Techno-Economic Pathways for Retrofitting Urban Residential Buildings with Solar Photovoltaics: Enabling Smart Grid Transition in Alexandria, Egypt

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Abstract:

The residential sector in Alexandria, Egypt, consumes a considerable portion of the total electricity use, but energy efficiency and renewable integration have not been much studied. This paper proposes a novel framework for retrofitting existing residential buildings with building-integrated photovoltaic (BIPV) systems connected to smart grids that allow passive consumers to become active players in decentralized energy networks. The study adopts an analytical design-research methodology that integrates field surveys, GIS mapping, digital simulations, and solar performance modeling within the Al-Shalalat district. Monocrystalline silicon PV modules were optimized for roof and façade integration by considering shading and spatial constraints. Results show that 55% of buildings can generate surplus electricity while 45% partially meet their demand indicating high potential for residential solar retrofitting. This paper will further describe the importance of smart grids as a prerequisite to achieve efficient energy distribution, load management, and household engagement. Recommendations include comprehensive building and consumption databases, financial incentives, façade-integrated PV research, public awareness campaigns, and ICT infrastructure.

Keywords: Keywords: BIPV, Smart Grids, Residential Retrofitting, Renewable Energy, Sustainable Cities, Alexandria, Egypt.

INTRODUCTION

Problem Statement and Contextual Background

The residential building sector in Alexandria, Egypt is an important consumer of electricity. This is in line with national trends in urbanization, population growth, and increasing standards of living (Attia, 2012; Boko et al., 2007). Long hot summer periods together with high indoor thermal comfort requirements have increased energy use. Heavily subsidized electricity has reduced incentives for efficiency and conservation (Abdallah, 1995). Traditional climate-responsive architectural strategies—such as building orientation shading thermal mass natural ventilation daylighting—have been largely neglected resulting in poorly performing repetitive residential blocks (Attia 2012). Informal vertical expansion limited construction oversight inconsistent building quality further stressed urban infrastructure placing unsustainable loads on electrical networks. Residential electricity consumption is concentrated among high-use households and projections indicate continued growth due to expanding housing stock increased appliance ownership heightened expectations for thermal comfort (Boko et al., 2007; Georgy et al., 2007). Even though initiatives such as the Egyptian Standard for Enhancement of Energy Usage in Residential Buildings (ECP306 – 2005) offer regulatory support for energy efficiency, actual implementation has not gone beyond the pilot stage (Huang et al., 2003). Subsidized pricing together with minimal private-sector participation in energy generation contributes to the absence of a market for energy-saving and renewable technologies. In this context, building-integrated solar energy systems connected to smart grid infrastructure represent an appropriate solution. Retrofitting existing residential buildings can turn them from passive consumers into active players within resilient decentralized sustainable urban energy networks which will help achieve Egypt Vision2030 and UN Sustainable Development Goals related specifically to energy SDGs 7,11&13.

Table 1. Key Statistics on Residential Energy Consumption in Alexandria (2011- 2025)

Year	Total Residential Energy Consumption (kWh)	Average Consumption per Household (kWh)	Growth Rate (%)
2011	8,950,000,000	3,250	—
2012	9,320,000,000	3,310	**4.1%**
2013	9,780,000,000	3,390	**4.9%**
2014	10,420,000,000	3,520	**6.5%**
2015	11,050,000,000	3,640	**6.0%**
2016	11,630,000,000	3,720	**5.2%**
2017	12,140,000,000	3,780	**4.4%**
2018	12,760,000,000	3,860	**5.1%**
2019	13,420,000,000	3,950	**5.2%**
2020	13,980,000,000	4,020	**4.2%**
2021	14,620,000,000	4,110	**4.6%**
2022	15,340,000,000	4,230	**4.9%**
2023	16,120,000,000	4,360	**5.1%**
2024	16,950,000,000	4,480	**5.1%**
2025	17,820,000,000	4,600	**5.1%**

Chapter I: Aim and Objectives

Aim

This study assesses the architectural feasibility of integrating building-integrated solar energy systems into existing residential structures within Alexandria under consideration of their compatibility with emerging smart electrical grids toward sustainable decentralized production of such energy.

Objectives

- Explore appropriate architectural strategies for integrating solar electricity generation systems into existing residential buildings by considering aspects related to building form development envelope design as well as urban context's characteristics.
- Analyze a typical residential case study located in Alexandria while considering climatic conditions prevailing urban density levels social acceptance aspects plus economic feasibility parameters.
- Identify different types of BIPV systems available regarding their spatial aesthetic functional suitability.
- Develop an architectural framework that can be applied at scale to retrofit clusters of residential buildings.
- Position smart grids as part of the enabling infrastructure for distributed energy generation efforts toward energy efficiency improvements plus strengthening overall grid resilience.

Chapter II: Methodology

This study adopts an analytical design-research methodology through field surveys, digital simulation, and spatial analysis. It starts with a literature review of solar retrofitting, smart grid integration, and international best practices. The on-site survey supported by GIS and other environmental modeling tools documents building orientation, shading, density, street networks, roof and façade performances. Climatic data and solar data are taken from official meteorological records validated digital databases. Data are synthesized through GIS mapping, performance diagrams as well as design-driven analytical models to assess various scenarios of solar integration. Architectural form, spatial constraints related to the building-integration feasibility for solar technologies will be assessed along with installation possibilities; where direct integration is not feasible then design adaptations will be proposed. The methodology includes the concepts of smart grids and their pilot projects as residential buildings participating actively in energy systems towards a sustainable low-carbon urban energy network (Attia 2012; Huang et al. 2003). Residential Occupants as Active Participants in Smart Power Systems Distributed generation integrated into the grid transforms a conventional passive grid into an active intelligent network (Micheli et al., 2012). Households participate in this transformation through load management, demand response, micro-generation using smart meters and the ICT infrastructure backbone (Clastres 2011; Krishnamurti et al. 2011; Ngar-yin Mah et al. 2012). Demand-side management (both emergency and economic) can help reduce peak loads by up to 20% of total consumption (Clastres 2011). Residential concerns regarding upfront costs, electricity pricing reforms, privacy issues concerning cybersecurity as well as equity in access need to be addressed for adoption (Hidayatullah et al., 2011; Krishnamurti et al., 2011; Welsch et al., 2012). Market strategies such as dynamic pricing, incentive-based demand response plus energy service contracts induce active participation plus support equitable access. Advanced ICT infrastructure allows real-time monitoring plus automated control providing stability for the grid while households acting like micro-generators could sell surplus energy inducing a two-way participatory system of energy (Zhang 2009; Ngar-yin Mah et al.,2012). In developing countries like Egypt, smart grids provide an opportunity for bypassing conventional limitations toward expanded electrification plus inclusive low-carbon urban development (Welsch et al.,2012). Residential buildings thus become architectural hubs as well as energy hubs bridging design with technology plus sustainability objectives.

International Pilot Projects

Egypt has recognized the strategic importance of renewable energy. The EEHC (2010) states that the national energy strategy emphasizes diversification and aims to create an increase in renewable energy contributions up to 20% by 2020, with further ambitions for greater shares by 2025. Some initial steps included the Kriemat solar thermal power plant (140 MW total, 20 MW solar) financed through the Global Environmental Facility and the Japan Bank for International Cooperation. International experiences carry critical lessons for integrating solar technology into residential buildings and connecting them with smart grids. In Germany, the "100,000 Rooftop Photovoltaic Program" (1999–2004) supported installation of rooftop PV on 100,000 rooftops. Financial incentives comprising 10-year zero-interest loans plus feed-in tariffs subsidized costs by 30-40% achieved a cumulative installed capacity of 300 MW by 2004 (Wissner, 2011). The Renewable Energy Law (EEG, 2000) required grid operators to connect renewable plants buy feed-in power at statutory rates and pay an additional purchase price resulting in achieving a share of 16% electricity from renewables by 2009 (Wissner, 2011). Germany has also integrated ICT into household and grid systems that allow smart appliances control, data collection, and real-time management of energy. Wireless networks such as GPRS, WiMAX, and LTE enabled mobile monitoring as well as the remote control of household devices thus promoting a smart residential energy system(Wissner,2011). In South Korea, a large-scale pilot on Jeju Island(2009) involved about two thousand households testing integration with renewable energy management via smart meters from the consumer side(Ngar-yin Mah et al.,2012). The limited regulatory support resulted in low consumer trust and minimal stakeholder engagement indicating that policy frameworks are important as well as public awareness and institutional incentives if deployment is to be successful(Ngar-yin Mah et al.,2012). These cases prove that residential solar integration works best with smart grids when there is supportive policy, financial incentives, ICT infrastructure, and active consumers. The lessons from Germany and the experience of South Korea can practically guide how Egypt's residential buildings may transition from passive consumers to active participants in energy management through both technological and social strategies, converting existing buildings into dynamic power nodes.

Field Survey and Applicability of Solar Systems

This analytical research attempts integration of building-integrated solar photovoltaic (BIPV) systems into already existing residential buildings via a case study based on an analytical solar field survey. The study is conducted in a representative residential area of Al-Shalalat district, Alexandria, Egypt. The architectural, environmental, and technical feasibility of retrofitting the systems while connecting the buildings to a smart power grid infrastructure has been evaluated. The methodology uses field observations together with geographic mapping and computer simulations, as well as official data sources to achieve reliable results.

Study Area Delineation and Mapping

The study area was selected in order to represent typical characteristics of residential buildings within Alexandria city. Accurate mapping is an important prerequisite for capturing building footprints, dimensions of roofs, widths of roads, orientation as well as heights of the surrounding landscape. Since standard mapping tools such as Google Maps are limited by low-resolution imagery, high-resolution map tiles were obtained using Google Maps Static API at zoom level 25 which is sufficient for accurate solar analysis. The study area is bounded by Sultan Hussein Road and Horreya Road (east-west) on one side, while on another side it is bounded by Nouh Affendie Street and Victoria Basseli Street (north-south). These streets provided reference points for assessing building shadowing and solar exposure.

Figure 1. Residential Neighborhood subjected to Solar Field Survey

Source: Rana Elbakly, 2026. Figure created by the author.

Solar Field Survey Parameters

The solar field survey consisted of three categories of parameters:

- Site- and Buildings-related Parameters
- Occupants-related Parameters
- PV-Modules-related Parameters

Site- and Buildings-related Parameters included geographic location, building orientation, heights, density, roof inclination, available roof and façade areas as well as road widths which are necessary for assessing mutual overshadowing (Attia 2012; Goetzberger et al. 2005). The following solar and weather data were obtained:

- Direct normal radiation (kWh/m²/day)
- Maximum and minimum insolation
- Clear sky insolation and clearness index
- Cloud cover and no-sun days
- Frost days per year

Occupants-related Parameters included household electricity usage patterns, age and occupation demographics, economic-cultural backgrounds as well as appliance ownership (Acharjee 2012; Dimas 2011; Ngar-yin Mah et al. 2012). These factors influence daily load profiles peak demand plus participation in smart grid programs.

PV-Modules-related Parameters covered the choice of module type plus dimensions-orientation-tilt-integration feasibility inverter capacity plus expected electricity yield (Goetzberger et al. 2005; Maiden 2011). For this study monocrystalline silicon modules were chosen since they have high efficiency with low environmental impacts plus being dominant in the market (Mitsubishi Electric PV-MLT265HC).

The Methods of Collecting Data

Data were collected using four complementary methods: Live Field Visits - Quantitative and qualitative data were taken, such as the heights of buildings, numbers of floors, roof sizes, numbers of apartments, directions on façades, and local landscape features. Interviews with occupants provided information on age distribution, occupation households, economic status, and educational background. Computer Software - Google Maps Static API helped in high-resolution mapping. Autodesk Ecotect 2010 Weather Manager provided solar and climatic data for Alexandria hourly, daily, and monthly temperature solar radiation daylight hours heating/cooling degree hours. Autodesk 3ds Max created 3D models of the study area to shadow analyze and visualize sun exposure at different times of year. Official Data Reports - Governmental sources and utility records provided supplementary data on benchmarks for electricity consumption and local climate statistics. Literature Review Previous studies validated consumption rates parameter references (Attia 2012; Jha 2010).

Figure 2. Land Use in the Study Area

Source: Rana Elbakly, 2026. Figures created by the author.

Figure 3. Building Heights in the Study Area

Source: Rana Elbakly, 2026. Figures created by the author.

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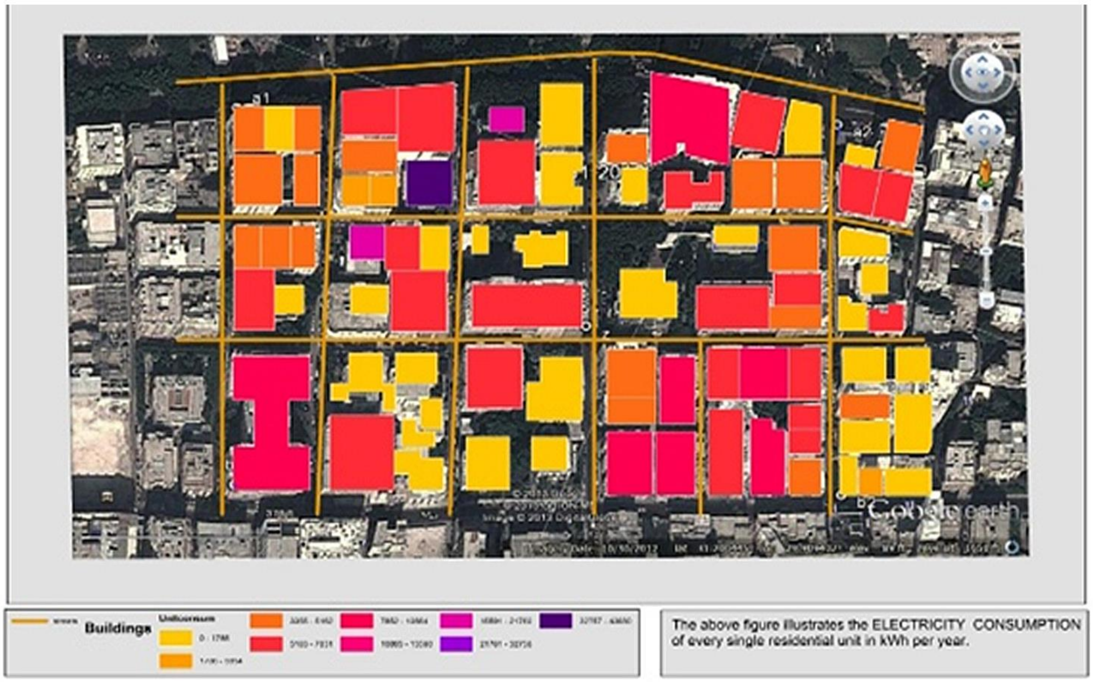
Figure 4. Electricity Consumption of Buildings in the Study Area



Source: Rana Elbakly, 2026. Figures created by the author.

Calculations and Analysis Steps

The analysis was performed in the following steps: Determination of Building and Apartment Areas The building footprints were traced in AutoCAD including common circulation spaces (staircases lifts corridors). The floor area of each apartment was calculated by multiplying the footprint with 0.88 then divided by the number of units per floor. Estimation of Electricity Consumption Average annual electricity consumption per unit was updated to 24 kWh/m²/year for projections for 2025 reflecting increasing appliance penetration and thermal comfort demands. Building-level consumption was calculated by multiplying apartments with individual unit consumption. PV-Module Selection and Configuration Monocrystalline silicon PV-modules having an output power of 265 W were selected. The optimal tilt was calculated as 25°, which is aligned with Alexandria latitude; hence module spacing considered mutual shading using the following equation:

$d = [\cos\beta + (\sin\beta/\tan\varepsilon)] \cdot a$ where $\varepsilon = 90° - \delta - \phi$; a is module height; δ is the ecliptic angle (23.5°); and ϕ is geographic latitude.

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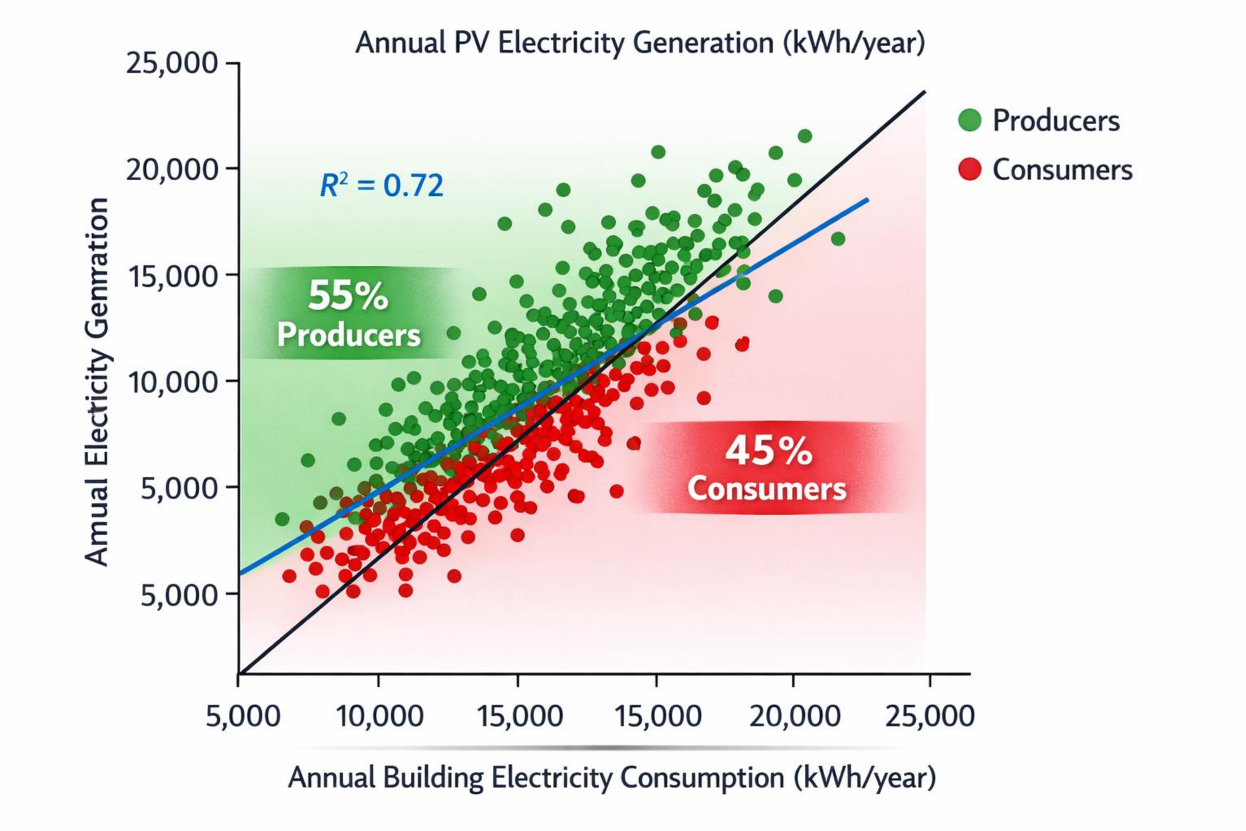
Calculation of Electricity Yield The net PV area of modules was multiplied by average yearly solar radiation (6,018 Wh/m²), PV efficiency (0.16), and performance loss factor (0.65) accounting for dust, roof obstructions, and maintenance. Comparison with Consumption Each building's expected PV electricity generation was compared with its annual electricity consumption to classify buildings into two classes labeled "producers" or "consumers." Producers generate surplus electricity for the grid while consumers meet only part of their demand Visualization All data were compiled in Excel then imported into ArcMap 9.3.1 to produce thematic maps for: Land use and building functions Building heights and floor numbers Residential unit floor areas Electricity consumption per unit and building Roof areas and PV module allocation Expected PV electricity yield Field Survey Findings Land Use: 70% plus of the total area under study is residential. Non-residential buildings (schools, religious, banking, cultural) were not considered for the PV analysis. Public buildings do not exceed two stories in height; hence, there is little risk of overshadowing. Building Heights Residential buildings range from 1–14 floors. This variation comes about because of the historical evolution of the city and some unauthorized extensions that have taken place over time. Height data are essential for façade PV integration and roof shading calculations. Floor Areas and Consumption Most apartments are between 200–400 m² with annual electricity consumption per unit between 3,500–5,500 kWh/year. Larger units (>600 m²) are infrequent. Building-level consumption averages 35,000–50,000 kWh/year with some few buildings exceeding 60,000 kWh/year. Roof areas fall mostly within the range of 700–1,200 m² which translates to an installation capacity of about 150–250 PV modules per building, and more for larger roofs that can support over 350 modules. After taking into account rooftop obstructions as well as maintenance requirements, module placement was optimized for efficiency. Slightly more than half (55%) of the buildings are classified as "producers," meaning they export surplus electricity to the grid while the remaining 45% are “consumers” whose needs are at least 50% covered by PVs on their rooftops.

The survey results indicate that most residential buildings in Al-Shalalat are suitable for retrofitting with photovoltaic panels, thus supporting Alexandria’s current trend towards renewable energy and its integration with smart grid technology.

Figure 5. PV Generation vs. Building Electricity Consumption (Energy Balance Plot)



Source: Rana Elbakly, 2026. Figures created by the author.

Chapter III: Discussion and Conclusion

This research has investigated the applicability of solar PV-systems in existing residential buildings in Alexandria, Egypt, demonstrating through a solar field survey a systematic methodology for assessing electricity consumption patterns and PV-generation potential. The study also considered the emerging trend of smart grids as a prospective framework to improve the efficiency, reliability, and distribution of renewable energy across residential areas. The results of the survey, limitations, and key conclusions are discussed in this chapter, with recommendations for further research and development.

Discussion of the Solar Field Survey Results

The solar field survey confirms a high degree of suitability for rooftop PV installations in the study area and its residential buildings. Alexandria and most Egyptian cities benefit from high annual solar radiation; an average value of direct solar radiation over the year 2025 amounts to 6,018 Wh/m²/year. Field visits revealed that most roofs are available for PV installation with very little obstruction from water tanks or antennas. Electricity yield calculations show that 55% of residential buildings in the study area can produce more electricity than they actually consume - classifying them as 'producers'. The remaining 45% are 'consumers', who can generate only part of their annual electricity needs. These results provide strong justification for integrated energy management whereby PV producers supply surplus electricity to the grid for use by consumers; without such coordination, rooftop PV installation potentials will not be fully realized as contributors towards energy transition in Alexandria. The survey results also emphasize the role smart grids play in enabling efficient distribution between producers and consumers so that residential buildings may participate actively in generation instead of being passive consumers. Adoption of smart grids will improve energy efficiency, load balancing, and integration of renewable energies within urban settings.

Table 2. Summary of Key Survey Findings and Energy Classification

Parameter	Value	Interpretation
Average Solar Radiation	6,018 Wh/m²/year	High PV potential
Buildings Classified as Producers	55%	Net-positive generation
Buildings Classified as Consumers	45%	Partial self-sufficiency
Roof Area Reduction Assumption	25%	Accounts for obstructions
Ancillary Load Assumption	25%	Shared services consumption

Survey Limitations

Though results seem promising there were several limitations that could affect both accuracy and generalizability: Data Gaps in Residential Sector — Lack of comprehensive and up-to-date databases on apartment sizes, electricity consumption, and ownership of appliances constituted challenges. Most residents with homes and building owners were reluctant to share accurate information due to privacy concerns especially within post-political turbulence contexts. Roof Area Uncertainties Exact measurements were not available for space taken up by water tanks, satellite dishes, or other roof equipment. Therefore roof areas were reduced by 25% in calculations to account for obstructions. Electricity Demand Estimation - Ancillary electricity demand (for lifts, water pumps, corridor lighting) could not be quantified accurately. An assumption was made that these would amount to 25% of total building consumption. Smart Grid Implementation - The management of PV-producers and consumers through smart grids has technical, infrastructural, market and public challenges to overcome (including cybersecurity concerns) before they can be effectively deployed. These limitations highlight the necessity for systematic government-supported data collection and monitoring to enhance accuracy and reliability for future research and implementation.

CONCLUSION and RECOMMENDATIONS

The current study has established a large existing residential building PV potential in Alexandria. Rooftop PV-systems are very appropriate for energy generation, and most buildings can either fully satisfy their electrical needs or produce excess energy that can be fed into the grid.

The following recommendations are made in order to facilitate full-scale implementation as well as optimization of rooftop PV integration:

- Develop Comprehensive Databases - A detailed government database should capture building architectural properties (height, number of apartments, vacant roof area, net apartment area) and electricity consumption profiles (appliance types and saturation rates). This database should be updated regularly.
- Government Incentives - Financial support or subsidies would be necessary to promote residential uptake of PV since installation costs may still prove prohibitive for some consumers at the initial stage. Programs like Germany's 100,000 Rooftop Photovoltaic Program could act as a model for successful governmental intervention.
- Façade-Integrated PV Research - More studies are needed on integrating PV systems into building façades (BIPV), which could allow increasing energy generation potential without taking up more roof space.
- Public Engagement and Education - It is important to create public confidence in technology literacy as a way of encouraging participation in generation from PV and joining smart grids. The study recommends government institutions working with NGOs.
- Smart Grid Infrastructure - Infrastructure adequacy plus cybersecurity measures together with market liberalization strategies will enable smart grid deployment plus peer-to-peer energy exchange between residential PV-producers and consumers.
- Continuous Research and Development - Continuous R&D is essential for improving the efficiency of photovoltaics, smart grid technologies, plus renewable energy integration into urban residential areas.

In conclusion, this study has demonstrated the extent to which residential rooftop PV installation can contribute towards achieving Alexandria's 2025 renewable energy target, and beyond. Given supportive government policies together with technological advancement plus active public participation-these systems would place Egypt on the path toward a sustainable urban energy transition.

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- Ethical approval and consent to participate: Participation in the research was approved in accordance with the journal's guidelines.
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