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Article

Energy plus concept application on Stadia: Simulation based research on International Olympic stadium Challenges in Egypt

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Abstract: Large-scale sports infrastructure represents one of the most energy-intensive building typologies, posing significant challenges to national climate strategies especially the urgent need to reduce carbon emissions and enhance the integration of renewable energy systems within the built environment. This research proposes a decision-support framework to transition sports stadia from high-demand consumers to Net Plus-Energy (NPE) hubs within decentralized Energy Communities, supplying the main grid with excess energy within the surrounding community. Using TRNSYS simulation software, the study evaluates the renewable energy potential of the International Olympic Stadium in Egypt's New Administrative Capital. The methodology integrates environmental data analysis with smart storage management to develop various energy autonomy scenarios. Results indicate that the optimized configuration not only meets the stadium's total annual demand but generates a significant surplus represent 46% excess energy of the stadium renewable sources generation, validating the feasibility of the stadium as a primary energy node. This study provides a quantitative framework for evaluating energy autonomy in mega-scale buildings and offers strategic recommendations for the Egyptian Building Code to enhance renewable technology integration and opens up for a new section within the Code regarding new building types, directly supporting Egypt Vision 2030 and global energy transition goals.

Keywords: Energy plus; Sustainable architecture; Energy management; Renewable energy; TRNSYS simulation.

1. Introduction

The study begins with an overview of the stadium and its environmental context, followed by an analysis of the expected energy demand associated with various operational patterns. Based on the climatic conditions of the New Administrative Capital, the renewable energy potential particularly solar and wind resources is assessed. Subsequently, simulation models are developed to evaluate the performance of building-integrated photovoltaic systems, wind energy generation, and energy storage solutions within the stadium environment. To support decision-making during the design phase, multiple energy autonomy scenarios are investigated. These scenarios include a maximum autonomy configuration, a cost-efficient solution, and an optimal balanced scenario that considers both technical performance and economic feasibility. The results provide insights into the achievable renewable energy coverage, system autonomy, and overall sustainability performance of the stadium.

The development of sustainable sports infrastructure has become an important objective in contemporary stadium design, particularly in regions characterized by high solar potential and growing energy demand. Large-scale sports venues are energy-intensive facilities due to lighting systems, cooling, broadcasting, and operational services during events. Thus, integrating renewable energy technologies and energy management strategies assists to reduce cost of operation and environmental impacts (Yehia et al., 2024).

This research presents a case study of the proposed International Olympic stadium located in the New Administrative Capital of Egypt as mentioned in Figure 1 The objective of this case study is to evaluate the potential of renewable energy integration in achieving higher levels of energy autonomy for large stadium facilities. The analysis is conducted using software TRNSYS for simulation framework, which allows the assessment of different renewable energy technologies and operational scenarios (Artuso et al., 2020).

Figure 1. The International sport city for Olympic games master plan (Yehia et al., 2024), Researcher 2022.

2. Overview

The main stadium of the International Sports City in the New Administrative Capital (NAC) is situated in a hot desert climate zone as mentioned in Figure 2, characterized by extremely high solar irradiation, low annual precipitation, and significant diurnal temperature variation. The geographic coordinates of the site are approximately 30.01° N latitude and 31.73° E longitude. These climatic conditions provide high renewable energy potential, particularly for solar technologies. The region receives global horizontal irradiance (GHI) values ranging between 2,100 and 2,300 kWh/m² per year, making it one of the most favorable solar environments in the Middle East and North Africa region. Average summer temperatures often exceed 36°C, which increases cooling demand but simultaneously enhances photovoltaic production potential (Yehia et al., 2024). Wind speeds in the area are moderate, which suggests a limited yet potentially useful contribution for small or medium-scale wind turbines (Attia, 2018).

Figure 2. The International sport city for Olympic games location (Global Wind Atlas, 2026), Researcher 2025.

The architectural design of the stadium reflects contemporary large-span sports structures with a focus on extensive roof coverage as mentioned in Figure 3 and large surrounding circulation zones, both of which provide significant opportunities for renewable energy integration. The stadium is designed to accommodate approximately 90,000 spectators, positioning it among the largest sports venues in the region. One of the most significant architectural features relevant to this research is the large roof canopy covering the spectator stands, which creates a substantial surface area suitable for building-integrated photovoltaic (BIPV) or building-applied photovoltaic systems. Preliminary architectural assessments indicate that the available roof and facade installation area ranges between 45,000-50,000 m², depending on structural segmentation and shading constraints, and parking area that accommodate up to 21,000 vehicles. Such a large surface can support multi-megawatt photovoltaic systems capable of contributing to a significant portion of the stadium's energy demand (Ali and Prime, 2023).

Figure 3. The Olympic stadium canopy (Yehia et al., 2024), Researcher 2023.

In addition to the roof structure, the stadium complex includes extensive parking zones surrounding the facility, designed to accommodate thousands of vehicles during major sporting events. These parking areas present an additional opportunity for solar carport installations and wind turbines, which simultaneously provide vehicle shading while. The parking canopy area is estimated to exceed 180,000 m², which significantly expands the potential photovoltaic installation footprint beyond the main stadium structure (Reiche, 2020).

The combination of high solar irradiation, extensive roof surfaces, and large parking areas creates an optimal physical environment for implementing large-scale renewable energy systems within the stadium infrastructure. Consequently, the New Administrative Capital stadium provides a suitable case study for evaluating energy autonomy strategies through simulation-based renewable integration (Attia, 2018).

3. Energy demand analysis

The evaluation of energy autonomy scenarios for the main stadium within the International Olympic City of the New Administrative Capital requires first establishing a clear understanding of the baseline energy demand and operational load characteristics. Stadium buildings represent a unique typology within large-scale public infrastructure, as their energy consumption is not constant throughout the year but instead fluctuates significantly depending on event schedules, occupancy density, and operational requirements. Consequently, the energy demand analysis considers both baseline operational loads during non-event periods and peak loads during large-scale sporting events. The baseline annual energy demand typically ranges between 8 and 10 GWh/year, depending on seating capacity, climatic conditions, and technological infrastructure. Considering the size and operational scale (Ghani, 2023), which is designed to accommodate 93,440 spectators, a representative baseline annual demand for analytical purposes can be estimated at approximately:

$$E\_annual \approx 9" \text{ GWh/year}"$$

This demand includes electricity consumption associated with HVAC systems, lighting, broadcasting infrastructure, vertical transportation, water pumping, security systems, and auxiliary services as summarized in Table 1 (Ghani, 2023). In hot-arid climates such as Egypt, cooling loads represent a significant portion of total energy consumption, particularly during summer events and daytime activities (Ali and Prime, 2023).

Table 1. The energy consumption breakdown for the main stadium (Ali and Prime, 2023), Researcher 2026.

Consumer item	Annual Consumption (GWh/year)	Percentage of Total Demand (%)
HVAC systems (cooling & ventilation)	3.60	40 %
Stadium lighting & floodlights	1.80	20 %
Broadcasting & media	1.08	12 %
Vertical transportation (elevators & escalators)	0.72	8 %
Water pumping	0.63	7 %
Security systems & surveillance	0.54	6 %
Auxiliary services	0.63	7 %
Total annual demand	9.00 GWh/year	100 %

The stadium operates under two distinct electrical load profiles: regular non-event loads and high-intensity event loads. During non-event periods, energy demand remains moderate, driven by administrative functions, maintenance activities, training facilities, and limited public access. Under these conditions, the instantaneous electrical load typically ranges between 0.3 and 0.8 MW, depending on climatic conditions and internal activity levels.

In contrast, major sporting events generate significantly higher demand due to the simultaneous operation of floodlighting, large-scale HVAC systems, media broadcasting equipment, digital displays, security systems, and increased ventilation requirements associated with high occupant density (Attia, 2018). During these events, the peak electrical load reaches approximately 3–4 MW, with the ratio between regular and peak loads illustrated in Figure 4.

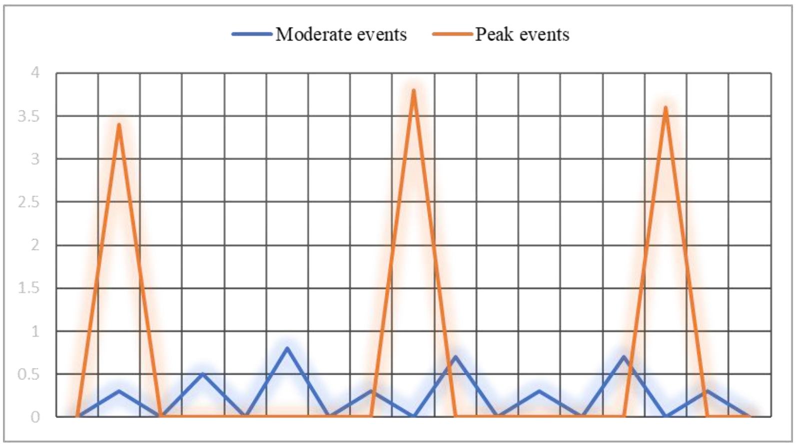

Figure 4. The frequency of moderate events and peak events energy demand monthly (Hussein, 2022), Researcher 2026.

The scale and nature of major events hosted by the stadium significantly influence its annual energy profile. Designed to support a broad spectrum of international sporting and entertainment activities—including professional football matches, continental tournaments, international competitions, concerts, and Olympic-scale ceremonial events—the facility experiences substantial energy demand during these occasions. Such events require extensive lighting, advanced audiovisual systems, and enhanced security and crowd-management infrastructure, all contributing to elevated operational peaks (Reiche, 2020).

In terms of annual utilization, the stadium typically hosts a mix of major events and smaller routine activities. For analytical modeling, it is assumed to accommodate approximately 25–30 major events per year, as illustrated in Figure 5, including national league matches, international competitions, and special events. Although each event lasts 3–4 hours, associated preparation and post-event procedures extend the effective high-load period to 4–6 hours (Hussein, 2022), consistent with operational patterns observed at Cairo Stadium—the primary national venue prior to the construction of the current facility (Zhang and Azari, 2023).

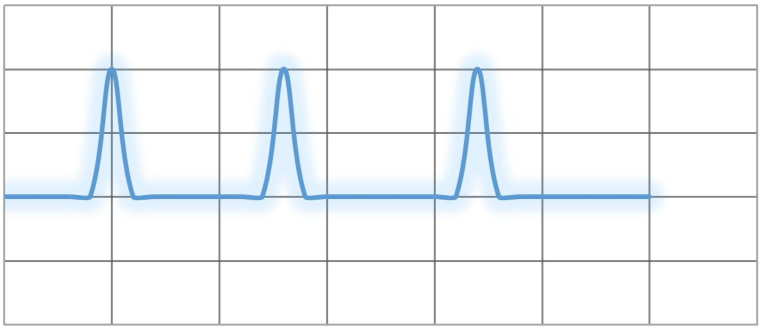

Figure 5. The frequency of major events occurrence per month (Hussein, 2022), Researcher 2026.

4. Simulation layouts

The evaluation of renewable energy integration and energy autonomy for the main stadium of the Olympic Sports City requires a structured simulation framework capable of representing the interaction between energy demand, renewable generation, and storage systems. Within this framework, simulation layouts are developed to define the spatial configuration, technological parameters, and operational assumptions implemented in TRNSYS. These layouts form the basis for testing alternative renewable energy strategies and assessing their contribution to the stadium's overall energy reliance balance (Figaj and Żołądek, 2020).

The simulation process begins with an assessment of renewable energy potential based on available installation areas and local climatic conditions. Solar radiation levels, wind availability, and seasonal variations are analyzed to determine the theoretical generation capacity of different renewable technologies. Based on this assessment, the simulation layouts specify the configuration of BIPV systems integrated into the stadium roof and façades, as well as BAPV systems deployed over parking areas and auxiliary structures. These configurations are modeled to estimate annual electricity generation while accounting for panel orientation, tilt angle, shading, and available surface area. The roof canopy, due to its large area and favorable solar exposure, represents the primary location for photovoltaic deployment. In addition to PV systems, the layouts incorporate wind energy potential to evaluate the feasibility of small- or medium-scale turbines as part of a diversified renewable strategy. Wind generation is particularly relevant for supporting evening operations when solar energy is unavailable, aligning with the reliance balance concept (Zhang and Azari, 2023). An initial MATLAB-based trial was conducted using the stadium's location, parameters, and climatic conditions to verify the adaptability of the facility to renewable energy coverage before initiating full TRNSYS simulations:

```
clc
close all
% Total energy demand
E = 9000; % MWh/y
P = 4; %MW
% panel power peak
install_efficiency = 0.75;
p = 0.5*install_efficiency; % kW
A = 2.25*1.13; % m
% Available surface
Sc = 45e3; % m2
Sp = 262e3; % m2
Stot = Sc;
```

```
%
nhy = 365*24; %h/y
CF = 0.16; %[-]
% Available maximum energy
N = Stot/A;
Ed = N*CF*nhy*p/1000; %MWh/y
Pd = N*p/1000;
disp("Energy demand: "+E+", Maximum energy expected: "+Ed+ " , with "+ N + " panels")
disp("Peak power demand: "+P+", Maximum power available: "+Pd+ " , with "+ N + " panels")
```

Energy storage systems constitute a critical component of the simulation framework. Given the stadium's highly variable load profile and the sharp peaks associated with major events, battery storage is introduced to enhance system reliability and maximize renewable energy utilization. Modern storage technologies enable the accumulation of excess daytime generation and its use during peak or nighttime events (Zhang and Azari, 2023). Storage system parameters—including capacity, charge–discharge characteristics, and integration with the stadium's electrical network—are incorporated into the simulation model (Ali and Prime, 2023). The complete simulation workflow is illustrated in Figure 6.

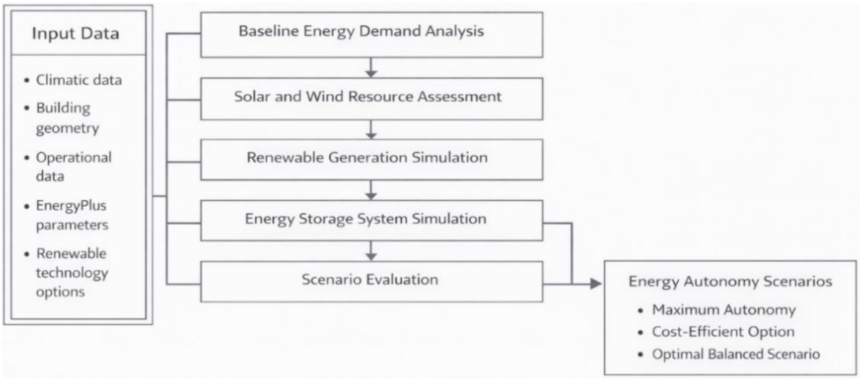

Figure 6. The simulation methodology for New Capital Stadium, Researcher 2026.

TRNSYS provides a dynamic environment capable of modeling complex energy systems and evaluating interactions between renewable generation, storage technologies, and variable building loads. Its modular structure and time-dependent simulation capabilities allow the creation of detailed system configurations that reflect the operational conditions of large sports facilities. The simulation layouts establish the relationships between demand profiles, photovoltaic systems, wind components, and battery storage, forming the structural basis for comparing different renewable energy scenarios (Figaj and Żołądek, 2020).

The modeling process incorporates two primary demand scenarios representing the stadium's hourly electricity consumption under moderate operational conditions and peak event conditions (Ghani, 2023). Results derived from these layouts provide insight into the capacity of renewable systems to offset demand, the effectiveness of storage in managing peak loads, and the feasibility of achieving higher levels of energy independence in arid urban environments. Overall, the simulation process enables a systematic evaluation of how different design configurations influence the stadium's energy performance. The following subsections detail the modeling assumptions and technological parameters used to assess photovoltaic potential, wind integration, and storage performance for the New Capital Stadium (Reiche, 2020).

4.1. Renewable energy potentials

This assessment stage identifies the available environmental resources that can be harnessed for renewable energy production and establishes the input parameters required to simulate system performance within TRNSYS. Given the climatic conditions of the New Capital, the renewable energy strategy primarily focuses on solar energy, while also considering wind energy potential as a complementary source. The region receives direct normal irradiance (DNI) frequently exceeds 2,200 kWh/m² annually, making it one of the most favorable solar environments in the Middle East and North Africa region. Average summer temperatures often exceed 40°C, which increases cooling demand but simultaneously enhances photovoltaic production potential. Wind speeds in the area typically ranging between 4–6 m/s at 10 m height, which suggests a complementary contribution for small or medium-scale wind turbines (PVGIS, 2026).

For the simulation purposes, several solar radiation parameters must be defined to accurately represent the environmental conditions affecting photovoltaic performance:

• Direct Normal Irradiance ≈ 2,100 – 2,300 kWh/m² /year

Measures the direct component of solar radiation received perpendicular to the sun's rays, which influences photovoltaic and solar thermal performance as mentioned in Figure 7.

• Ambient Temperature ≈ 28-32° C

Temperature directly affects photovoltaic module efficiency and must be included in the simulation weather dataset.

• Solar Altitude Angle ≈ 55° – 65°

Represents the vertical position of the sun above the horizon.

• Panel Orientation ≈ 0° True South

Defines the directional alignment of the photovoltaic system relative to geographic south.

• PV System Area ≈ 45,700 m² + 19,700 m² + 262,500 m²

Represents the total surface area allocated for photovoltaic installation, particularly on the stadium roof canopy and surrounding parking structures.

Within TRNSYS, photovoltaic systems are typically modeled using Type 94 or Type 567 components, which simulate the performance of PV arrays based on solar radiation and temperature inputs derived from weather data files (Barrena, 2024).

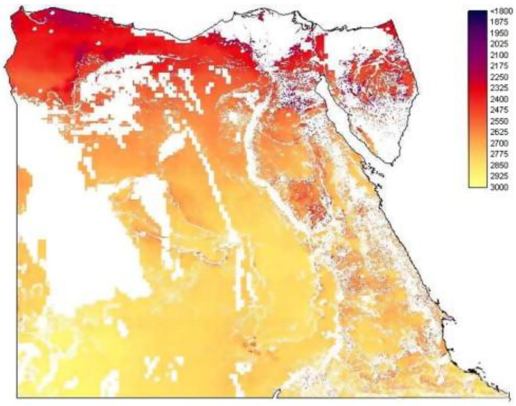

Figure 7. The solar radiation intensity map for Egypt (Khalil, 2010).

Wind energy potential at the site depends on wind power density or average wind speeds, wind direction patterns, and turbulence intensity (Dawg, 2021). These parameters are essential inputs for modeling wind turbine performance:

• Wind power density ≈ 200 – 300 W/m²

Indicates the available kinetic energy in the wind per unit area, to estimate wind energy potential.

• Average Wind Speed ≈ 6.5 – 7 m/s

Measured at a standard reference height, typically 100 m above ground level.

• Wind Direction Frequency ≈ 28% for North, 25 for Northeast

Represents the percentage of time wind comes from a certain direction. Prevailing winds in eastern Cairo desert areas typically come from north and northeast.

• Turbulence intensity ≈ 0.10-0.14

Represents the fluctuation of wind speed relative to the average wind speed.

In TRNSYS simulations, wind turbines can be modeled using Type 90, which calculate turbine power output based on wind speed profiles and turbine performance curves (Barrena, 2024). A summary of these parameters will be concluded in Table 2.

Table 2. The simulation parameters about renewable resources for TRNSYS software (PVGIS, 2026) (Global Wind Atlas, 2026), Researcher 2026.

Simulation parameter	Range	Average
Direct Normal Irradiance	2,100 – 2,300	2,200
Temperature	28 – 32	30
Solar Altitude Angle	55 – 65	60
Wind power density	200–300	259
Wind speed	6.5 – 7	6.73
Roof top area	40,000 – 50,000	45,700
Façade panels	18,500 – 20,500	19,700
Parking area	260,000 – 265,000	262,500
Moderate events load	0.3 – 0.8	0.55
Peak events load	3 – 4	3.5
Annual energy demand	8 – 10	9
Event regularity	25 - 30	28

4.2. Building-integrated photovoltaics simulation

The simulation model was developed by importing hourly meteorological data, including solar radiation parameters and temperature, through the weather data processor component within TRNSYS. The photovoltaic system performance was then simulated using standard PV array models that calculate electricity generation based on solar irradiance, module efficiency, panel orientation, and tilt angle for crystal silicon panels sized: $2.25x1.13=2.5m^2$. The PV modules were assumed to be installed on the canopy with a south-facing orientation and $25°$ tilt angle suitable for the climatic conditions of Egypt. The software output includes hourly, monthly, and annual electricity generation profiles (Figaj and Żołądek, 2020). The following subsection presents a detailed analysis of the simulation results and discusses their implications for renewable energy: BIPV + BAPV, as the model mentioned in Figure 8.

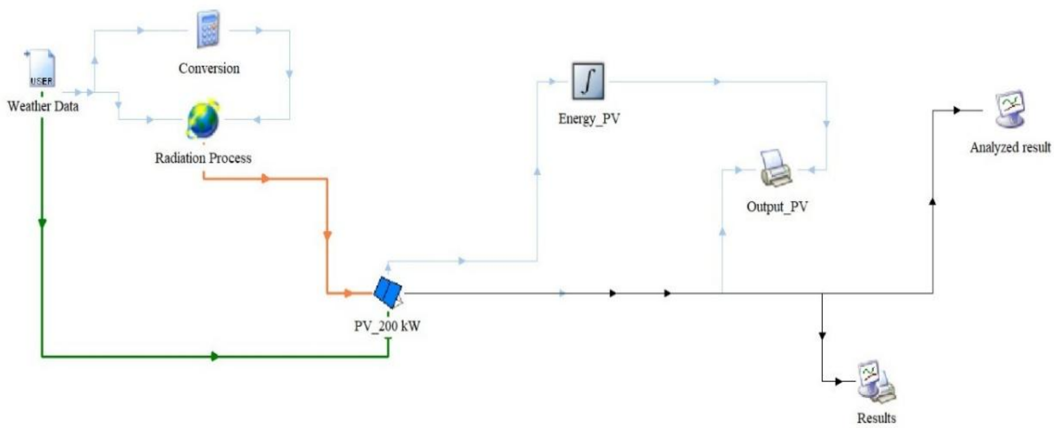

Figure 8. The TRNSYS layout for the rooftop BIPV, Researcher 2026.

The simulation process was first testing the available area of the canopy to accommodate 45.7 solar module of capacity 200KW, with total stadium capacity 6.6 MWp. The simulation outputs a graph of 8,760 bar for the annual production which starts from the winter in the form of hourly generation and then analyzed results are concluded. Thus, the BIPV canopy annual production of energy is 7 GWh which represents around 78% of the stadium energy demand.

$$E\_PV \approx 7.0\text{" GWh/year"}$$

While the available parking area can be partially covered 60% to supply shading for cars and generate energy with total available area 157,500m² to accommodate 160 solar modules of the same rooftop capacity. To generate 24 GWh annually as an external energy source but connected to the same energy system of the stadium.

4.3. Wind potential simulation

The simulation framework incorporated meteorological wind data including hourly wind speed, wind direction distribution, air density, and turbulence intensity obtained from regional climate datasets, which is global wind atlas as mentioned in Figure 9 and 10 a screenshot of the website location assessment. These parameters were introduced into the TRNSYS model through the weather data reader component, which allows the system to simulate time-dependent wind conditions throughout the year. The wind turbine performance was then calculated using turbine power curves that relate wind speed to electrical output, taking into account operational parameters such as cut-in wind speed, rated wind speed, and cut-out wind speed. In the simulation configuration, turbines were assumed to be installed in open areas surrounding the stadium complex. The results obtained from the TRNSYS simulation provide an estimate of the potential electricity generation that could be achieved through wind energy integration within the stadium complex. However, wind turbines can provide electricity during nighttime periods when photovoltaic systems are inactive, which helps improve the overall balance of renewable energy generation (Barrena, 2024).

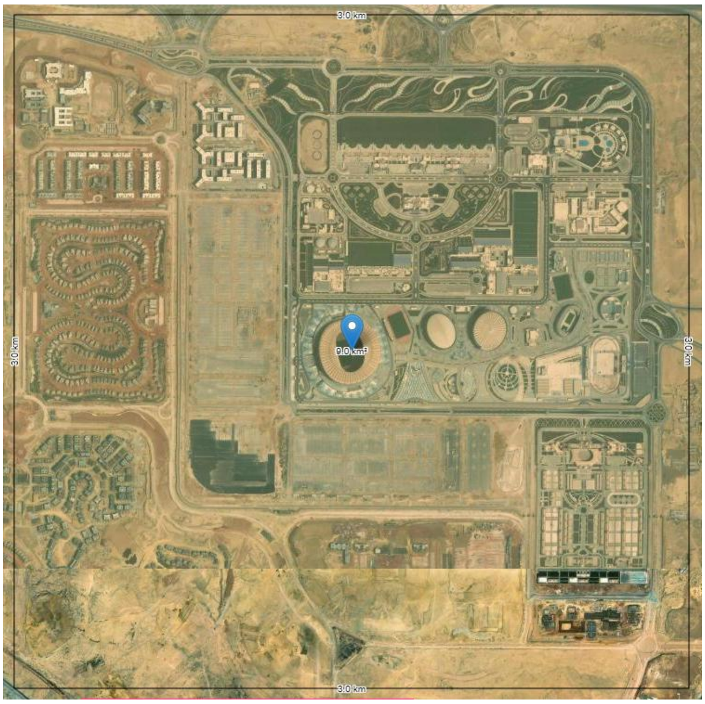

Figure 9. The wind parameters source according to 9 km area around the stadium location (Global Wind Atlas, 2026).

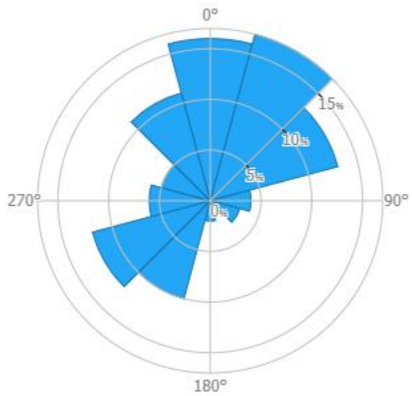

Figure 10. The wind power rose at the stadium accurate location (Global Wind Atlas, 2026).

The simulation results according to Figure 11 model highlight the role of wind energy as a secondary but supportive component within the hybrid renewable energy system designed for the stadium. The simulation process tests the amount of energy generated by 1 wind turbine of height 80 meters and capacity 1 MWp. Wind speed varies from 6.5-7 m/s and realistic capacity factor 30%. The simulation outputs a graph of 8,760 bar for the annual production which starts from the winter in the form of hourly generation in accordance to the wind speed of the same hour, then analyzed results are concluded. Thus, the annual production of energy is 2.14 GWh which represents around 23% of the stadium energy demand.

$$E\_wind=2,144,500\text{" kWh/year"}\approx 2.14\text{" GWh/year"}$$

The turbines number and dimensions could vary based on the available space, the amount of energy needed, and the dependency on the wind power contribution ratio to the stadium energy according to the climatic environment. Therefore, this turbine is the researcher proposal as initial simulation then it will be balanced in the autonomy scenarios. The turbine height is the only parameter that affect the amount of energy generated as on each height the wind speed varies.

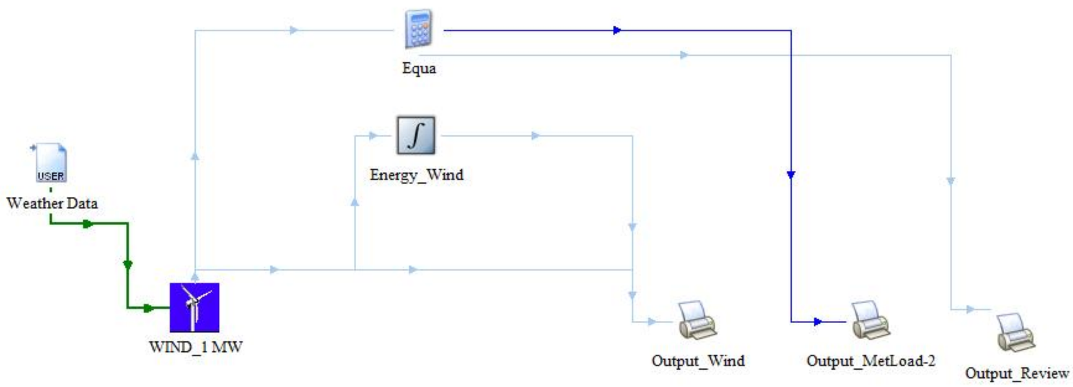

Figure 11. The TRNSYS layout for the wind turbines, Researcher 2026.

4.4. Energy storage system

Proposed Lithium-ion technology battery energy storage system for the stadium is estimated to range between 12 and 14 MWh to cover 4 hours of totally absence of renewable sources, which is approximately the event duration with the preparation session. This capacity enables excess photovoltaic electricity generated during daytime hours to be stored and utilized during evening events or peak operational periods, improving renewable energy utilization and enhancing system reliability. During these events, the peak electrical load may reach approximately:

$$P\_peak\approx 3\text{-}4\text{" MW"}$$

Assuming lithium-ion battery modules with an average capacity of 50 kWh, the stadium energy storage system would require approximately 240 battery modules. These modules can be arranged within containerized battery units integrated into the stadium energy infrastructure, which needs around 350 m² of well-ventilated storing areas inside the stadium facilities area only for the batteries without the related facilities, connections, and maintenance paths. Minimum height of 4 meters for this area is required (Haddad et al., 2025).

5. Energy autonomy scenarios

The integration of renewable energy systems within large sports infrastructures requires the evaluation of different operational configurations that balance energy production, demand variability, and economic feasibility. Based on the renewable energy potential analysis and the simulation results obtained through TRNSYS, a set of energy autonomy scenarios was developed for the International Olympic Stadium located in the New Administrative Capital. These scenarios aim to investigate the degree to which locally generated renewable energy can satisfy the stadium's annual electricity demand while maintaining operational reliability during both moderate and peak event conditions.

5.1. Maximum autonomy scenario

The maximum autonomy scenario investigates the highest achievable level of renewable energy independence for the stadium complex. In this configuration, photovoltaic systems are deployed across all available installation surfaces, including the stadium roof canopy, façade elements, and 100% of the surrounding parking areas through solar carport structures. According to the simulation results, the roof-integrated photovoltaic system contributes approximately 7 GWh/year, while the photovoltaic installations above 100% on the parking areas generate approximately 40 GWh/year (Haddad et al., 2025). The façade elements will be neglected for now as it will not be that efficient as the roof top panels due to their fixed tilt angle and orientation of the panels. Thus, the total generated energy of solar system is:

E_PV≈47" GWh/year"

In addition to solar generation, wind energy systems are incorporated to provide supplementary electricity production during periods when solar resources are unavailable, particularly during evening hours or night events. The simulation results as shown in Figure 12 model, indicate that 1 wind turbine with a rated capacity of 1 MW could produce approximately 2.14 GWh/year under the prevailing wind conditions of the New Administrative Capital.

E_wind≈2.14" GWh/year"

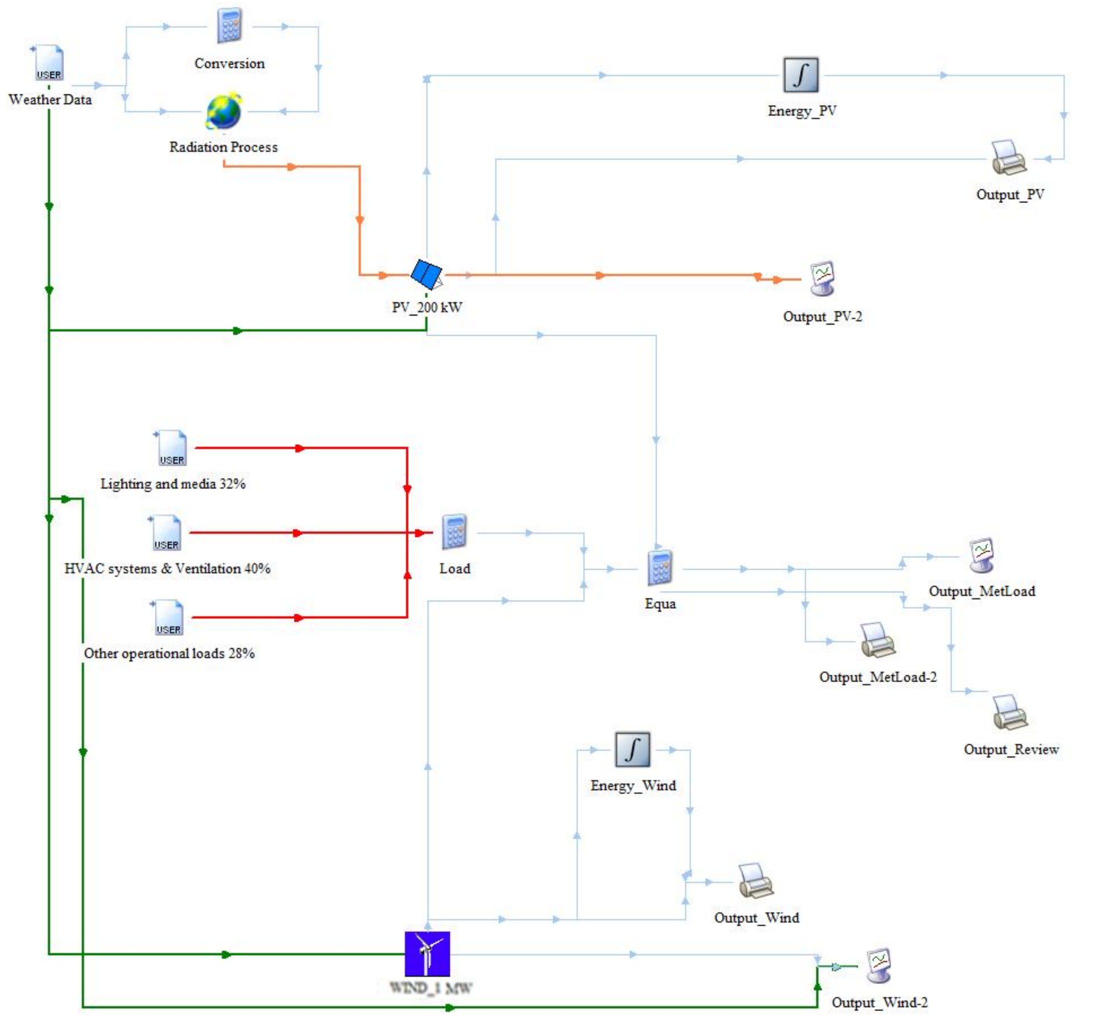

Figure 12. The TRNSYS layout for the maximum autonomy scenario, Researcher 2026.

Under this configuration, the total renewable energy generation reaches approximately 49.14 GWh/year, exceeding the estimated annual stadium demand of 9 GWh/year. This scenario theoretically enables the stadium to reach complete annual energy autonomy. However, achieving such a configuration would require substantial capital investment due to the extensive photovoltaic installations and wind turbine infrastructure.
The total renewable coverage ratio (RCR) becomes:

RCR=E_generated/E_generademandted =49.14/9.0=546%

Autonomy factor=49.14/9.0≈5.46

5.2. Cost efficient scenario

The cost-efficient scenario focuses on achieving meaningful renewable energy integration while minimizing capital investment. In this configuration, photovoltaic installations are limited primarily to the stadium roof canopy only, where structural integration is most feasible. Wind energy system is only 1 turbine with 1MW capacity to lower installation and maintenance costs (Villa-Arrieta and Sumper, 2018). Under this scenario in Figure 13, photovoltaic generation is estimated to supply approximately 7 GWh/year. Wind energy contributes a smaller supplementary share which is 2.14 GWh/year., primarily intended to improve system diversity rather than significantly increase total generation capacity.

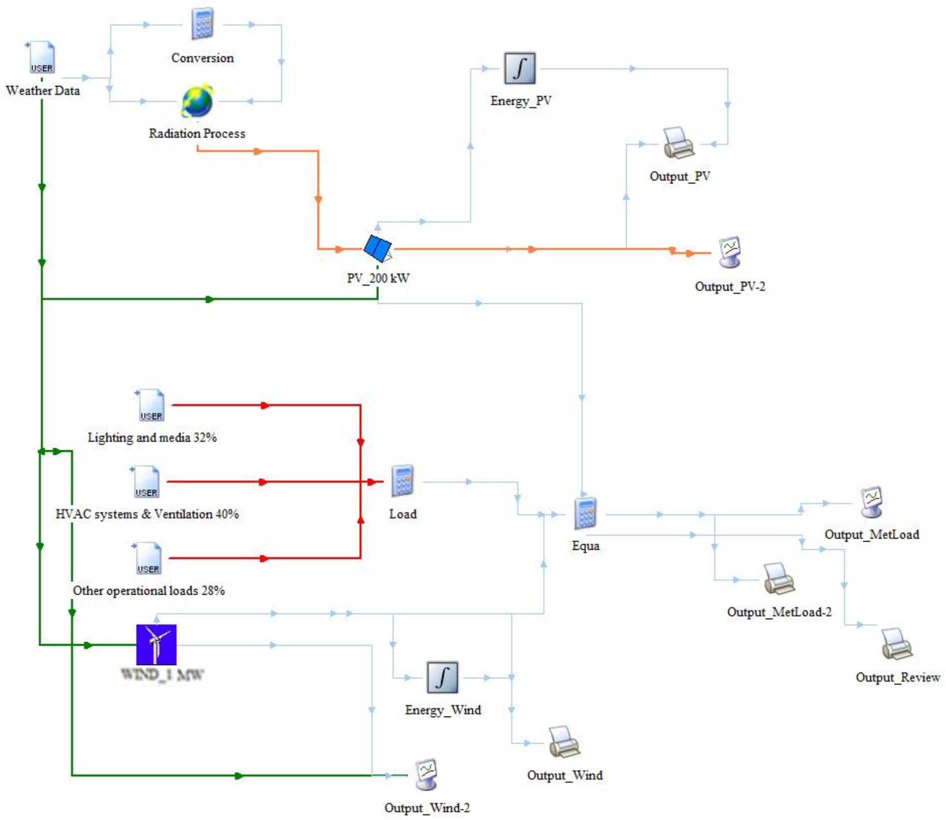

Figure 13. The TRNSYS layout for the cost-efficient scenario, Researcher 2026.

Although this configuration just achieves energy autonomy with minimal excess energy for the public grid, it significantly stops dependence on grid electricity while maintaining a more economically feasible installation scale. This approach may therefore represent a realistic implementation strategy during the initial development phase of the stadium complex.

RCR=E_generated/E_generademandted =9.14/9.0=101%

Autonomy factor=9.14/9.0≈1.01

5.3. Optimal balanced scenario

The optimal balanced scenario represents a compromise between maximum renewable integration and economic feasibility. In this configuration, photovoltaic installations are deployed across the entire stadium roof canopy and 10% of the surrounding parking areas, while 1 only of 1 MWp wind turbines are incorporated into the stadium. Battery storage systems are also introduced in this scenario to improve energy management and support peak demand periods. The storage system enables excess solar energy generated during daytime hours to be stored and later utilized during evening events or peak events when photovoltaic production is unavailable or insufficient.

Under this configuration, the renewable energy systems are capable of generating approximately 13.14 GWh/year. The remaining electricity demand is considered a reserve for any unplanned increase in the annual demand and to cover the batteries capacity by smart grid integration through the energy community concept as applied in Johan Cruyff arena, or to be supplied to the grid when it is unnecessary periods or excess renewable generation.

$$RCR=E\_generated/E\_generademandted =13.14/9.0=146\%$$

$$\text{Autonomy factor}=13.14/9.0\approx 1.46$$

This scenario provides a balanced solution that combines high renewable energy penetration with reasonable system costs and operational reliability, making it the most practical configuration for long-term stadium operation.

6. Results and discussion

The simulation results obtained from the TRNSYS modeling framework provide a comprehensive evaluation of the renewable energy integration potential within the International Olympic Stadium located in the New Capital. By combining photovoltaic systems installed on the stadium canopy and parking structures with supplementary wind energy generation, the analysis demonstrates the feasibility of achieving significant levels of renewable energy coverage for large-scale sports infrastructures operating in hot-arid climatic environments. However, stadium energy consumption exhibits irregular patterns depending on event scheduling, which introduces significant variability in hourly demand profiles. Thus, the variety in renewable sources covered this point even if PV panels only are sufficient, as some of the stadium usage could be at night which could depend more on wind turbine than the batteries as calculated in the cost-efficient scenario. And also, the dependence on the excess area of the parking makes it a bit easier to achieve the energy reliance balance but with an extra cost. The role of smart batteries covered the mismatch by depending on stored energy for 4 hours. In the optimal balance scenario, there was a customized case modification to fit the stadium demand with excess amount to match the sudden increase in range while maintaining the minimum cost of achieving net Plus energy building not net zero only.

For this reason, the incorporation of battery storage systems and smart energy management strategies becomes essential for improving system performance to increase generation and decrease cost. Energy storage redirected the generated energy in a better way to achieve maximum benefit, also allows excess solar electricity generated during daytime hours to be stored and subsequently used during evening events or peak demand periods. This capability enhances renewable energy utilization and reduces reliance on the external electricity grid. Furthermore, the results demonstrate that renewable energy integration in stadium infrastructures can significantly contribute to reducing operational costs and environmental impacts over the building lifecycle as compared in Table 3.

Table 3. The comparison between the simulation scenarios results, Researcher 2026.

Simulation scenario	PV generation	Wind generation	Total generation	RCR	Autonomy factor
Maximum Autonomy	47 GWh	2.14 GWh	149.14 GWh	546 %	5.46
Cost Efficient	7 GWh	2.14 GWh	9.14 GWh	101 %	1.01
Optimal Balanced	11 GWh	2.14 GWh	13.14 GWh	146 %	1.46

As for the net plus energy integration cost compared to the traditional energy sources, it was calculated in details for the cost-efficient scenario in the following table. Resulting in total cost of 7.2million USD for the renewable integration while the annual energy demand cost is 0.3million USD with average annual increase 28%. Which leads to pay in advance the amount of 14 years of stadium generation in renewable resources to be energy independent and a viable energy hub as summarized in Table 4, and any increase in the production will be sold to the grid to decrease the coverage years of the system (Tim, 2026) (Udoh, 2025) (Mile, 2026) (Ahram, 2025) (Catsaros, 2025).

Table 4. The comparison between the cost of traditional and renewable sources for the cost-efficient simulation scenario (Tim, 2026) (Udoh, 2025) (Mile, 2026) (Ahram, 2025) (Catsaros, 2025). Researcher 2026.

Energy source	PV cost in USD	Wind turbine cost in USD	Batteries cost in USD	Total cost	Years of coverage
Renewable	3.2m	1.3m	2.7m	7.2m	14
Traditional / year	0.3m				

Overall, the results confirm that the combination of photovoltaic systems, supplementary wind energy generation, and energy storage technologies provide a viable pathway toward achieving high levels of energy autonomy in large sports infrastructures located in high solar potential regions such as Egypt. The proposed renewable energy integration strategy therefore represents a promising approach for future stadium developments within rapidly expanding urban environments.

7. Conclusion

Thes simulation results demonstrate that the stadium can theoretically achieve net-positive annual energy performance, meaning that the renewable energy systems are capable of producing more electricity than the facility consumes on an annual basis. The surplus energy can either be stored within the battery systems, exported to the electricity grid, or integrated into local energy communities through smart grid systems, similar to the operational model implemented at the Johan Cruyff Arena. Overall, the case study confirms that large stadium infrastructures located in high solar potential regions can significantly reduce their reliance on conventional electricity networks through the strategic integration of renewable energy technologies. The findings highlight the importance of incorporating renewable energy strategies during the early stages of stadium design in order to maximize the use of available architectural surfaces and environmental resources, Figure 14 is summarizing the research scenarios.

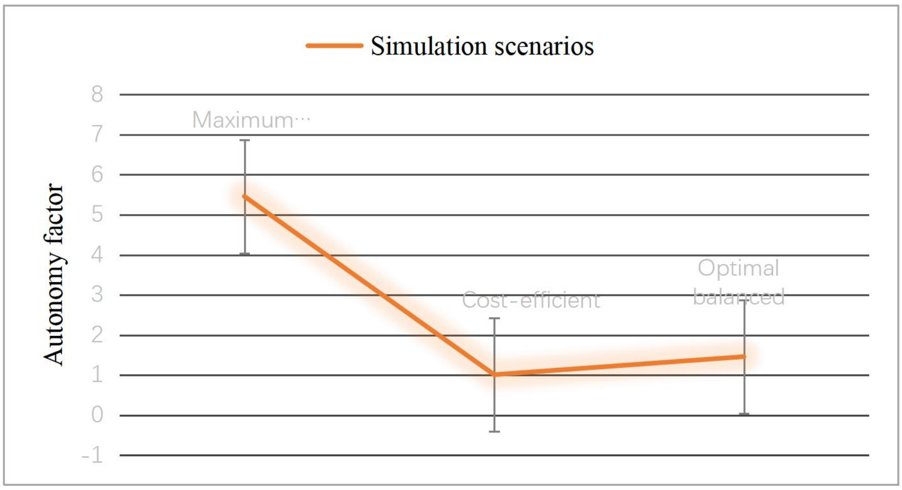

Figure 14. The output of the energy autonomy scenarios, Researcher 2026.

The results of this research further demonstrate that achieving high levels of renewable energy autonomy for mega-stadium infrastructures in Egypt is technically feasible when renewable energy systems are integrated during the early stages of architectural design. The climatic conditions of Egypt, characterized by high solar irradiation and favorable environmental resources, provide a significant advantage for implementing photovoltaic-dominated hybrid energy systems in large-scale sports facilities. Within the context of Egypt Vision 2030, such developments support the national objective of expanding renewable energy deployment while improving the sustainability performance of emerging urban districts such as the New Capital. Moreover, the findings of this case study suggest that the proposed energy autonomy framework can be replicated in other stadium projects both regionally and globally, particularly in countries with similar climatic conditions and growing investments in mega sports infrastructure. Consequently, the integration of renewable energy technologies, energy storage systems, and smart grid management strategies presents a viable pathway toward transforming stadiums from energy-intensive facilities into energy-generating urban assets within future sustainable cities.

Author Contributions

Conceptualization, A.M. and Y.F.; methodology, A.M.; software, A.M.; validation, A.M., Y.F. and A.E.; writing—original draft preparation, A.M.; writing—review and editing, A.E.; supervision, Y.F.

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Conflict of Interest Statement

The authors declare no conflicts of interest.

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