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# Grid-Connected Rooftop Solar Photovoltaic and Wind Turbine for Net-Zero Student Housing in Saudi Arabia

Abdulrhman Alnome and Awad Bin Saud Alquaity*

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**ABSTRACT**

Studies that compare commercial photovoltaic modules and wind turbines for a dormitory-scale load under a clear roof-area limit are scarce. This study evaluates rooftop photovoltaic (PV) and wind-turbine options for a prospective grid-connected renewable energy supply system that can power the KFUPM student-housing dormitories in Dhahran, Saudi Arabia. The solar PV and wind-turbine systems were sized to meet the dormitory annual electricity demand of 48 GWh based on the rooftop area available for PV deployment, which was limited to 153,796 $m^2$. RETScreen Expert was used to model three monocrystalline PV modules (Trina 600 W, Jinko 595 W, and JA Solar 545 W) and three wind-turbine candidates (AAER A-2000-100, Enercon E-101, and Vestas V90-3.0 MW). The PV results showed that rooftop solar power alone could almost match the annual dormitory demand. All PV-module options resulted in a similar capital cost of US$20.95–US$21.12 million and simple payback of approximately 5.3 years when calculated under a net-zero billing framework. Among the three options, the Jinko module exhibited the highest efficiency; therefore, it requires the smallest roof area and lowest capital cost while still meeting the demand target. The wind turbines produced 51,665–52,821 MWh/year and showed clear differences in financial performance. Among the wind turbines considered, Enercon E-101 achieved the shortest payback (4.9 years) and best cost-to-performance ratio when matched to the load. Overall, this study identified Jinko Solar and Enercon E-101 as the preferred technology candidates for standalone or hybrid deployment to meet the energy requirements of the student-housing dormitories.

**Keywords:** hybrid renewable energy, rooftop photovoltaic, wind turbine, RETScreen, techno-economic analysis

## 1. INTRODUCTION

Residential electricity demands have increased with population, building services, and cooling requirements. In hot–arid climates, air-conditioning loads place pressure on the grid, making the residential sector an important target for decarbonization. University campuses are especially relevant in this context because they combine high-density residential communities with centralized services and repeatable daily load patterns that are well suited for renewable-energy deployment and performance monitoring[1].

A typical approach for reducing emissions in these communities is the integration of distributed renewable-energy generation. Solar photovoltaic (PV) systems are attractive in Saudi Arabia because of the abundant solar resources in the region and suitability of rooftops and parking structures for installation. However, PV power generation is inherently daytime-dependent. Wind energy can complement PV systems by contributing power at different hours and seasons; therefore, hybrid PV/wind systems are often proposed as a more robust solution than single-resource systems[1].

Dhahran has high solar potential and moderate wind resources. Previous research at KFUPM showed that both 6 kW PV and wind systems can produce useful electricity under local weather conditions. However, this research recommended further evaluation of combined wind–PV configurations to improve overall reliability and performance[2]. Therefore, the feasibility of using solar and wind energy to meet the energy needs of the KFUPM student-housing dormitories in Dhahran is evaluated in this study.

At this stage, merely determining whether solar and wind resources are available is insufficient. Moreover, the selected technologies need to remain practical when losses, costs, and operating assumptions are included. Therefore, this study employs RETScreen, which is widely used for screening renewable-energy technologies because it couples energy-yield estimation with financial and environmental evaluations. A recent RETScreen-based analysis has also shown that seemingly modest changes in modeled loss assumptions can noticeably shift exported energy and key financial indicators such as the internal rate of return and payback period[3].

Campus electrification is important, and local studies have already shown solar and wind potential in Dhahran; however, few screening studies compare commercial PV modules and wind turbines for a dormitory-scale load under a clear roof-area limit. To address this gap, this study uses RETScreen to compare different solar and wind options for KFUPM student housing.


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This study aims to (i) define a realistic demand and deployment boundary for the site, (ii) compare multiple commercial PV and wind candidates using the same case-study basis, and (iii) identify the most feasible PV and wind options for a subsequent unified hybrid-system analysis.

## 2. BACKGROUND AND LITERATURE REVIEW

**2.1. Renewable-Energy Systems and Sizing Considerations.** The combination of PV and wind resources has been well-established in the literature on hybrid renewable energies. Early sizing studies showed that hybrid systems must be designed around a reliability–cost trade-off rather than by maximizing the installed capacity alone. In autonomous and weak-grid applications, this trade-off is typically expressed through energy adequacy, the loss-of-power probability, or levelized cost metrics[4]. More recent optimization studies have extended the comparison to include economic, environmental, social, and reliability dimensions, which are useful when renewable systems are evaluated for community-scale infrastructure instead of isolated equipment[5].

The main benefit of a hybrid system for powering student housing on the KFUPM campus is that solar and wind resources can complement each other at different times[4,5]. PV typically dominates daytime production, whereas wind can contribute during the evenings, nights, or seasons in which the solar output is low. This complementarity can smooth the aggregated renewable supply and reduce the need for oversizing or storage, especially when two resources share the same grid connection and serve a common load. The present analysis evaluates PV and wind systems independently to assess their potential. Demonstrating the actual temporal complementarity at KFUPM would require hourly generation and load profiles, which will be a priority for future work[5].

**2.2. Saudi Arabian Context: Wind Resources, Rooftop PV Potential, and Arid-Climate Losses.** Resource characteristics vary by region within Saudi Arabia, which strongly influences renewable-energy system design. For the Eastern Province, wind-assessment studies have shown that Dhahran and nearby coastal locations exhibit moderate but usable wind speeds, with hub height playing a major role in the annual energy yield. This makes turbine selection, hub height, and loss assumptions particularly important in local contexts[6].

Rooftop PV systems have good potential in Saudi Arabia, and previous studies have shown that rooftops can make an important contribution to electricity generation when installation limits are considered. However, practical deployment depends on the usable roof area rather than the gross roof area alone, because access routes, mechanical equipment, setbacks, and shading reduce the deployable surface[7].

Another Saudi Arabia-specific issue is soiling. In arid and dusty climates, performance losses caused by dust accumulation can become significant, unless cleaning and maintenance are considered. A review of Saudi PV systems has shown that soiling can considerably reduce PV output; therefore, conservative loss assumptions are essential during feasibility screening instead of after the system is selected[8].

Recent review studies on distributed PV systems in Saudi Arabia reinforce this by emphasizing the influence of tariff structure, technology selection, design quality, and operational losses on the final economics of building-integrated and rooftop PV systems. These studies also show that appropriate technology screening becomes more important when projects are space-constrained[9].

**2.3. RETScreen-Based Feasibility Screening.** RETScreen has become a common tool for early-stage clean-energy feasibility studies because it integrates climate data, energy modeling, financial screening, and emission analysis in a single workflow. Recent RETScreen-based case studies on PV plants have shown that this software is useful for comparing scenarios before detailed design or dispatch optimization is performed[10].

Reviews on campus microgrids have identified universities as valuable demonstration environments because they operate similarly to small utility systems with a concentrated demand, defined ownership, and institutional sustainability goals. The same reviews also note that campus renewable-energy projects are highly sensitive to weather variability, system sizing, and the choice of component technologies[11].

The accuracy and suitability of RETScreen for PV screening in Saudi Arabia were also examined through comparative studies. For example, a recent comparison of the System Advisor Model (SAM) and RETScreen for a 600 kW PV case in Riyadh confirmed that RETScreen can provide useful screening-level results when the inputs are carefully defined, although more detailed software may be subsequently required for high-resolution design studies[12].

More broadly, a recent study on PV–wind hybrid plants and retrofitted hybrid-power parks has shown that resource complementarity, shared infrastructure, and a balance between solar and wind characteristics can substantially affect techno-economic feasibility. This is particularly relevant for this study as the aim is not to optimize a single technology in isolation but to identify the preferred PV and wind candidates for subsequent integrated hybrid analysis[13].

Previous studies have shown three main points. First, PV–wind hybrid systems can be useful for community-scale power supply. Second, Dhahran is a suitable location for rooftop PV and wind turbines. Third, the results of feasibility studies strongly depended on losses, resource data, and technology choices. However, a screening study focused specifically on KFUPM student housing that compares multiple commercial PV modules and wind turbines under the same dormitory-scale demand and an explicit roof-area constraint is still required. This study addresses this need by conducting a structured RETScreen analysis to select the best technological components for future hybrid systems.

## 3. METHODOLOGY

RETScreen Expert was used as a screening tool to evaluate different solar PV and wind-turbine systems. The PV and wind technologies were first evaluated separately to identify their strongest candidates before conducting any future unified hybrid runs. This

approach is suitable when the immediate objectives are technology selection, site screening, and practical constraint checking, rather than detailed hourly dispatch optimization [10,12].

**3.1. Case Study Description, Demand Basis, and Area Constraint.** This case study represents the KFUPM student-housing dormitories in Dhahran, Saudi Arabia. The annual electricity demand adopted for the analysis was 48 GWh/year, which served as the target demand for all technology-screening cases. This screening value is consistent with the KFUPM Energy-consumption Report, which shows a total campus electricity consumption of 380 GWh in 2022 and student-dormitory share of 12.9%. These values correspond to approximately 48 GWh/year for dormitory use, which supports the adoption of a 48 GWh/year design target for the present study [14]. The second defining constraint is the available rooftop area for solar deployment, which was 153,796 $m^2$. These two values establish the technical boundary of the study: PV systems must remain within the available roof area, and both the PV and wind scenarios are judged against the same 48 GWh/year demand target.

Notably, the available rooftop area of 153,796 $m^2$ represents the total measured rooftop footprint of the dormitory buildings and covered parking structures. In practice, a portion of the rooftop must be reserved for maintenance-access routes, cleaning pathways, safety clearances, structural equipment, and existing mechanical services. Based on general rooftop PV-design guidelines, approximately one-third of the gross roof area is typically unavailable for panel installation [7]. Therefore, the present study represents an upper-bound, ideal deployment scenario, and additional rooftop areas from other parking structures and dormitory buildings will be needed if the usable fraction is limited to 67%.

The covered parking structures are treated as identical rectangular roofs. For one representative parking roof, the measured plan dimensions are 135.62 m and 72.27 m; thus, the roof area is

$$A_{\text{parking}} = 135.62 \times 72.27 = 9,806\, m^2. \quad (1)$$

For six parking structures of the same size, the total parking-canopy area is

$$6 \times 9,806 = 58,836\, m^2. \quad (2)$$

The remaining rooftop area was provided by student dormitory buildings. Based on the measured representative dormitory roof shown in Figure 2, the dormitory plan was approximated by dividing the L-shaped footprint into simpler rectangular sections using the measured dimensions, yielding an estimated roof area of approximately 1,187 $m^2$ per dormitory.

Eighty dormitory buildings were considered in this study. Therefore, the total rooftop area is

$$A_{\text{total}} = 58,836 + (80 \times 1,187) = 153,796\, m^2. \quad (3)$$

**3.2. Resource Data and Screening Procedure.** Dhahran climate and resource data were obtained from the RETScreen database. For the present screening study, the PV and wind cases shared the same site location and export structure, whereas the technology-specific inputs were changed based on the selected module or turbine. The study workflow consisted of five main steps: the definition of the case-study boundary, RETScreen resource setup, PV screening under the roof-area limit, wind screening under common wind-loss assumptions, and a comparison of technical and financial outputs. RETScreen is a validated simulation platform that has been compared to other tools, including System Advisor Model (SAM). Jordaan et al. [12] conducted a direct comparison of RETScreen and SAM for a 600 kW rooftop PV system in Riyadh, Saudi Arabia and confirmed that RETScreen produces consistent screening-level results when input parameters are carefully defined. This further supports the validity of the RETScreen-based approach adopted herein for technology comparison and preliminary economic screening. However, higher-resolution dispatch tools are required for a detailed design.

**3.3. Photovoltaic Technology Screening.** Three commercial monocrystalline PV modules were investigated: Trina

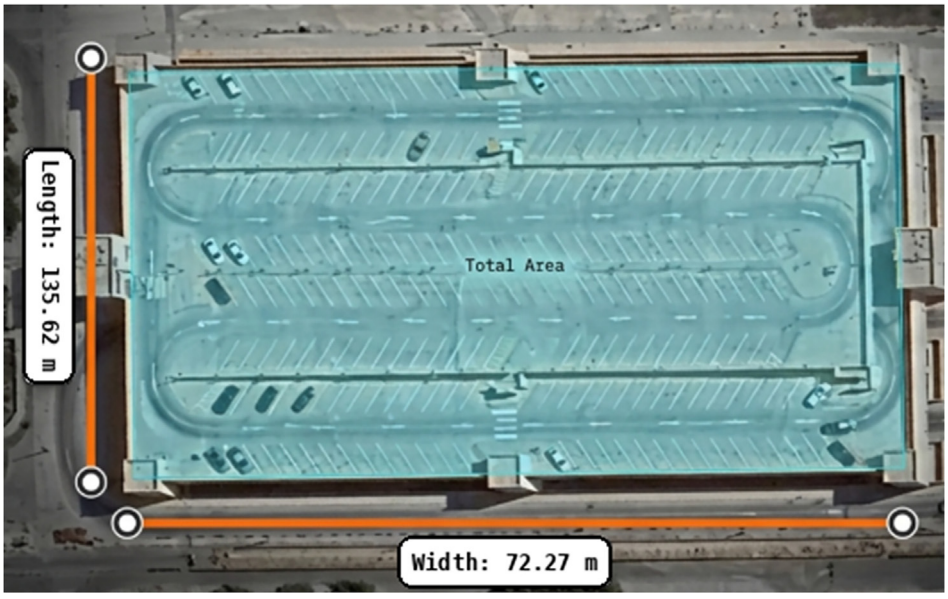



**Figure 1.** Satellite-image measurements of a representative parking roof used in the rooftop-area calculation

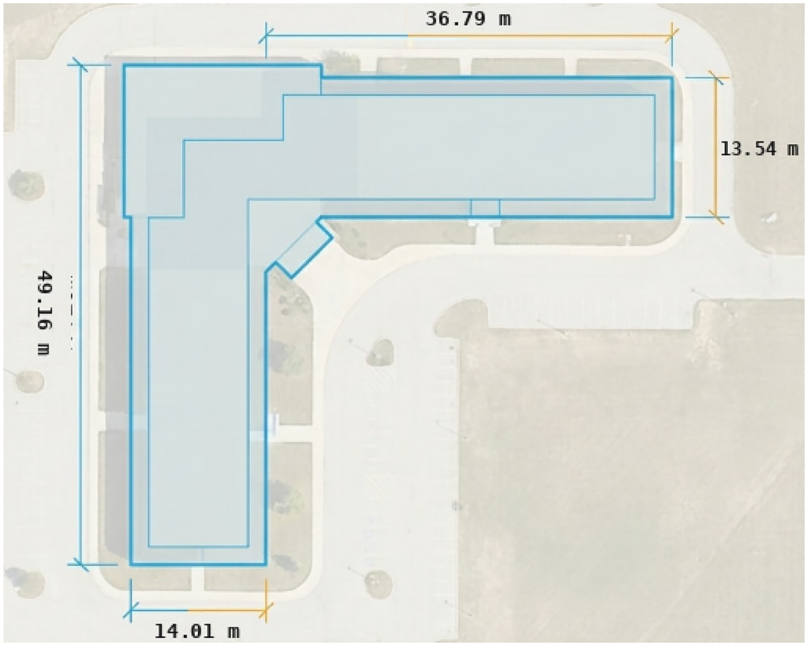



**Figure 2.** Satellite-image measurements of a representative student dormitory rooftop. The L-shaped footprint was divided into rectangular sections to estimate the deployable roof area of approximately 1,187 $m^2$ per building

600 W, Jinko 595 W, and JA Solar 545 W. The rooftop PV cases were modeled as fixed installations with the same general balance-of-system assumptions. Module-temperature behavior was represented by the nominal operating-cell temperature of 45 °C, the inverter efficiency was considered to be 90%, and miscellaneous losses were taken as 10%. An inverter efficiency of 90% represents a conservative industry-standard value for utility-scale string inverters, which is consistent with the values used in comparable rooftop studies in Saudi Arabia[8,9]. The 10% miscellaneous loss factor includes wiring losses, module mismatch, shading, and soiling, in line with the IEC 61724 guidelines and loss budgets reported in the regional literature[8,9]. The PV-design capacity for each case was adjusted such that the collector area remained within the available rooftop area[7–9].

**3.4. Wind-Turbine Technology Screening.** Wind-screening cases employed three commercial turbines: AAER A-2000-100, Enercon E-101, and Vestas V90-3.0 MW. All wind cases used the same measured reference speed of 5.5 m/s at 10 m; therefore, the differences in annual performance primarily reflect the turbine characteristics, hub height, rotor diameter, and capital cost. Turbine counts were selected such that the annual exported electricity would be of the same order as the dormitory demand[2,6].

## 4. RESULTS AND DISCUSSION

**4.1. Photovoltaic Screening Under the Rooftop-Area Constraint.** In this study, "exported electricity" refers to the annual amount of electricity generated by the PV or wind system that is delivered to the KFUPM grid; this is calculated after applying all modeled system losses. A dormitory load of 48 GWh/year was used as the design target and PV/wind systems were designed to slightly exceed the annual dormitory load. Grid imports and exports still occur during the hours that experience a mismatch between instantaneous generation and demand.

**Table 1.** *Common modeling and financial assumptions used in RETScreen screening cases*[15]

| Parameter | PV cases | Wind cases |
|---|---|---|
| Annual load target | 48,000 MWh/year | 48,000 MWh/year |
| Site | Dhahran, Saudi Arabia | Dhahran, Saudi Arabia |
| Resource mode in RETScreen | Solar | Wind |
| Operating mode | Fixed tilt rooftop (grid connected) | Standard grid – connected wind |
| Technical losses | 10% miscellaneous; inverter efficiency = 90% | 2% array; 6% airfoil; 7% miscellaneous |
| Export rate | $85.33/MWh | $85.33/MWh |
| Project life | 15 years | 15 years |
| Initial cost | $652/kW [19] | $1,035/kW [19] |
| O&M cost | $5.60/kW · year [19] | $38/kW•year [19] |

*Note: All monetary values reported in this study are in US dollars ($).*

**Table 2.** *PV-candidate specifications and roof-area utilization* [15]

| Module | Rated power (W) | Units | Capacity (MW) | Efficiency (%) | Area ($m^2$) | Roof use (%) |
|---|---|---|---|---|---|---|
| Trina Solar | 600 | 54000 | 32.400 | 21.20 | 152,830 | 99.76 |
| Jinko Solar | 595 | 54000 | 32.130 | 21.29 | 150,916 | 98.51 |
| JA Solar | 545 | 59000 | 32.155 | 21.10 | 152,393 | 99.47 |

**Table 3.** *Wind-turbine candidate specifications* [15]

| Turbine | No. of turbines | Rated power (MW) | Total capacity (MW) | Hub height (m) | Swept area per turbine ($m^2$) |
|---|---|---|---|---|---|
| AAER | 11 | 2.0 | 22.0 | 100 | 5,542 |
| Enercon | 7 | 3.0 | 21.0 | 99 | 8,011.85 |
| Vestas | 9 | 3.0 | 27.0 | 90 | 6,361.73 |

The PV simulations show that all three monocrystalline module options can be sized to meet the annual dormitory electricity target within the available roof area. The exported electricity ranges from 48,040 to 48,444 MWh/year; therefore, each case can meet the 48 GWh/year demand at the screening level. The available rooftop area is 153,796 $m^2$, whereas the modeled collector-area requirement ranges from 150,916 to 152,830 $m^2$. This implies that the PV designs use approximately 98.5%–99.8% of the available roof area, leaving only a small residual margin for access paths, setbacks, and layout adjustments. Therefore, the main differences among the PV options are not in annual energy adequacy but in roof-area efficiency and capital cost.

The modeled collector areas represent an optimistic deployment, covering 98.5% of the available area. Under a more practical 67% usable fraction, the deployable area would be reduced to approximately 103,000 $m^2$, which would require the addition of more rooftop areas from nearby parking structures and dormitories.

The details of the capital expenditure (CAPEX), operating and maintenance costs (O&M costs), and payback time are given below:

$$CAPEX = \frac{(Initial\ cost \times Capacity)}{10^6}, \tag{4}$$

where

- Initial cost is in $/kW.
- Capacity is in kW.
- CAPEX is capital expenditure in $ million.

$$\text{Annual cost}(\$\text{million/year}) = \frac{(O\&Mcost \times Capacity)}{10^6} \tag{5}$$

$$\text{Annual revenue}(\$\text{million/year}) = \frac{(\text{Exported electricity} \times \text{Export rate})}{10^6} \tag{6}$$

$$Payback\ (years) = \frac{CAPEX}{(Annualrevenue - Annualcosts)}, \tag{7}$$

where

- Annual revenue and annual costs are in $ million/year.

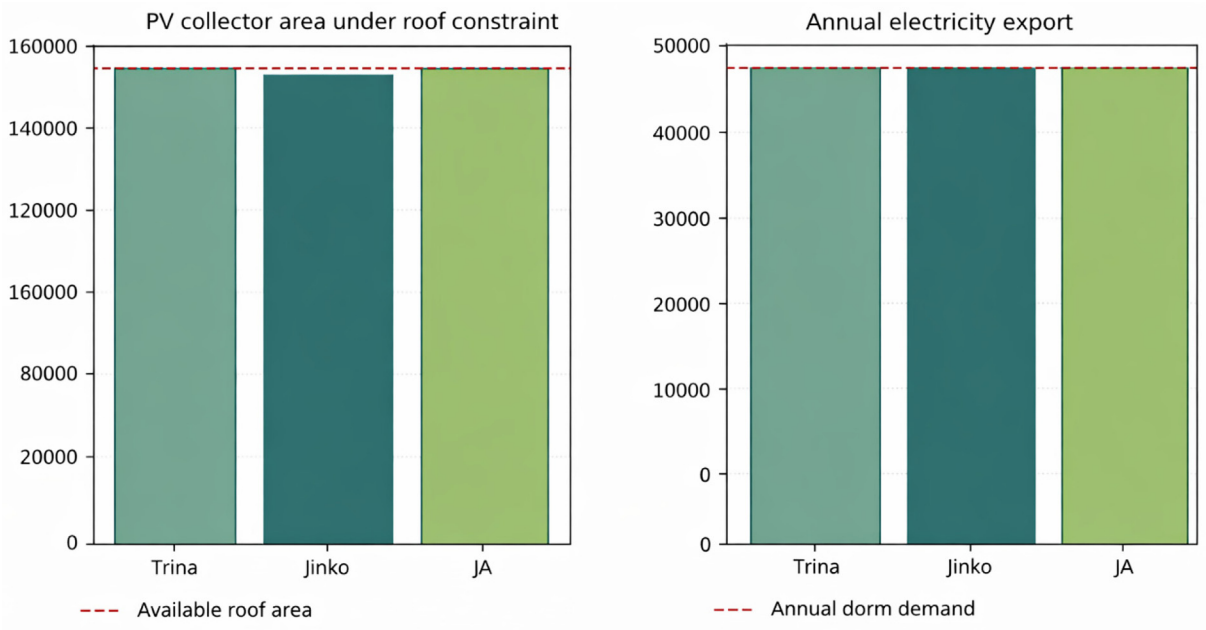



**Figure 3.** Comparison of the three PV module candidates showing roof-area utilization and annual exported electricity relative to the 153,796 $m^2$ available rooftop area and 48 GWh/year dormitory-demand target. All three options exceed 98.5% roof utilization and meet the annual demand target

**Table 4.** *PV-screening results for the three rooftop-module options*

| Module | Exported electricity (MWh/year) | CAPEX ($ million) | Annual costs ($ million) | Annual revenue ($ million) | Payback (years) |
|---|---|---|---|---|---|
| Trina Solar | 48,444 | 21.125 | 0.181 | 4.134 | 5.3 |
| Jinko Solar | 48,040 | 20.949 | 0.180 | 4.099 | 5.3 |
| JA Solar | 48,078 | 20.965 | 0.180 | 4.102 | 5.3 |

**Table 5.** *Wind-screening results for the three turbine candidates*

| Turbine | Capacity factor (%) | Exported electricity (MWh/year) | CAPEX ($ million) | Annual costs ($ million) | Annual revenue ($ million) | Payback (years) |
|---|---|---|---|---|---|---|
| AAER | 27.3 | 52,541 | 22.770 | 1.641 | 4.483 | 5.1 |
| Enercon | 28.1 | 51,665 | 21.735 | 1.567 | 4.409 | 4.9 |
| Vestas | 22.3 | 52,821 | 27.945 | 2.014 | 4.507 | 6.2 |

The payback time is calculated by assuming a net-zero billing framework on an annual basis.

Among the PV modules, the Jinko module is the strongest rooftop candidate. It delivers 48,040 MWh/year, effectively matching the demand target, while using the smallest roof area (150,916 $m^2$ or approximately 98.5% of the available roof) and lowest capital cost ($20.949 million). The Trina and JA Solar cases are also feasible; however, they occupy a slightly larger rooftop footprint and incur marginally higher capital costs. This result is similar to that of many studies on rooftop systems with limited space, where higher-efficiency modules are often selected because of their lower area requirement even though they have the same annual energy yield per kilowatt as that of lower-efficiency modules [16].

The systems were sized to meet the same annual load and evaluated with the same RETScreen PV cost structure; therefore, the economics remained highly similar. Once the energy target is met, the module choice primarily depends on how well it fits the available roof area and as well as its cost. Similar tendencies have been reported in schools and public-building PV assessments in Saudi Arabia, which showed that module efficiency becomes particularly valuable when rooftop area is limited [17,18].

**4.2. Wind-Turbine Screening Under Common Resource and Loss Assumptions.** The considered wind turbines produce more than the annual dormitory demand in their current RETScreen layouts, with the exported electricity ranging from 51,665 to 52,821 MWh/year. However, unlike the PV cases, the wind alternatives show clear differences in capacity factor and financial performance. This is because the turbine models differ substantially in terms of rotor size, hub height, installed capacity, and capital cost. The annual wind electricity is calculated for the three wind turbines as follows:

$$E_{annual} = CF \times (P_{rated} \times 8760), \quad (8)$$

where

- CF is the capacity factor
- $E_{annual}$ is the annual exported electricity in kWh
- $P_{rated}$ is the installed capacity in kW
- 8760 is the number of hours in one year.

Among the wind turbines considered, Enercon E-101 combines the highest capacity factor (28.1%) with the lowest capital cost ($21.735 million) and shortest simple payback (4.9 years). The AAER module performs reasonably well and is close to Enercon in terms of load-matched capital costs; however, its capacity factor and financial indicators remain slightly weaker. The Vestas module generates a similar annual total energy only because it has the largest installed capacity (27 MW). However, it becomes the least attractive option in the present dataset owing to its associated costs.

These results are consistent with broader findings in the literature on hybrid renewable energy. Enercon E-101 has a capacity factor of 28.1%, which compares favorably with those reported for wind projects in the Eastern Province of Saudi Arabia. Elhadidy and Shaahid [6] showed that the hub height and rotor diameter strongly determine the annual yield at coastal sites with moderate wind speeds. The relatively short payback of 4.9 years is also consistent with the favorable export tariff assumed in this study and reflects the lower capital cost of the Enercon configuration per unit of annual energy delivered.

**4.3. Selection of Preferred Technologies for Future Hybrid Integration.** The screening presented in this study suggests a clear next step in hybrid development. The Jinko 595

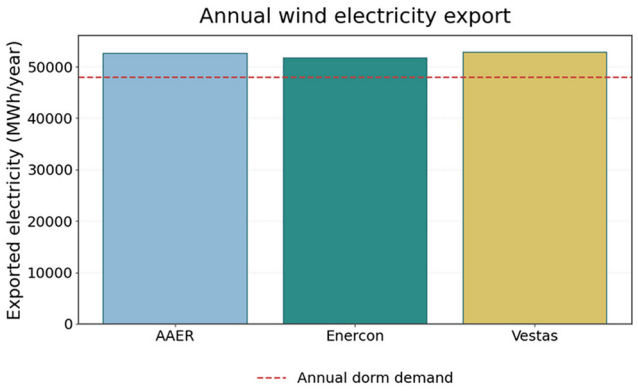



**Figure 4.** Annual exported electricity for the three wind-turbine candidates: AAER A-2000-100 (52,541 MWh/year, 11 turbines); Enercon E-101 (51,665 MWh/year, 7 turbines); and Vestas V90-3.0 MW (52,821 MWh/year, 9 turbines). All three configurations exceed the 48 GWh/year dormitory demand target

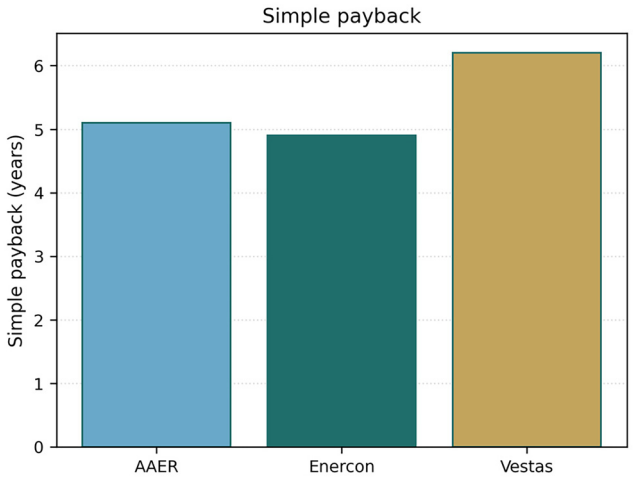



**Figure 5.** Comparison of simple-payback periods for the three wind-turbine candidates. Enercon E-101 achieves the shortest payback (4.9 years), followed by AAER A-2000-100 (5.1 years) and Vestas V90-3.0 MW (6.2 years)

W is the strongest candidate for the PV module because it meets the annual load target with the smallest roof-area requirement and lowest capital cost among the PV options. Enercon E-101 is preferred for the wind module because it provides the highest capacity factor and strongest economic performance among the wind options. These results do not constitute a complete hybrid dispatch optimization, but they identify Jinko 595 W and Enercon E-101 as the preferred candidates for a subsequent hybrid model.

In future hybrid systems, a rooftop PV system can supply a large portion of the daytime demand, whereas wind can contribute power during hours when the PV output is low or unavailable. This type of pairing is consistent with the logic emphasized in hybrid-system design studies, where resource complementarity and shared campus infrastructure are central to improving the renewable-energy fraction and reducing reliance on a single technology[4,5].

**4.4. Sensitivity of Economic Results to Key Parameters.** The payback-period results presented in Sections 4.1 and 4.2 are based on fixed assumptions for electricity-export tariffs, capital costs, and O&M costs. The robustness of these results were assessed based on a one-at-a-time sensitivity analysis for the two preferred technology candidates, Jinko 595 W (PV) and Enercon E-101 (wind), as presented in Table 6. Each parameter was varied by ±20% while all other inputs were constant, and the resulting payback period was recalculated using Equation 7. The export tariff has the largest influence on payback, whereas the O&M cost has a relatively minor effect. Both technologies remain economically attractive (payback under seven years) across all tested variations, supporting the robustness of the screening conclusions. Capital-cost uncertainty has a moderate effect, which reinforces the importance of obtaining accurate procurement quotes in detailed feasibility studies.

## 5. CONCLUSIONS

This study used RETScreen for evaluating commercial PV-module and wind-turbine options for a prospective standalone or hybrid renewable system powering the KFUPM student-housing dormitories in Dhahran. The following conclusions are drawn based on the results of this study:

- The Rooftop PV system can be sized to match the 48 GWh/year dormitory demand within an available rooftop area of 153,796 $m^2$. All three PV candidates remained technically feasible under this constraint.
- Within the PV options, the Jinko 595 W module is the preferred candidate because it meets the energy target with the smallest collector area (150,916 $m^2$) and lowest capital cost ($20.949 million).
- Within the wind options, Enercon E-101 is the strongest candidate. It achieved the highest capacity factor (28.1%) and shortest simple payback (4.9 years) among the screened turbines.
- The combined evaluation supports the use of Jinko Solar and Enercon E-101 as the preferred technology candidates for subsequent unified hybrid modeling of the KFUPM dormitory campus.

There exist some limitations to this study. For instance, battery storage was not included because the study objective was technology selection rather than dispatch optimization. The grid connection allows surplus generation to be exported, and storage sizing requires hourly load profiles that were unavailable at this stage; this exclusion will be addressed in future analysis. Moreover, the loss assumptions were not derived from site-specific measurements in Dhahran. The Eastern Province experiences both high dust loading and significant coastal humidity for several months each year. Unlike purely arid inland sites, the combination of fine dust and moisture creates a more adhesive soiling layer on panel surfaces, which is more difficult to remove and may cause persistent performance degradation. Ambient temperatures in Dhahran can also exceed 50 °C in summer,

**Table 6.** *One-at-a-time sensitivity of simple payback period for Jinko 595 W (PV) and Enercon E-101 (wind)*

| Parameter varied | Change | Jinko PV paybacks (years) | Enercon E-101 payback (years) |
|---|---|---|---|
| Base case | — | 5.3 | 4.9 |
| Export tariff | −20% | 6.8 | 6.2 |
| Export tariff | +20% | 4.4 | 4.1 |
| Capital cost | −20% | 4.3 | 3.9 |
| Capital cost | +20% | 6.4 | 5.9 |
| O&M cost | −20% | 5.3 | 4.2 |
| O&M cost | +20% | 5.4 | 4.9 |

which increases PV-cell temperatures above the nominal operating cell temperature of 45 °C assumed in the model and further reduces output through the temperature coefficient of power. A higher soiling allowance combined with a temperature correction specific to the Eastern Province climate would reduce the exported electricity estimates and increase the modeled payback period; this represents a key uncertainty in the present results and should be addressed using measured soiling data in a detailed design study. Furthermore, the wind-turbine cases in this study represent a techno-economic screening exercise and do not constitute a practical deployment plan. The practical installation of multimegawatt turbines with hub heights of 90–100 m and rotor diameters of approximately 100 m on or adjacent to a university campus requires further evaluation of the minimum safety setback distances from occupied buildings, noise levels, and structural- and civil-engineering requirements for large turbine foundations. The local airspace regulations and permit requirements should also be assessed; therefore, the wind results presented in this study are best interpreted as a resource and economic benchmark for technology comparison, and a dedicated implementation study is required before any campus wind deployment can be considered.

•These results will be useful in screening and selecting candidates for grid-connected renewable energy supply systems. Given these limitations, future work should use the same financial assumptions for PV and wind systems, add hourly load and resource matching, study battery storage, and include a more detailed campus layout and wind-siting limitations.

## AFFILIATIONS AND AUTHOR DETAILS


### Undergraduate Author

**Abdulrhman Alnome** – *Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*; 0009-0003-1518-8421
Email: s202275260@kfupm.edu.sa

### Corresponding Author

**Awad Bin Saud Alquaity** – *Research Mentor, Associate Professor, Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*; 0000-0002-9306-0154
Email: awad.alquaity@kfupm.edu.sa


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