NOAA/NASA, via Google Earth Engine), Sentinel-2 imagery (ESA, via Microsoft Planetary Computer), GRACE/GRACE-FO gravimetry (NASA/JPL), Sentinel-5P NO_2 and CO (ESA Copernicus), MODIS NDVI (NASA), and Dynamic World land-cover classification for cropland and built-up area (Google, Sentinel-2-derived). These were combined with a secondary literature register of 16 sources spanning World Bank, UNDP, IRENA, academic, and market-report publications, and with official IRENA capacity statistics.

3.3 Two-Stream Methodology and Triangulation

Findings draw on two independent evidence streams, remote sensing and secondary literature which are cross-checked against one another rather than treated as a single blended source. Agreement between streams is treated as validation; divergence is treated as a finding in its own right. A minimum two-independent-source rule governs any figure drawn from secondary literature; single-source figures are reported and labelled as such, never presented as consensus.

3.4 Scope Corrections Made During Execution

Two scope decisions were made mid-study and are recorded here for transparency. First, Sentinel-2-based utility-scale solar footprint mapping was narrowed after determining that only one detectable national-scale site exists (the Aden Solar Plant, 120 MW, operational July 2024), a single site is insufficient to support trend analysis, so this was retained as a documented reference point rather than pursued as a standalone geospatial workstream. Second, an investigation into built-up area expansion, initially undertaken to test whether population displacement was confounding the nighttime-lights findings, was deliberately narrowed after it began to extend into socioeconomic and migration analysis, which falls outside this study's defined scope. Its findings are retained here strictly as an interpretive caveat on the energy-use indicator (Section 4.3), not as a standalone socioeconomic analysis.

4. Findings (2013–2024)

Findings are organized using the Driver–Pressure–State–Impact–Response (DPSIR) framework. Within each subsection, national or full-distribution statistics are presented first; specific governorates are discussed only as explicitly labelled illustrative examples, not as representative of the national picture.

4.1 Driver — Conflict and Grid Collapse

The pre-conflict baseline is presented as a range rather than a single figure, reflecting a genuine, unresolved conflict between three credible sources: DIW Berlin's household survey found 36 percent national public grid access; CEOBS reports approximately 50 percent; World Bank sources report approximately 67 percent ("two-thirds") for grid access nationally, or for poor households specifically depending on the publication. These figures rest on different survey methodologies, years, and population bases, and are not reconciled to a single number here, doing so would manufacture false precision the underlying data does not support. On-grid access collapsed to approximately 10 percent by 2016–2017 under any of the three baselines.

4.2 Pressure — Mass Decentralized Adoption

Household solar adoption occurred at a scale with few global precedents, with an estimated USD 1–2 billion in cumulative household investment between 2014 and 2016 alone. A widely-cited November 2016 estimate (50 percent rural / 75 percent urban household solar penetration) has been re-cited without an updated survey in market reports as recent as 2023–2025; this study explicitly retires that figure as a current statistic and replaces it with the most recent primary survey identified (DIIS, 2024, n=1,000 households), which found 73 percent of respondents adopted solar only after 2015, consistent with continued reliance on solar, though not a like-for-like penetration percentage.

4.3 State — Current Energy-Use and Capacity Trends

Nighttime-light radiance, averaged across all 22 governorates, fell from a national mean of 1.066 (2013) to 0.166 (2016) — an 82 percent decline — before recovering only partially to 0.759 by 2024, roughly 71 percent of the 2013 level. Governorate-level results vary widely (full range: −63.3 percent to +690.2 percent change 2013–2024); the extremes at the high end are concentrated in governorates with very low 2013 starting values converging toward a common national baseline by 2024, and are not evidence of exceptional real-world change. The most substantively significant single result is Sana'a City, which shows the largest real decline in the dataset (14.77 to 5.42, absolute radiance units) , a genuine, large-magnitude loss of energy-use intensity that has not recovered.

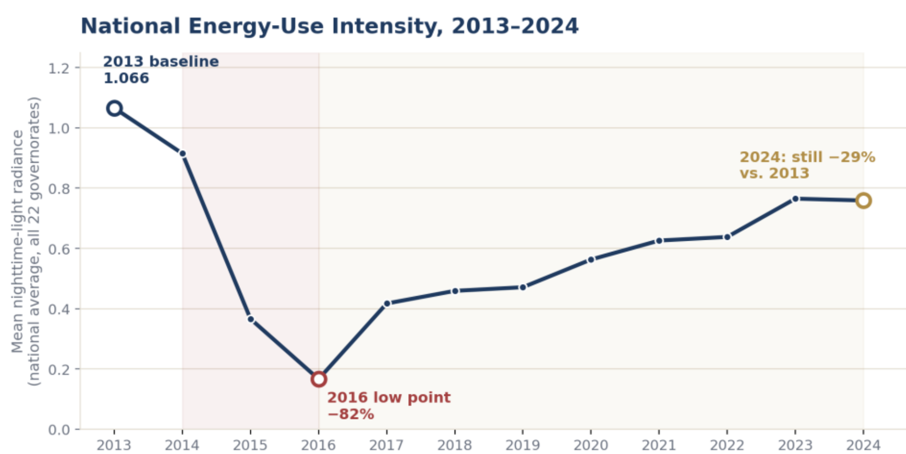
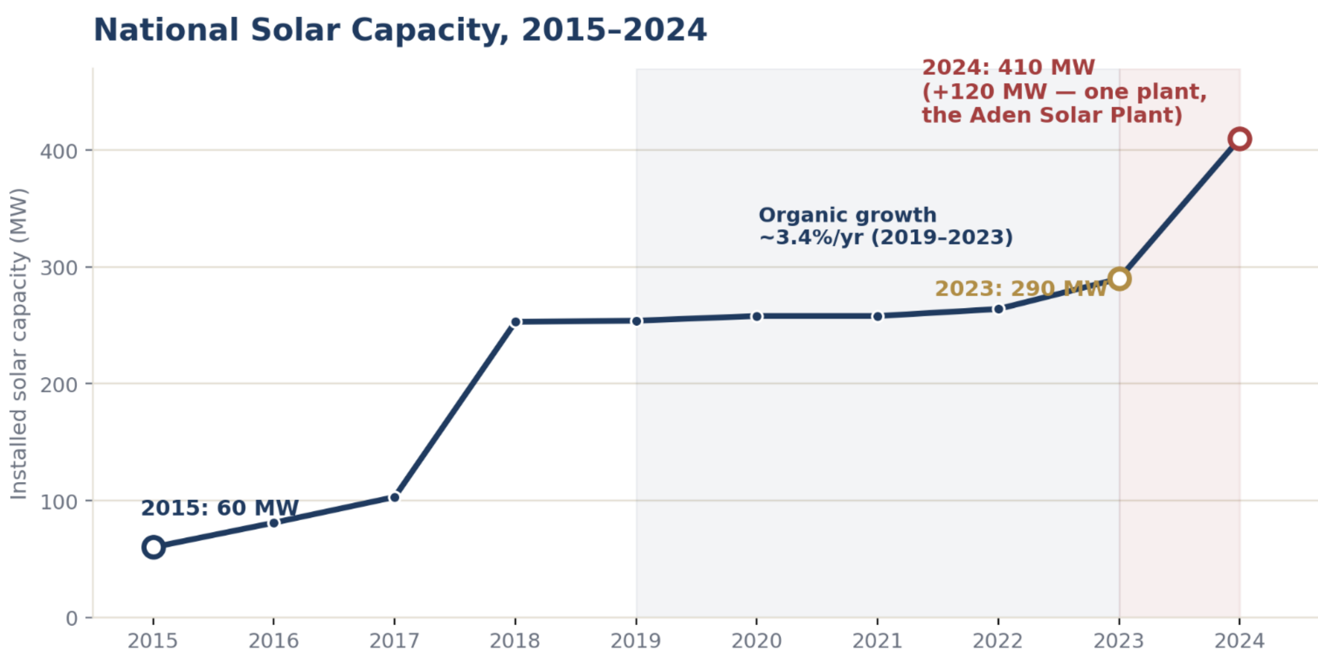


Figure 1. National mean nighttime-light radiance, 2013–2024. Shaded regions mark the collapse phase (2014–2016, red) and the partial-recovery phase (2016–present, gold). See Appendix A for governorate-level mapping of this trend.

Interpretive caveat: governorate-level nighttime-light growth may partly reflect population redistribution — rural-to-urban migration driven by the broader war economy — rather than energy-use recovery alone. A supplementary check found that Al Hudaydah and Hajjah's high light growth coincides with genuine, substantial built-up area expansion (consistent with durable urban resettlement), while Ma'rib shows negligible built-up growth despite comparable light growth — consistent with informal, camp-based population presence rather than permanent construction, which standard land-cover classifiers do not register. This distinction affects how governorate-level VIIRS figures should be read, but is not pursued further here as it falls outside this study's environmental-impact scope.



National solar capacity (IRENA official statistics) grew from 60 MW (2015) to 410 MW (2024). Disaggregating this trend reveals that background household/commercial growth has been slow and steady (approximately 3.4 percent per year, 2019–2023), while the 2023–2024 jump to 410 MW is attributable almost entirely to the single 120 MW Aden Solar Plant, independently corroborated three ways (IRENA capacity statistics, IRENA's own country-profile net-change table, and multiple news sources). This distinction, organic growth versus lumpy, discrete utility-scale additions — is material to how future capacity should be projected (Section 7).

A distinct and necessary caution: Yemen's "access to electricity" as reported in composite international indicators (86.3 percent, World Bank, 2024) counts any electricity source grid, solar, or generator and should never be presented alongside or compared directly to public grid access figures (which remain near 10 percent), as doing so implies a grid recovery that has not occurred.

4.4 Impact — Environmental Consequences

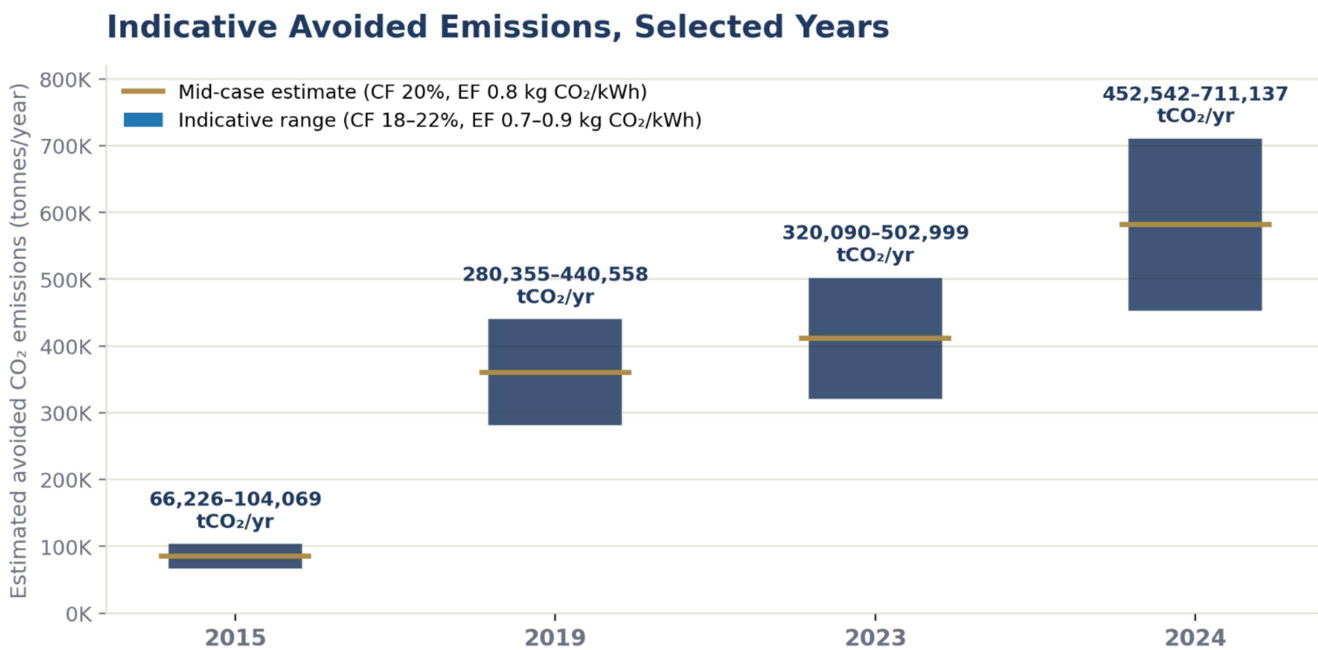
This section assesses the environmental consequences of Yemen's growing shift to decentralized solar power, distinguishing throughout between impacts directly observable in remote-sensing data and those that still rest on estimates or indirect evidence. Four areas are covered: changes in energy-use patterns, avoided emissions, the potential interaction with groundwater resources, and the future waste stream from solar systems, alongside land use, vegetation, and air quality, each treated within the limits of the data actually available rather than beyond them.

4.4.1 Cross-Validation of the Energy-Use Finding

Independent secondary literature (a 2018 World Bank blog, using a specific satellite image-pair comparison) claims a two-thirds decline in nighttime light emissions between 2014 and 2015. This study's own extraction, using entirely independent calendar-year averaging across all 22 governorates, found a 60 percent decline over the same period. The two figures were derived independently, using different methods, years apart, their agreement is a genuine cross-validation of the remote-sensing methodology.

4.4.2 Avoided Emissions — Indicative Estimate

Modeled using installed capacity (IRENA), an assumed capacity factor of 18–22 percent, and an assumed diesel-displacement emission factor of 0.7–0.9 kg CO_2/kWh, avoided emissions are estimated at 66,000–104,000 tonnes CO_2/year (2015), rising to 453,000–711,000 tonnes CO_2/year (2024). This is explicitly a modeled estimate, not a measurement, and has not been validated against Yemen-specific fuel-displacement data, which does not appear to exist at national scale.



4.4.3 Groundwater Interaction

The documented mechanism (CEOBS, 2021) is that cheap solar power removed the cost constraint that previously limited diesel-fuelled irrigation pumping, particularly in western Yemen. Satellite gravimetry (GRACE/GRACE-FO, full 2002–2024 series) shows a long-term national water-storage decline beginning around 2006–2009, predating the conflict and consistent with Yemen's known pre-existing over-extraction problem, followed by a renewed, accelerating decline from 2021 to 2024 that is timing-consistent with the period of fastest national solar capacity growth. This remains correlational: GRACE measures total water storage, not groundwater specifically, and Yemen's coverage in the dataset's grid is coarse (national-scale only, not governorate-resolved).

4.4.4 Photovoltaic End-of-Life Waste

Applying the standard 25–30 year PV service life to Yemen's installation history produces a projected first disposal peak of 2040–2042, attributable to the 2015–2017 emergency-adoption cohort (approximately 43 MW). A material caveat: this is based on officially tracked IRENA capacity, which may understate the true installed base given the large, informally-imported household market (S006 estimates USD 1–2 billion in cumulative investment 2014–2016 alone), if informal capacity is undercounted, the true first disposal peak could exceed this estimate. A second, distinct waste stream was identified during this study: lithium batteries entered the Yemeni market specifically in 2024 (not earlier, as initially hypothesized and subsequently corrected against a documented source), carrying a shorter failure cycle (5–10 years) than panels and a documented quality-control problem (counterfeit or low-grade cells shortening real-world lifespan below manufacturer specification). This is a forward-looking monitoring point, not yet an observed effect in the study's data window.

4.4.5 Land Use

Minimal nationally. The Aden Solar Plant (1.6 km², operational July 2024) is the only utility-scale example identified and is too recent and singular to represent a trend.

4.4.6 Agricultural Land and Vegetation Expansion

National mean NDVI rose from 0.162 (2013) to 0.202 (2024), a broad-based 24.5 percent increase; national cropland fraction (Dynamic World classification) rose from 5.78 to 7.15 percent (2016–2024). Al Hudaydah shows the clearest, cross-validated agricultural expansion signal (cropland +9.49 percentage points, the largest absolute change nationally; NDVI rank 2 of 22), consistent with local expert confirmation of it as an established agricultural governorate; Dhamar shows a similar, smaller pattern. A genuine, unresolved data conflict was identified in Raymah and Al Mahwit, where NDVI shows strong growth (+26.5 percent each) but cropland classification shows decline (−3.05pp and −3.31pp respectively) that most plausibly explained by a global-trained land-cover classifier's known difficulty distinguishing terraced highland agriculture from general tree/shrub cover, and is reported here as an open methodological limitation, not resolved either way.

Ma'rib governorate provides a specific and informative case: it retained cheap local diesel throughout the conflict (its own oil and gas resources), and shows no standout agricultural expansion on any measure (NDVI rank 17 of 22; cropland change squarely mid-pack once corrected for a small-base statistical distortion in the initial relative-percentage comparison). This is read as evidence that Yemen's solar transition was overwhelmingly crisis-driven substitution rather than value-driven adoption, where the fuel-cost "push" factor did not apply, solar-powered irrigation was not independently adopted at a comparable rate, despite equivalent economic logic. This has a direct, actionable implication (Section 8).

4.4.7 Air Quality

A genuine, reported non-finding. Satellite-measured tropospheric NO_2 (+3 percent) and CO (+4.2 percent) both show flat-to-slightly-rising trends nationally, 2019–2024, no detectable local air-quality improvement coincides with the solar transition at this resolution and timeframe. This is retained in the report as a genuine result, not omitted for not confirming an expected benefit.

4.5 Response — Institutional Programming

Documented institutional responses include the World Bank's Yemen Emergency Electricity Access Project and Yemen Integrated Urban Services Emergency Project (solar installations across 76 health facilities and multiple schools), and UNDP's ERRY programme (164 solar systems, projected to avoid 560 tonnes CO_2/year at the project level; 152 public facilities solarized since 2023, benefiting an estimated 199,745 people). These are project-level figures, useful as evidence of institutional response but not nationally representative, and should not be scaled to imply national coverage.

5. Cross-Validation Summary

This study's design deliberately used two independent evidence streams so that agreement or divergence between them could itself be evaluated. Three cross-validation results stand out:

- Energy-use decline: this study's independent VIIRS extraction (60 percent decline, 2014–2015) closely matches literature's independently-derived claim (two-thirds decline, different method and years), a genuine methodological validation.
- Solar capacity: the 2023–2024 capacity jump (290→410 MW) is corroborated three independent ways — IRENA statistics, IRENA's own net-change reporting, and multiple news sources that all pointing to the same 120 MW Aden Plant.
- Agricultural expansion: NDVI and cropland classification agree strongly for Al Hudaydah and Dhamar, but genuinely disagree for Raymah and Al Mahwit, reported as an open limitation rather than forced into agreement.

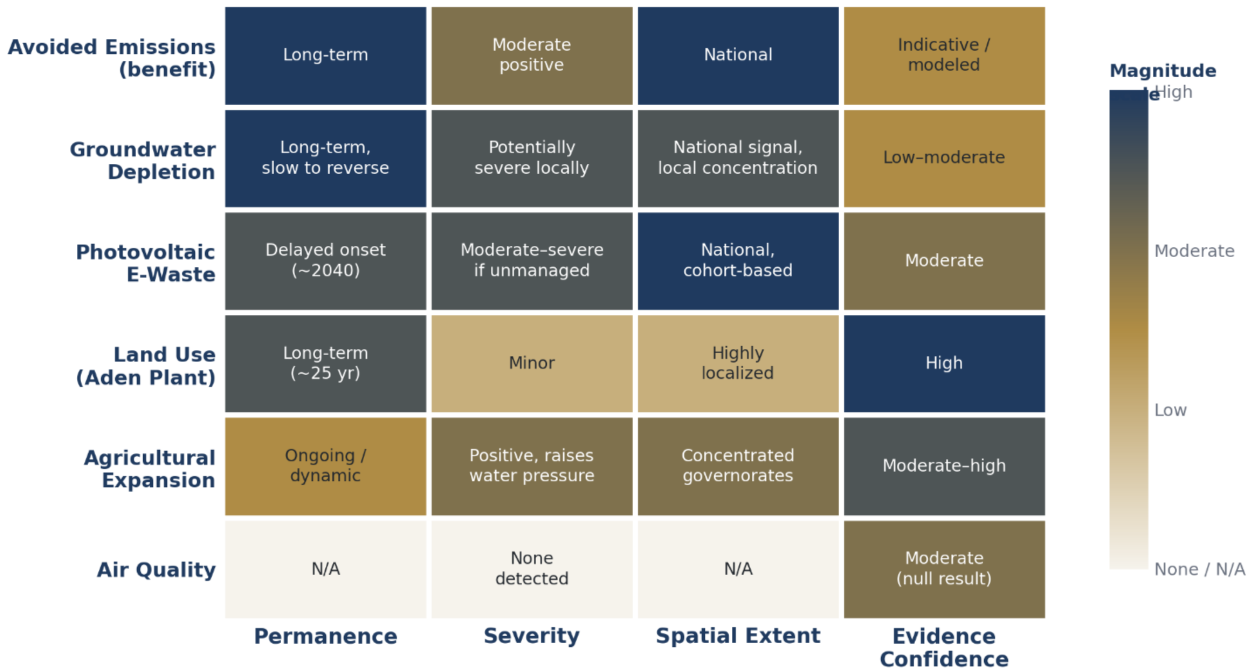
6. Significance Assessment

Each impact identified in Section 4.4 is rated below by permanence, severity, and spatial extent, alongside the confidence level of the underlying evidence, addressing a structural component of standard environmental impact assessment methodology not present in earlier drafts of this study's working documents. The purpose is to place findings in practical context, distinguishing impacts backed by strong evidence from those resting on preliminary indicators or indirect estimates.

Impact	Permanence	Severity	Spatial Extent	Evidence Confidence
Avoided emissions (benefit)	Long-term, contingent on capacity remaining installed	Moderate positive; modest relative to national/global totals	National	Indicative / modeled, not measured
Groundwater depletion	Long-term, potentially slow to reverse	Potentially severe locally; unquantified nationally	National signal; likely locally concentrated	Low-moderate; documented mechanism, correlational timing
Photovoltaic e-waste	Delayed onset (~2040), long-term once realized	Moderate-to-severe if unmanaged; no current framework	National, cohort-based	Moderate; standard lifespan modeling
Land use (Aden Plant)	Long-term (plant lifetime, ~25 years)	Minor; small area, non-agricultural land	Highly localized (1.6 km²)	High; directly documented
Agricultural expansion	Ongoing / dynamic	Positive for food security; raises water-use pressure	Concentrated in specific governorates	Moderate-high; cross-validated, with one open conflict
Air quality	N/A — no effect detected	None detected	N/A	Moderate confidence in the null result

Significance Assessment — Six Identified Impacts

Color intensity reflects magnitude on each dimension, derived from the qualitative ratings in Section 6 — a reading aid, not a new independent score

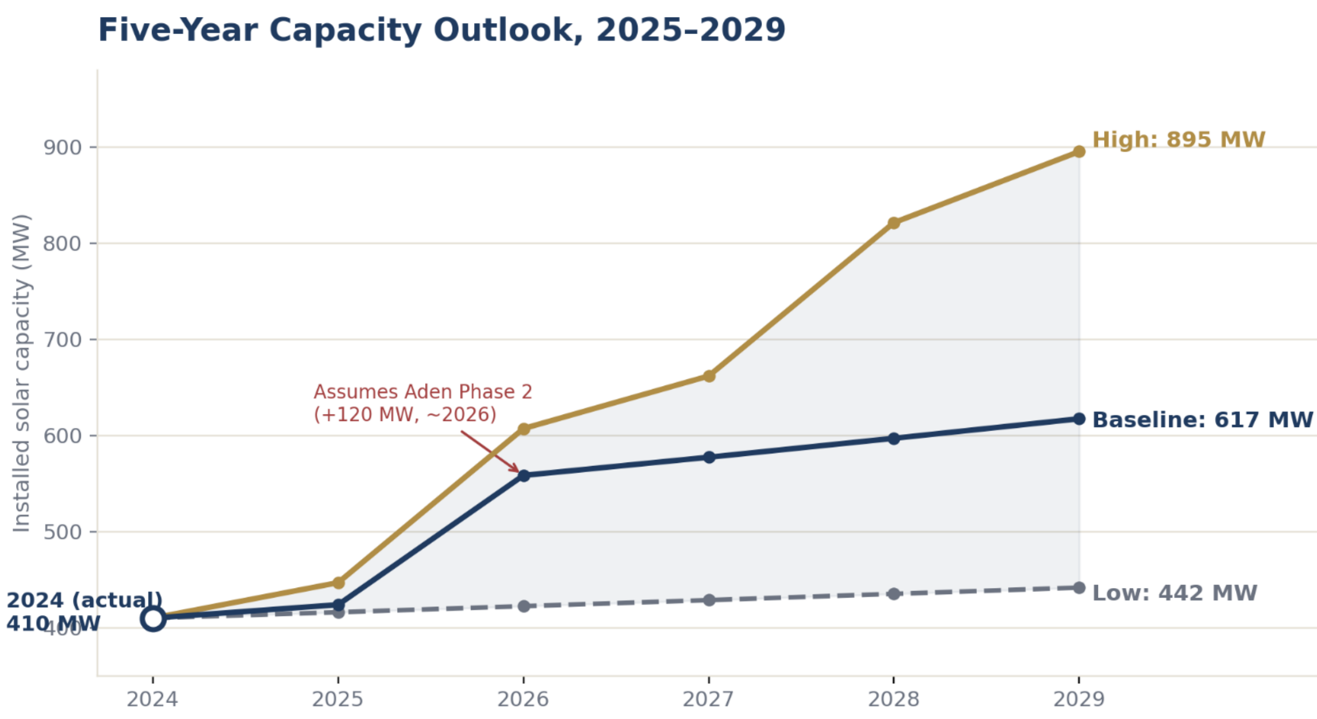


7. Five-Year Outlook (2025–2029)

This outlook is a trend-based scenario projection, not a formal econometric forecast, appropriate given roughly a decade of underlying data and Yemen's continued political and economic volatility, either of which could invalidate any single-point projection without warning. The three scenarios below deliberately separate background organic capacity growth from discrete, lumpy utility-scale additions, reflecting the Section 4.3 finding that these are genuinely different phenomena.

Scenario	Key Assumptions	2029 Capacity	2029 Avoided Emissions (indicative)
Low	Organic growth slows to 1.5%/yr; no further utility-scale projects	442 MW	~619,000 tCO_2/yr
Baseline	Organic growth continues at 3.4%/yr; Aden Phase 2 (+120 MW) proceeds ~2026	617 MW	~865,000 tCO_2/yr
High	Organic growth accelerates to 9%/yr (lithium-driven C&I uptake); Aden Phase 2 on schedule; one additional regional project materializes	895 MW	~1,255,000 tCO_2/yr

Energy-use intensity, groundwater, and e-waste are deliberately not projected numerically. Energy-use recovery depends on political outcomes (grid restoration) beyond the scope of trend extrapolation; groundwater data is too thin to responsibly project forward; e-waste's 2040–2042 projection already is the forward-looking figure and is not recalculated here, though it is noted qualitatively that a High-scenario capacity trajectory implies a proportionally larger future disposal cohort in the 2045 and beyond window.



8. Mitigation and Recommendations

8.1 Groundwater

- Establish local groundwater monitoring (piezometers) in known heavy-extraction basins, particularly the Sana'a basin, to pair macro-scale satellite signal with ground-truthed data.
- Explore regulatory or incentive frameworks that pair low-cost solar irrigation access with water-extraction metering, given that the removal of the fuel-cost constraint appears to have removed the only mechanism previously limiting extraction.

8.2 Photovoltaic and Battery Waste

- Begin take-back and recycling framework planning now, despite the 2040s onset, a 15-plus year lead time is a genuine planning asset, not a reason to defer.
- Treat lithium battery waste as a distinct, nearer-term risk from panel waste, given its shorter failure cycle and the documented counterfeit/low-quality battery problem in the Yemeni market specifically.

8.3 Unlocking Solar's Untapped Agricultural Potential

- The Ma'rib finding that solar's cost advantage alone did not drive adoption absent a fuel crisis suggests real, actionable potential in similar governorates: targeted financing or outreach programs could unlock solar-irrigation adoption without waiting for the next fuel-supply shock to force it.

8.4 Continued Monitoring

- This study's zero-budget, satellite-based methodology is demonstrably repeatable. Re-running the core Earth Engine scripts annually would extend every time series at negligible cost, and 2025–2027 is specifically the window in which the newly-identified lithium battery market effect should first become observable.

9. Limitations

- No primary field validation findings describe observable trends and correlations, not ground-verified causal impact.
- Reliance on secondary data of varying age, method, and reliability, addressed through the triangulation protocol but not eliminated by it.
- GRACE/GRACE-FO groundwater data is national-scale only; Yemen's coverage in the satellite's measurement grid is too coarse for governorate-level resolution.
- The avoided-emissions estimate is assumption-based (capacity factor, emission factor) and has not been validated against Yemen-specific fuel-displacement data.
- Official capacity statistics likely undercount the informal household solar market, affecting both the e-waste projection and any capacity-based estimate.
- Sentinel-2 solar footprint mapping was narrowed to a single reference site rather than pursued as a national trend, given genuine resolution and data-availability constraints.
- Population displacement and rural-to-urban migration were identified as a real confounding factor for governorate-level energy-use interpretation but were deliberately not investigated beyond a single interpretive caveat, as full investigation falls outside this study's defined environmental scope.
- Dynamic World land-cover classification shows a known, unresolved disagreement with NDVI in terraced highland terrain (Raymah, Al Mahwit), reported as an open limitation rather than forced into resolution.

10. Conclusions

Yemen's transition from public grid electricity to decentralized solar power is best understood as crisis-driven substitution, not planned energy transition or value-driven technology adoption. It measurably softened without resolving, the country's energy crisis, delivers real but indicatively-estimated emissions benefits, and carries two genuine, currently under-monitored environmental risks whose timelines this study has, for the first time, attempted to quantify: a plausible acceleration of groundwater depletion, and a foreseeable photovoltaic and battery waste stream beginning in the 2040s.

The methodology applied throughout this study, cross-validating satellite remote sensing against secondary literature, executed at zero budget, proved workable for a data-scarce, conflict-affected setting, and the approach is transferable to comparable contexts where field access and funding are similarly constrained.

11. About Adaa Foundation:

Adaa Foundation for Studies and Research is an independent Yemeni research and consultancy foundation working across monitoring and evaluation, institutional diagnostics, and applied data analysis. This study was conducted as a self-initiated, non-budgeted knowledge product, built entirely on free satellite and secondary data sources and cross-validated using a two-stream triangulation protocol.

The methodology demonstrated here is repeatable at negligible marginal cost and represents a durable internal capability independent of this study's specific findings. Adaa Foundation is positioned to extend this work through a funded, field-validated follow-on study, building on the data-availability groundwork established here, and welcomes partnership inquiries toward that end

12. References

Secondary Literature and Reports

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Appendix A: Summary Data Tables

Full governorate-year datasets for all eight indicators (VIIRS, NDVI, cropland fraction, built-up fraction, NO2, CO, GRACE-FO, and solar capacity) are maintained in the companion workbook, Yemen_Solar_EIA_Data_Register.xlsx, including the full 264-row governorate-year panel and the aggregate governorate summary. The tables below are national-level summaries only.

A.1 National VIIRS Mean Radiance, 2013–2024

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
National mean radiance	1.066	0.915	0.366	0.166	0.417	0.459	0.471	0.563	0.626	0.638	0.765	0.759

A.2 National Solar Capacity (MW), 2015–2024

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Capacity (MW)	60	81	103	253	254	258	258	264	290	410

Appendix B: Methodology and Tools Notes

All satellite data was accessed through Google Earth Engine (Community Tier, noncommercial registration) and Microsoft Planetary Computer (no registration required). Governorate boundaries were sourced from the geoBoundaries public community catalog. Zonal statistics (governorate-level means) were computed using Earth Engine's reduceRegions function; results were exported as CSV via Google Drive and processed into the data register using Python (openpyxl, csv). No paid tools, commercial imagery, or field equipment were used at any stage of this study, consistent with its zero-budget design.

Appendix C: Maps of Environmental Transition Indicators Associated with Solar Energy

This appendix presents choropleth maps illustrating governorate-level changes between 2013 and 2024 based on four remote sensing indicators: energy-use intensity, vegetation cover, agricultural land, and built-up areas. All maps display absolute changes rather than percentage changes to ensure consistent and reliable comparison across governorates.