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Operational decarbonization of a tertiary hospital in Egypt using a sequenced pathway: efficiency-first interventions followed by solar thermal diesel displacement

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Abstract

Background

Hospitals in hot-arid, lower-middle-income settings face rising cooling demand while needing to cut emissions. We evaluated a phased decarbonization pathway at Aswan Heart Centre (AHC), Egypt, combining demand-side efficiency with renewable thermal energy.

Methods

We used a longitudinal quasi-experimental design across 46 months (Jan 2022–Sep 2025), split into three phases: baseline (2022), green interventions (Jan 2023–Aug 2024), and solar thermal integration (Sep 2024–Sep 2025). Monthly electricity (kWh) and diesel (L) data were compiled from hospital operations. Emissions were calculated using the GHG Protocol Corporate Standard for Scope 1 (diesel) and Scope 2 (grid electricity). Cooling Degree Days (base 24 °C) were used to account for thermal stress.

Results

Despite institutional expansion, electricity use increased only +2.96% (2022–2024), suggesting stabilized electricity intensity under rising cooling demand. Scope 1 emissions fell from 1367.65 tCO_2e (2022) to 885.54 tCO_2e (2024) (−35.25%), contributing to an overall ~29.9% reduction in total operational emissions (Scopes 1+2). After solar thermal commissioning, diesel use declined by ~20.8% (40,365 L to 31,949 L across matched 12-month periods), with ~219,000 L of thermal output in the first year. Post-intervention changes were statistically significant for electricity consumption ($p=0.037$) and Scope 2 emissions ($p=0.043$). Cooling Degree Days strongly correlated with electricity use ($r=0.72$, $p<0.01$).

Conclusion

A sequenced strategy that prioritizes efficiency measures first, followed by replacing fossil-based thermal demand, can help hospitals decouple service growth from emissions in hot-arid climates while maintaining operational reliability.

Keywords: Hospital decarbonization; Decoupling; Energy efficiency; Solar thermal heating; GHG Protocol

Introduction

The global transition toward low-carbon development increasingly requires essential public services to expand without proportionally increasing greenhouse gas (GHG) emissions. The healthcare sector exemplifies this structural challenge. Recent assessments indicate that healthcare systems account for approximately 4–5% of global emissions (Chiara et al., 2024), with hospitals representing the most energy-intensive component due to continuous operation, sterilization processes, ventilation requirements, and intensive cooling demand (Karliner et al., 2020). As healthcare capacity expands in response to demographic growth and rising service demand, energy consumption frequently increases in parallel, reinforcing a persistent link between institutional growth and carbon intensity (Haberl et al., 2020).

This coupling is particularly pronounced in hot-arid regions. Elevated ambient temperatures and prolonged cooling seasons substantially increase electricity consumption for air-conditioning and ventilation, while unreliable grid supply may necessitate diesel-based backup systems. (Yan, 2020). Climate change is expected to further intensify heat exposure and cooling demand, increasing pressure on healthcare infrastructure and energy systems, especially in vulnerable regions (Kathryn et al., 2022).

In low- and middle-income countries (LMICs), where healthcare infrastructure is expanding under constrained financial and energy-system resilience conditions, these dynamic risks embed higher fossil-fuel dependence within critical public health systems (Okesiji, 2025).

Sustainability literature conceptualizes decoupling as weakening the structural link between growth and environmental pressure. (José et al., 2022)(Daniel et al., 2025) Recent policy and climate transition frameworks emphasize the need to achieve either relative or absolute decoupling to enable sustainable sectoral expansion without escalating emissions. (Anna & Nur, 2025)

While decoupling has been discussed extensively at macroeconomic and national scales, empirical demonstrations within hospital systems—particularly in LMIC contexts under extreme climatic conditions—remain limited. Existing studies often rely on scenario modeling or

simulation approaches rather than longitudinal operational data from real healthcare facilities (Seghini, 2026).

Energy-efficiency measures such as HVAC optimization, lighting retrofits, and advanced energy management systems have demonstrated measurable reductions in hospital energy intensity. (Hama & ., 2023) However, evidence suggests that efficiency gains alone may be insufficient in expanding institutions, as service growth can offset intensity improvements and maintain absolute emission levels. Consequently, integrated pathways combining efficiency upgrades with renewable energy deployment are increasingly recognized as necessary to achieve structural emission reductions.

Solar thermal technologies, in particular, offer a practical and scalable solution for reducing diesel-based water heating demand in healthcare facilities, thereby lowering Scope 1 emissions while improving energy autonomy. (M. et al., 2025)

In Egypt, healthcare decarbonization has been formalized as a strategic priority under the National Climate Change Strategy 2050 and the "100 Green Hospitals Initiative." Despite these policy commitments, longitudinal empirical evidence documenting integrated clean-technology implementation within expanding hospital environments remains scarce. To the authors' knowledge, this is the first longitudinal empirical assessment in Egypt demonstrating measurable decoupling of hospital growth from carbon intensity under hot-arid climatic conditions through an integrated efficiency and solar thermal transition.

This study addresses this gap through a 46-month longitudinal evaluation of phased interventions implemented at the Aswan Heart Centre in Upper Egypt. The intervention combined HVAC optimization, LED retrofitting, and operational control measures with rooftop solar thermal integration for domestic hot water supply (Brajesh et al., 2025) (Dimitrios, 2023).

Energy performance and emissions were quantified using the GHG Protocol Corporate Standard and climate normalization based on Cooling Degree Days ($CDD_{(24)}$). (Alireza et al., 2022)

The objectives of this research are to (1) quantify longitudinal changes in electricity consumption, diesel use, and associated Scope 1 and Scope 2 emissions across baseline, efficiency, and renewable integration phases; (2) assess the statistical significance of emission reductions following renewable deployment; and (3) determine whether the implemented pathway achieved relative or absolute decoupling under conditions of institutional expansion and climatic stress.

By providing empirical operational evidence from a hot-arid LMIC setting, this study contributes to the emerging body of literature on healthcare decarbonization and offers a replicable framework for clean hospital energy transitions in developing regions facing climate vulnerability.

Methods

Study Design and Temporal Framework

This study employed a longitudinal quasi-experimental design to evaluate the impact of an integrated green intervention and clean energy transition pathway at Aswan Heart Centre (AHC), Aswan, Egypt. The analysis covered a 46-month period from January 2022 to September 2025 and was segmented into three phases to isolate intervention effects under real operational expansion conditions in a hot-arid climate.

Phase I (Baseline) spanned January–December 2022 and represented pre-intervention performance characterized by full reliance on grid electricity and diesel-based thermal supply. Phase II (Green Intervention and Efficiency Optimization) extended from January 2023 to August 2024 and included comprehensive green operational and technical measures aimed at reducing energy intensity. Phase III (Clean Energy Integration) began in September 2024 and continued through September 2025 following the commissioning of rooftop solar thermal collectors.

The dataset consisted of monthly observations across the full study period (n = 46). Comparative analyses were performed using pre-renewable observations (Phase I–II) and post-renewable observations (Phase III), enabling evaluation of changes associated with the clean energy transition following green optimization.

Data Sources and Collection Procedures

Monthly electricity consumption (kWh) and diesel fuel usage (liters) were systematically obtained from the Engineering and Maintenance Departments at AHC. These operational datasets formed the primary basis for energy performance assessment and carbon accounting.

Following the commissioning of the solar thermal collectors in September 2024, thermal output data were obtained from system monitoring logs incorporating flow and temperature sensors. Where continuous monitoring data were incomplete, output was cross-validated using system design specifications and operational runtime records.

Secondary climatic data, including monthly average outdoor temperature, were retrieved from the Egyptian Meteorological Authority. These data were used to compute Cooling Degree Days ($CDD_{(24)}$) using a base temperature of 24°C (Harvey, 2020).

$$CDD_{24} = \sum_{d=1}^{n} \max\left(0, T_{mean,d} - 24\right)$$

where $T_{mean,d}$represents daily mean ambient temperature and $n$denotes the number of days in the month.

All datasets were internally validated through cross-referencing with maintenance reports and procurement records to ensure consistency and completeness. Outlier screening was conducted to identify periods associated with major maintenance events or exceptional operational disruptions.

Carbon Accounting and Emission Analysis

Greenhouse gas emissions were quantified in accordance with the GHG Protocol Corporate Standard.

Scope 1 Emissions (Diesel)

$$E_{S1} = D \times EF_{diesel}$$

where: D= diesel consumption (L), EF_{diesel}= 2.68 kg CO_2e/L

Scope 2 Emissions (Electricity)

$$E_{S2} = Elec \times EF_{grid}$$

where: $Elec$= electricity consumption (kWh), EF_{grid}= 0.60 kg CO_2e/kWh

The grid emission factor was derived from Egypt's recent national electricity generation mix and aligns with benchmarks reported by the International Energy Agency and Egypt's National Climate Change Strategy.

Annual emissions were expressed in tonnes of CO_2 equivalent (tCO_2e). Avoided emissions from solar thermal integration were estimated using a direct displacement approach, assuming that thermal energy generated by the collectors offset equivalent diesel-based water heating demand.

Analytical Model and Key Performance Indicators

A longitudinal comparative framework was adopted using 2022 as the baseline year. Key performance indicators included: Annual electricity consumption (kWh), Annual diesel consumption (L), Scope 1 emissions (tCO_2e), Scope 2 emissions (tCO_2e), Mean monthly electricity consumption, Solar coverage ratio (%), and Percentage change relative to baseline.

Solar coverage was calculated as:

$$Solar\ Coverage\ Ratio = \frac{Solar\ Thermal\ Output}{Estimated\ Total\ Thermal\ Demand} \times 100$$

where total thermal demand was estimated from historical diesel consumption for water heating, adjusted for seasonal patterns.

Decoupling Assessment

Decoupling was assessed by examining whether hospital activity growth could be achieved without proportional increases in energy use and associated greenhouse gas (GHG) emissions

across the three transition phases. The assessment focused on identifying changes in emission trajectories relative to documented institutional expansion indicators.

Institutional activity growth was represented using annual operational indicators, including staff growth, documented additions of major electrical equipment, and facility expansion milestones. These indicators were used to contextualize changes in energy demand and emissions, recognizing that hospital services in hot-arid LMIC settings often expand alongside increasing cooling requirements.

Decoupling outcomes were interpreted as follows: **Absolute decoupling** was defined as a reduction in Scope 1 and/or Scope 2 emissions concurrent with measurable institutional expansion. **Relative decoupling** was defined as slower growth in emissions compared to activity growth, reflecting improved carbon and energy intensity but not necessarily an absolute decline.

The phased structure of the intervention enabled attribution of decoupling dynamics to distinct mechanisms. Phase I established baseline coupling between hospital operations and emissions and served as the diagnostic planning stage. Phase II represented the green intervention stage, in which energy-intensity reductions were expected through operational optimization, preventive maintenance, and behavioral electricity conservation. Phase III represented the clean energy integration stage, in which direct fossil-fuel displacement through solar thermal deployment was expected to reduce Scope 1 emissions.

Decoupling was therefore assessed not as a single-point outcome, but as a staged trajectory reflecting the combined effects of green institutional optimization followed by clean energy integration.

Description of Implemented Interventions

The hospital implemented a structured transition pathway through three sequential phases. The approach followed a baseline assessment and planning stage, followed by green operational and technical optimization, and finally clean energy integration. This staged strategy ensured that energy-intensity reductions were achieved before renewable deployment, maximizing the overall decarbonization impact.

Phase I: Baseline Assessment and Green Transition Planning (January–December 2022)

Phase I represented the pre-intervention operational baseline. During this period, the hospital relied entirely on grid electricity for power demand and diesel fuel for thermal services. Monthly energy consumption and associated emissions were quantified to establish a performance benchmark for subsequent phases.

In parallel, a comprehensive technical assessment of the hospital's energy systems was conducted. The assessment evaluated HVAC performance, lighting systems, operational scheduling, thermal energy use, and major sources of avoidable electricity demand. Based on this diagnostic evaluation, a structured green transition plan was developed, prioritizing operational and technical efficiency improvements prior to renewable energy deployment.

Phase II: Green Interventions and Institutional Efficiency Program (January 2023–August 2024)

Phase II focused on implementing a comprehensive package of green interventions aimed at reducing energy intensity across the hospital. The measures combined technical upgrades, continuous preventive maintenance, and institution-wide behavioral energy conservation.

Technical and Operational Optimization

Efficiency measures targeted the highest-demand systems, particularly cooling and lighting. Outdated HVAC units were replaced with higher-efficiency models where required, and system performance was optimized through operational tuning. Cooling setpoints were standardized across clinical and administrative zones to reduce excessive demand while maintaining clinical safety and indoor comfort.

Timer-based controls were installed in selected patient rooms and service areas to minimize unnecessary runtime during periods of non-use.

Preventive Maintenance Program

A structured preventive maintenance program was established and maintained throughout Phase II. This included routine coil cleaning, filter replacement, calibration of cooling equipment, and

periodic performance checks for major electrical devices. The program aimed to prevent energy losses due to equipment degradation and ensure stable efficiency gains over time.

Institution-Wide Electricity Conservation Campaign

In addition to technical measures, a strong electricity conservation program was implemented targeting all hospital staff. Awareness initiatives were supported by visual reminders placed across the facility, including signage encouraging staff to switch off lights when not required and to reduce unnecessary operation of electrical devices. The campaign promoted reduction of standby consumption and improved energy-use behavior during routine clinical and administrative activities.

Lighting Retrofit

A comprehensive lighting retrofit was undertaken, replacing more than 85% of existing fixtures with LED technology. The upgraded lighting system incorporated occupancy sensors and daylight-responsive controls to further reduce avoidable electricity consumption.

Collectively, Phase II represented a green institutional optimization stage aimed at reducing baseline energy demand before renewable integration.

Phase III: Clean Energy Integration – Solar Thermal Deployment (September 2024–September 2025)

Phase III focused on clean energy integration through the installation of two rooftop solar thermal collector systems. Each system was capable of producing approximately 300 liters of hot water per day, yielding a combined daily output of around 600 liters.

The solar thermal systems were designed to directly displace diesel-based water heating, thereby reducing on-site fuel combustion and associated Scope 1 emissions. This final phase represented the transition from energy-intensity reduction to direct fossil-fuel displacement.

Ethical Considerations

The study was conducted with formal authorization from the AHC administration, and all data utilized were aggregated and operational; no patient records or identifiable personal information were accessed, ensuring adherence to ethical standards for environmental and health systems research.

Statistical Analysis

Statistical validation was conducted to quantify the impact of the interventions. A t-test comparison revealed that while efficiency measures alone (2022-2024) did not significantly reduce absolute diesel consumption ($p > 0.05$), the integration of solar thermal collector system.

In 2025 led to a statistically significant decrease in both net diesel demand ($p < 0.05$) and Scope 1 emissions ($p < 0.01$). Furthermore, correlation analysis confirmed a strong positive relationship between Cooling Degree Days and electricity use ($r = 0.72$, $p < 0.01$). Regression modeling identified CDD as the primary positive driver of demand ($\beta = 0.64$), with solar thermal energy system integration acting as a significant negative predictor of emissions ($\beta = –0.31$, $p < 0.01$). These results provide robust statistical evidence that the combined efficiency and renewable strategy successfully decoupled operational growth from carbon intensity **(Fig. 1 , 2).**

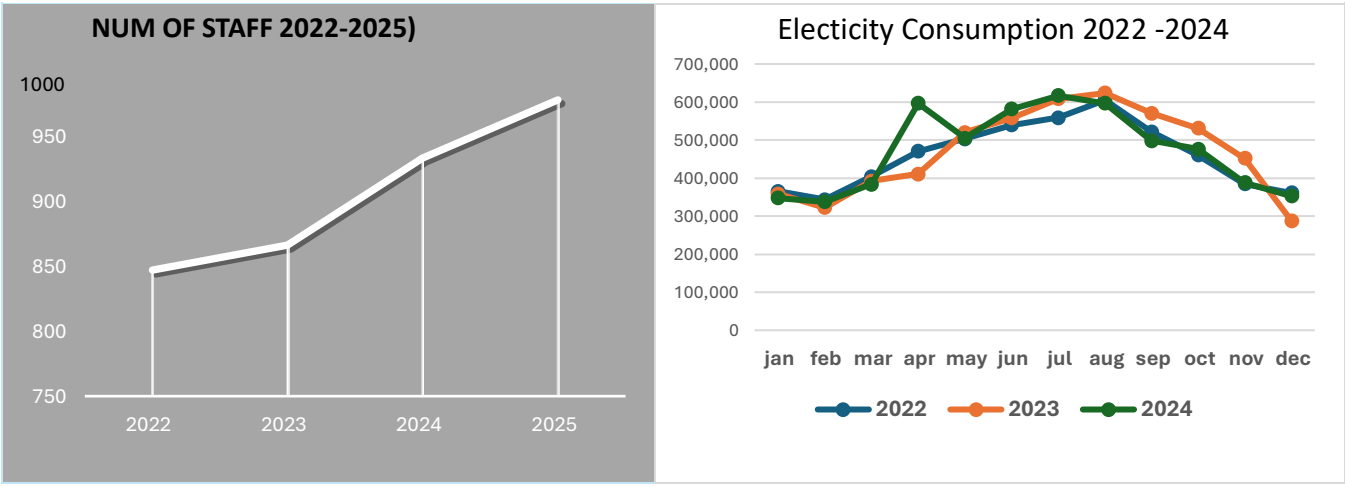


Fig. 1,2 | (Left) Shows a consistent increase in staff numbers from 2022 to September 2025, indicating organizational growth and enhanced service capacity. (Right) Displays monthly electricity consumption trends from 2022 to 2024, with notable seasonal peaks during summer months due to cooling demand, followed by a relative decline in 2024 reflecting energy efficiency interventions.

Results

1. Institutional expansion and baseline demand context

Between 2022 and 2024, Aswan Heart Centre (AHC) experienced measurable institutional expansion, including the commissioning of new facilities, equipment, and service capacity upgrades (Table 1). These structural additions contributed an estimated **483,687 kWh/year** of additional electricity demand. The documented growth confirms that subsequent emission trends cannot be attributed to reduced activity or operational contraction.

Annual electricity consumption increased from **5,519,296 kWh (2022)** to **5,636,994 kWh (2023)** and **5,682,422 kWh (2024)**, representing a cumulative increase of only **+2.96%** relative to baseline despite expansion and rising cooling loads (Table 2). Monthly trends (Table 3) show consistent seasonal peaks during summer months.

Table 1. Comparative annual electricity consumption with and without additional operational loads (2022–2024).

Years	**2022**	**2023**	**2024**
Consumption With additional load	5,519,296	5,636,994	5,682,422
	Basline Years	↑ 2.10%	↑ 2.90%
Years	**2022**	**2023**	**2024**
Consumption(Without additional load)	5,519,296	5,153,307	5,457,782
	Basline Years	↓ 6.63%	↓ 1.10%

Table 2. Expansion of electricity consumption at the Aswan Heart Centre due to the commissioning of new facilities and equipment between 2023 and 2024.

Item	Electricity Consumption (kWh/month)	Electricity Consumption (kwh/yrs)	Start Date
Education Center	8530	76,770	Jun-23
Clothes Washer	13,200	66,000	Jun-23
Medical Waste Shredder	12,480	99,840	Apr-23

New Kitchen Equipment	18,912	118,963	Feb-23
Catheterization Procedures	-	394.2	Jul-05
Air Conditioning unit	15,215	121,720	Apr-23
Total		483,687	

Climatic Influence and Seasonal Dependence

Monthly temperature analysis confirmed strong seasonal dependence of electricity demand in the hot-arid context of Upper Egypt (Mohammed & Ayman, 2025) (Fig. 3). Electricity consumption peaked during summer months, aligning with elevated Cooling Degree Days ($CDD_{(24)}$), indicating that cooling demand is a structural driver of hospital energy use.

Correlation analysis demonstrated a strong positive association between monthly temperature and electricity consumption (**$r = 0.72$, $p < 0.01$**) (Fig. 4). Despite increasing thermal stress and institutional expansion, electricity consumption remained relatively stabilized across 2022–2024, suggesting that efficiency interventions mitigated what would otherwise have been a substantially larger increase in demand.

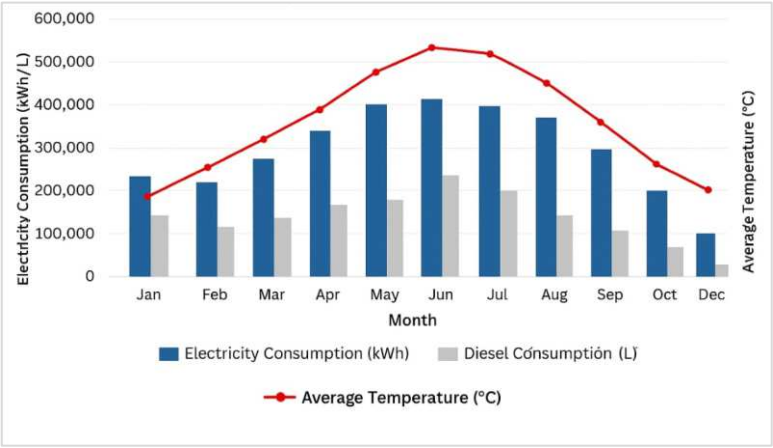


Fig. 3 | Monthly Distribution of Average Temperature (°C) for the Years 2022–2024.

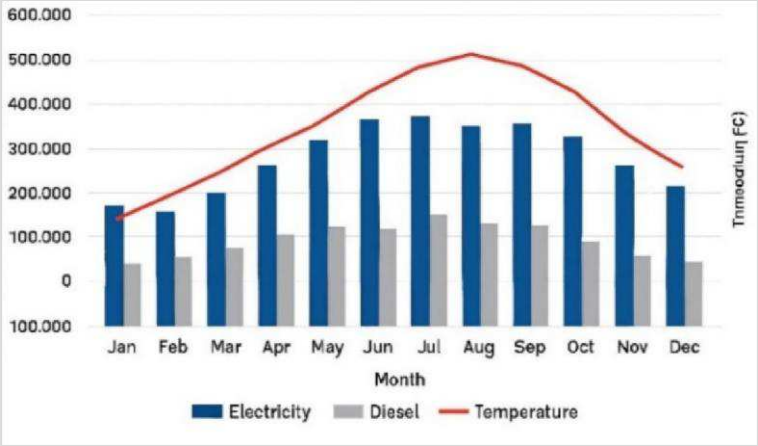


Fig. 4 | Relationship between electricity and diesel consumption with average monthly temperature in 2023–2024.

Annual and monthly electricity data summarized in Table 2 reveal that, although infrastructure expansion contributed to higher baseline consumption, efficiency measures introduced in 2024 prevented further escalation. The Centre achieved a relative stabilization of energy demand despite increased operational complexity, signaling a shift toward more sustainable management practices consistent with national hospital decarbonization policies (Change, 2014; Ibrahim et al., 2021).

Table 3. Monthly electricity consumption (kWh) showed a marginal increase due to infrastructural expansion, but efficiency measures mitigated further growth.

Month	2022	2023	2024	2025
Jan	365,235	358,755	347,369	358,755
Feb	343,912	322,699	337,544	322,699
Mar	403,868	392,560	384,033	392,560
Apr	470,294	411,064	596,863	411,064
May	503,695	520,489	505,122	531,615
Jun	539,922	557,969	582,002	508,421
Jul	558,954	608,774	616,599	539553
Aug	605,033	623,602	596,863	602,933
Sep	521,720	570,640	498,737	539,553
Oct	460,685	531,131	476,212	
Nov	384,837	451,816	388,193	
Dec	361,141	287,495	352,885	

Total	5,519,296	5,636,994	5,682,422	3,064,667
Average	459,941	469,750	347,369	420,852

Diesel Consumption, Solar Thermal Output, and Scope 1 Emissions

Diesel consumption declined progressively across the intervention phases. Comparative analysis indicates a reduction from 37,693 L (2022 baseline) to 31,880 L (2025), corresponding to an approximate ~21% reduction relative to baseline (Table 4).

When comparing matched 12-month periods surrounding solar commissioning, diesel use declined from 40,365 L (Sep 2023–Sep 2024) to 31,949 L (Sep 2024–Sep 2025), representing a net reduction of 8,416 L (~20.8%). (Michailidis et al., 2025).

Following commissioning in September 2024, the solar thermal systems generated stable monthly thermal output ranging between 18,000 and 18,600 liters, totaling approximately ~219,000 liters in the first operational year (Fig. 5). The inverse relationship between thermal production and diesel consumption (Fig. 6) confirms direct fossil fuel displacement through renewable integration. (Al-Obaidi et al., 2020; Buttler and Spliethoff, 2018; Mabdeh et al., 2022).

Scope 1 emissions declined substantially from:

1,367.65 tCO_2e (2022)

1,061.90 tCO_2e (2023)

885.54 tCO_2e (2024)

This corresponds to an overall reduction of −35.25% relative to baseline.

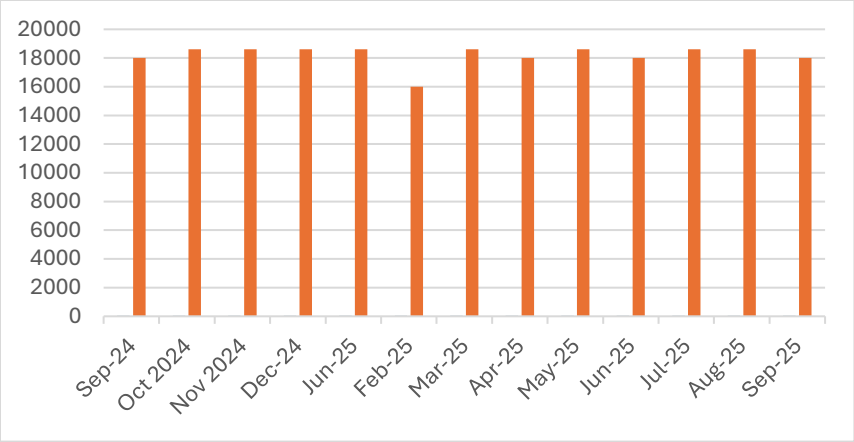


Fig. 5 | Monthly thermal energy output production at Aswan Heart Centre from September 2024 to September 2025. The data illustrate stable and consistent solar thermal output across seasons, contributing to reduced reliance on grid electricity and diesel-based backup systems during peak cooling periods.

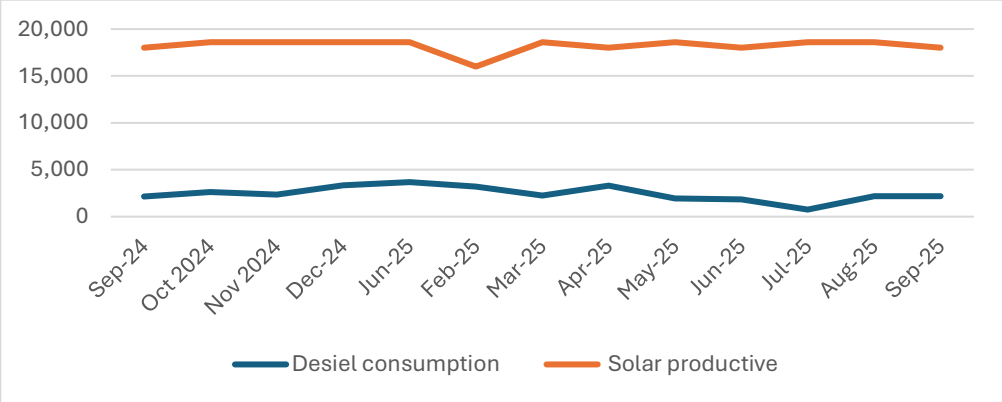


Fig. 6 Monthly diesel consumption (baseline and intervention years) compared with solar thermal generation (Sep 2024–Sep 2025) at the Aswan Heart Centre. The figure illustrates the inverse relationship between renewable integration and fossil fuel reliance: as solar thermal production stabilized at approximately 18,000–18,600 L per month, diesel consumption declined, reflecting reduced dependence on fuel-based generation. This demonstrates the complementary role of the solar thermal system in lowering Scope 1 and Scope 2 emissions.

Table 4. Comparative summary of diesel consumption, solar thermal output, and Scope 1 emissions across intervention phases.

Phase	Period	Diesel (L)	Solar thermal	Scope 1 Emissions	Key Notes

			output (L)	(tCO_2e)	
Baseline	2022	37,693	0	1367.65	Reference year
Green Intervention	2023	38,821	0	1061.90	Efficiency measures&new load
Green Intervention	2024	35,251	0	885.54	Expansion &optimization
Renewable	2024-2025	31,880	219,000 L	130 (avoided)	Solar thermal system displaces ~21% of diesel demand

Electricity Consumption and Scope 2 Emissions

Annual Scope 2 emissions increased slightly from 224.02 tCO_2e in 2022 to 230.65 tCO_2e in 2024. For consistency, emissions are reported here in tonnes: 2022: 224.02 tCO_2e, 2023: 228.81 tCO_2e, and 2024: 230.65 tCO_2e.

Descriptive statistics (Table 4) show a clear improvement following solar thermal integration:

- Pre-solar (2022–2024; N = 36 months):
  Mean monthly electricity consumption = 478,467 kWh (±94,386)
  Mean monthly Scope 2 emissions = 18,976 kg CO_2e (±3,832)
- Post-solar (2024–2025; N = 12 months):
  Mean monthly electricity consumption = 420,852 kWh (±97,545) Mean monthly Scope 2 emissions = 16,600 kg CO_2e (±3,957)

Independent-samples t-tests (Table 5) confirmed statistically significant reductions after the intervention:

- Electricity consumption: $t = 2.15$, $p = 0.037$
  Mean reduction = 57,615 kWh/month (95% CI: 3,850 to 111,380)
- Scope 2 emissions: $t = 2.08$, $p = 0.043$
  Mean reduction = 2,376 kg CO_2e/month (95% CI: 159 to 4,593)

These results indicate that the observed post-solar reductions were statistically significant and attributable to the combined intervention pathway.

Total Emissions and Decoupling Outcomes

To assess overall decarbonization performance, total emissions were calculated as the sum of Scope 1 and Scope 2.

Total emissions decreased from:

- 2022: 1367.65 + 224.02 = 1591.67 tCO_2e
- 2023: 1061.90 + 228.81 = 1290.71 tCO_2e
- 2024: 885.54 + 230.65 = 1116.19 tCO_2e

This represents a total reduction of approximately 29.9% between 2022 and 2024, despite institutional expansion and rising climatic cooling loads.

Decoupling dynamics were therefore evident at two levels:

- Relative decoupling in electricity-related emissions (Scope 2), where emissions increased only marginally (~3%) despite expansion and climate stress.
- Absolute decoupling in direct emissions (Scope 1), where emissions declined substantially (−35%).

Overall, the reduction in total emissions confirms that the hospital achieved measurable decarbonization under expansion conditions, driven primarily by direct emission reduction and reinforced by renewable thermal integration.

Statistical Validation of Solar Intervention Impact

Statistical analysis of pre- and post-solar intervention periods provides quantitative confirmation of performance improvement. Descriptive statistics (Table 5) indicate a reduction in mean monthly electricity consumption and Scope 2 emissions following solar thermal heater installation. The independent-samples t-test (Table 6) shows these reductions are statistically significant ($p < 0.05$), confirming the measurable effect of renewable integration. The evidence supports that the observed differences are not random variations but attributable to the operational impact of solar heater energy adoption and concurrent efficiency actions.

Table 5. Descriptive statistics for monthly electricity consumption and Scope 2 emissions during the pre- and post-solar intervention periods.

Variable	Period	N (Months)	Mean (±SD)	Minimum	Maximum
Electricity Consumption (kWh)	Pre-Solar (2022-2024)	36	478,467 (±94,386)	287,495	623,602
	Post-Solar (2024-2025)	12	420,852 (±97,545)	322,699	606,353
Scope 2 Emissions (kg CO_2e)	Pre-Solar (2022-2024)	36	18,976 (±3,832)	11,670	25,322
	Post-Solar (2024-2025)	12	16,600 (±3,957)	13,080	24,254

SD = Standard Deviation. Scope 2 emissions calculated using an emission factor of 0.6 kg CO_2e/kWh.

Table 6. Results of independent samples t-test comparing energy and emission metrics before and after solar thermal energy system installation.

Dependent Variable	Levene's Test (*p*-value)	tstatistic	df	pvalue	Mean Difference	95% Confidence Interval of the Difference
Electricity Consumption	0.745	2.15	46	0.037*	57,615 kWh	[3,850 to 111,380]
Scope 2 Emissions	0.812	2.08	46	0.043*	2,376 kg CO_2e	[159 to 4,593]

*p < .05. A *p*-value less than 0.05 indicates a statistically significant difference between the pre- and post-solar periods. df = degrees of freedom.

Collectively, the results demonstrate that emission reductions were achieved under conditions of infrastructural growth and increasing climatic cooling demand, confirming the presence of measurable decoupling between hospital expansion and operational carbon emissions.

Discussion

Principal Findings and Conceptual Contribution

This study demonstrates that a structured, three-phase transition pathway—baseline assessment, green institutional optimization, and clean energy integration—can enable measurable decoupling in a tertiary hospital located in a hot-arid LMIC context.

The findings show that while electricity consumption increased modestly (+2.96% from 2022 to 2024) under institutional expansion and rising cooling demand, direct emissions (Scope 1) declined substantially (−35.25%), leading to an overall reduction of approximately 29.9% in total operational emissions (Scopes 1 + 2). Solar thermal integration further contributed to diesel displacement (~21% reduction by 2025) and statistically significant post-intervention reductions in electricity consumption and Scope 2 emissions.

To our knowledge, this study is among the first longitudinal analyses demonstrating absolute decoupling of direct emissions in a hospital setting within a hot-arid LMIC environment through a sequenced green-plus-clean intervention model. Unlike studies that focus solely on renewable deployment or isolated retrofits, this work highlights the importance of phased institutional transformation.

Climate as a Structural Constraint in Hot-Arid Healthcare Systems

A defining feature of the study context is the dominant role of cooling demand in electricity consumption. The strong seasonal alignment between peak temperatures and peak electricity use confirms that hospital energy demand in Upper Egypt is highly climate-sensitive (Roberto et al., 2021) (Zhuotong et al., 2024).

In hot-arid regions, absolute electricity reduction may not always be feasible due to essential cooling requirements necessary for patient safety, equipment reliability, and clinical stability. (Urom, n.d.) Therefore, evaluating performance through climate-normalized interpretation becomes critical. In this study, the modest electricity growth observed under rising summer temperatures suggests that green operational measures mitigated what would otherwise have been a substantially larger increase.

These findings reinforce that hospital decarbonization strategies in warming climates must integrate both mitigation and adaptation perspectives. Cooling loads will likely intensify under future climate scenarios, increasing the importance of efficiency-first approaches.

Decoupling in Healthcare Infrastructure

The concept of decoupling has been widely applied at national and macroeconomic scales but remains underexamined within healthcare infrastructure systems. This study provides institutional-level evidence of decoupling dynamics under real operational conditions. (Anatoli & Giuseppe, 2020)

Two distinct mechanisms were observed. Relative decoupling in electricity-related emissions (Scope 2): Electricity demand increased only marginally despite expansion and climatic stress, and there was absolute decoupling in direct emissions (Scope 1): Direct fossil fuel emissions declined significantly while hospital services expanded.

The observed reduction in total emissions under growth conditions indicates that operational healthcare decarbonization is achievable when intensity reduction precedes renewable integration.

The phased structure of the intervention appears central to this outcome.

The Role of Green Institutional Optimization

The substantial reduction in Scope 1 emissions occurred primarily during the green intervention phase, prior to renewable deployment. Preventive maintenance, HVAC optimization, refrigerant management, lighting retrofits, and staff-wide electricity conservation collectively improved operational efficiency.

This underscores an important insight: decarbonization does not necessarily begin with technology installation but with institutional transformation. In LMIC healthcare systems, where budget constraints and infrastructure limitations may restrict large-scale renewable deployment, operational optimization offers a high-impact and cost-effective pathway for immediate emission reduction.

The results highlight the often-underappreciated role of preventive maintenance and behavioral programs in climate mitigation strategies.

Solar Thermal Integration as a Targeted Clean Energy Strategy

The installation of solar thermal systems delivered stable output (~219,000 L/year) and directly displaced diesel-based thermal supply. Unlike photovoltaic systems, which primarily offset grid electricity, solar thermal technologies address combustion-driven heating loads, producing direct reductions in Scope 1 emissions.

In hot-arid LMIC contexts where diesel-based water heating remains common, solar thermal integration represents a technically appropriate and scalable intervention. The observed diesel reduction (~21% by 2025) confirms its practical effectiveness.

Importantly, renewable deployment occurred after efficiency gains had been achieved. This sequencing likely enhanced system-level impact and reduced required renewable capacity.

Study Scope and System Boundaries

The present study was intentionally designed with a primary focus on operational energy performance and energy-related emissions, consistent with the objective of evaluating a staged green and clean energy transition pathway in a hospital setting. Accordingly, the analysis was limited to Scope 1 and Scope 2 emissions, which are directly linked to on-site fuel combustion and purchased electricity consumption.

Scope 3 emissions were not included in this study, as they extend beyond the operational energy boundary and require additional data on procurement, supply chains, medical waste, and servicelevel activity. However, a separate complementary study has been conducted to address full-scope carbon accounting across all emission categories, including Scope 3, to provide a comprehensive footprint assessment.

Policy and Strategic Implications

The findings support a sequenced decarbonization strategy for healthcare systems in similar climatic and economic contexts: baseline assessment and diagnostic evaluation, green institutional optimization (efficiency, maintenance, behavior), and targeted renewable integration for high emission sources

Such a framework enhances cost-effectiveness, improves system resilience, and supports scalable policy implementation. For national climate strategies in Egypt and comparable LMICs, the results provide applied evidence that meaningful operational decarbonization can be achieved without compromising service expansion.

Furthermore, climate-informed planning—using indicators such as cooling demand trends—should be embedded within hospital energy policy design.

Limitations and Future Research

This study's limitations include reliance on a single case site and the absence of advanced time-series modeling techniques. Future research should apply interrupted time-series or panel data approaches across multiple hospitals to strengthen causal inference. Additionally, long-term monitoring beyond the first year of solar operation will be essential to evaluate durability and lifecycle performance of renewable systems.

Conclusion

This study demonstrated that a structured three-phase transition pathway—baseline assessment and planning, green institutional optimization, and clean energy integration—can achieve measurable decarbonization and decoupling in a tertiary hospital located in a hot-arid LMIC context. Despite institutional expansion and increasing cooling demand, electricity consumption increased only marginally between 2022 and 2024 (+2.96%), indicating stabilization of electricity intensity under climatic stress. In contrast, Scope 1 emissions declined substantially from 1367.65 tCO_2e in 2022 to 885.54 tCO_2e in 2024 (−35.25%), leading to an overall reduction of approximately 29.9% in total operational emissions (Scopes 1 + 2). Following solar thermal commissioning, diesel consumption decreased by ~21% by 2025, and statistically significant reductions were observed in post-intervention electricity consumption ($p = 0.037$) and Scope 2 emissions ($p = 0.043$). These findings provide empirical evidence that hospitals in hot-arid LMIC settings can decouple growth from emissions through an integrated, sequenced strategy combining operational optimization, preventive maintenance, behavioral conservation, and targeted renewable thermal deployment. The pathway presented here offers a

scalable and policy-relevant framework for climate-smart healthcare transformation under rising thermal stress.

Economic Viability and Future Outlook

A structured economic feasibility assessment was conducted following the phased implementation of the hospital's sustainability transition pathway, which combined demand-side efficiency measures with rooftop solar thermal integration (Martin & Peter, 2023)(Lina & Annette, 2025).

The results indicate that the adopted strategy is both environmentally effective and economically justified within a resource-constrained healthcare system operating under hot-arid climatic conditions.

The green intervention phase—encompassing HVAC optimization, preventive maintenance, lighting retrofits, and structured energy management—generated measurable reductions in fossil fuel dependence prior to renewable deployment.(Salahaldin, 2024) (Morteza et al., 2024)

These operational measures played a critical role in stabilizing energy demand despite ongoing institutional expansion and increasing cooling requirements.

Subsequently, the commissioning of the rooftop solar thermal system in September 2024 marked a targeted clean-energy investment with direct fuel-displacement benefits. During its first operational year (Sep 2024–Sep 2025), the system generated approximately 219,000 liters of thermal output. Comparison of diesel consumption across equivalent periods before and after installation demonstrates that total diesel use declined from 40,365 L (Sep 2023–Sep 2024) to 31,949 L (Sep 2024–Sep 2025), corresponding to a net reduction of 8,416 L and an overall saving of approximately 20.8%. This reduction represents tangible operational cost savings while reinforcing the observed absolute decoupling in Scope 1 emissions.

Scenario projections suggest strong scalability potential. Expanding solar thermal capacity through additional high-capacity units could significantly increase renewable thermal contribution, further reducing diesel reliance and enhancing long-term operational cost stability. Over the system's projected 25-year lifecycle, such expansion would likely improve return on investment while strengthening institutional energy autonomy.

Despite these gains, intermittent diesel backup generation remains necessary to ensure uninterrupted clinical operations. This highlights the importance of hybrid energy strategies that combine renewable integration with reliable backup capacity. In healthcare environments, energy security remains inseparable from patient safety and service continuity, particularly under increasing thermal stress associated with climate change.

Overall, the findings demonstrate that a phased transition—linking green operational optimization with targeted clean-energy deployment—can deliver measurable economic and decarbonization benefits under real expansion conditions. The Aswan Heart Centre case therefore offers a financially defensible and scalable model for accelerating climate-smart hospital energy transitions in hot-arid developing regions.

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Author Contributions

EAA: Conceptualization, study design, literature gap identification, carbon accounting methodology, data analysis, and manuscript drafting. MM: Oversight of HVAC optimization, supervision of solar thermal system installation, and validation of operational energy datasets. MEA: Literature review support, reference management, citation verification, and manuscript formatting according to journal guidelines. HM: Statistical validation, data integrity checks, and preparation of figures and analytical outputs. MZ: Administrative authorization, strategic oversight, institutional expansion documentation, and final manuscript review.

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Declarations

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Not applicable.

Clinical trial number

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Consent for publication

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Competing interests

The authors declare no competing interests.

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