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A Simplified Method for BIPV Retrofitting of Emirati Public Housing with Preserved Architectural Identity: A Pilot Study

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Abstract: The United Arab Emirates (UAE) has tailored its own sustainability initiatives and a local agenda for realizing Sustainable Development Goals (SDGs) by 2030. This Agenda includes providing clean sustainable energy and achieving sustainable communities. In accordance with these efforts, this 'pilot' study aims at, first, exploring an appropriate, simplified method of integrating photovoltaic (PV) panels in existing single-family public housing in the UAE without compromising the architectural style and identity of the original designs. Second, it aims at assessing the sufficiency of the generated electricity through this proposed Building Integrated Photovoltaic (BIPV) system. Finally, it aims at conducting a pilot survey to explore the Emirati residents' acceptance of the proposed BIPV system. A frequently developed design model of single-family public housing projects in the UAE was selected to undertake the research investigations where the most suitable architectural elements of its envelope were defined for accommodating the integrated PV panels. Afterwards, a complete set of BIPV panel designs tailored to fit with the defined architectural elements of the selected house was prepared. The dimensions and areas of the BIPV panels were defined and digitally constructed through Building Information Modeling (BIM) software. After considering the efficiency and adequacy of the selected type of BIPV panels and figuring out the expected system losses, the PVWatts Calculator was used for simulating the expected electricity output in kilowatt hours (kWh) for the four façades of the selected model house in their four possible different orientations, as well as the overall average electricity output from the whole BIPV system. The results of the yearly electricity output were very close regardless of the orientation of the four façades of the retrofitted model house, with the total average annual output exceeding the estimated yearly average electricity consumption of this model house. This obviously indicates the potential benefit of the proposed BIPV system, especially with the continuous decrease in the capital cost of the PV panels and their increasing efficiency. With the Emirati residents' clear acceptance of the proposed BIPV system, it might be also considered as an efficient alternative to the currently limited application of rooftop PV solutions in the UAE.

Keywords: BIPV; retrofitting; SDGs; public housing; architectural identity; Emirati; UAE

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1. Introduction

The United Arab Emirates (UAE) is experiencing rapidly increasing demographic and economic growth with a parallel increase in the demand for water and electricity. The conventional source of energy generation in the country is essentially based on fossil fuels, which have serious environmental impacts [1]. The UAE is considered among the highest energy consumer countries per capita; as of 2019, the demand of electricity usage reached about 137 billion kilowatt hours (kWh) with about 9% expected annual increase in energy demand as the economy continues to grow [2,3]. Buildings in the UAE are consuming about 80% of the country's total generated energy. As a result, the federal authorities have set some initiatives and regulations that aim to achieve more efficient energy consumption in buildings [4]. For example, one of the main pillars of the National

Vision 2021 in the UAE is to increase the contribution of clean energy and implement green growth plans [5]. Moreover, three main sustainability programs have been launched in the last decade in Abu Dhabi, Dubai, and Ras Al Khaimah. Launched in 2009, Estidama (which means 'Sustainability' in Arabic) was the pioneering sustainable building initiative in the Abu Dhabi Emirate. Estidama implements a rating system in the new buildings to ensure the realization of sustainability measures. In Dubai, another building rating system called Alsa'fat (meaning 'Palm tree branches' in Arabic) has been recently implemented. It first targeted public buildings in 2011; then, since 2014, it became mandatory for all new buildings. The applied measures of this initiative ensure that the building is constructed and operated in a sustainable manner [6]. The Ras Al Khaimah Emirate followed the same steps and devised its rating system for sustainable buildings called Barajeel (traditional wind towers in the region).

On the same sustainability track, the UAE is taking local actions regarding realizing the Sustainable Development Goals (SDGs) that were launched by the United Nations in its "2030 Global Agenda for Sustainable Development". This Agenda aims at enhancing living conditions through 17 different sectors, including affordable and clean energy, sustainable cities and communities, and climate change actions [7]. The UAE has developed its own local 2030 Plan to meet the SDGs [8]. In this local plan, considerable efforts have been directed towards providing clean sustainable energy where mega scale projects have been either fully developed or are under construction to produce clean energy for buildings. For example, Shams 1 (meaning 'the Sun' in Arabic) project in Abu Dhabi has the capacity to feed the national grid with 100 Megawatts (MW), enough to serve the power needs of approximately 20,000 homes. In addition, the first phase of the Concentrated Solar Power (CSP) project in Dubai, which has a power generation capacity of 150 MW, began operating last year (2021). A third mega project is Mohammed Bin Rashid Al Maktoum Solar Park in Dubai, which will be completed by 2030, and is planned to increase its generated power from 1000 MW in 2020 to 5000 MW by 2030. More projects are being constructed to implement the country's vision for the provision of sustainable energy resources [9].

In line with these efforts for meeting the SDGs requirements in the sustainable energy production and consumption sectors in the UAE, this pilot research is exploring the potentials of utilizing the Building Integrated Photovoltaic (BIPV) system in retrofitting existing single-family public housing, which forms a major portion of the building sector in the UAE. The exiting stock of public housing in the UAE has been developed federally by the Ministry of Public Works and Housing in the 1970s and the Sheikh Zayed Housing Program at a later stage. Besides these federal public housing providers, each Emirate in the UAE has its own local public housing provider. In the early 2000s, the developed housing models by these federal and local public housing providers considered the requirement of Estidama, especially in terms of the house envelope insulation [10]. Meanwhile, although the design of the façades of these housing models has reflected a unique architectural identity, no attempt has yet been made to integrate photovoltaic panels with the building envelope as a retrofitting strategy.

While contributing to the UAE's sustainable development initiatives and the SDGs 2030 Plan, this investigation aims also at blending architectural identity with the technicality of solar renewable energy in such a way that it achieves both environmental and socio-cultural sustainability in existing single-family public housing projects in the country. The importance of this research is affirmed by the fact that the magnitude of the existing stock of public housing in the UAE constitutes a significant opportunity for sustainable retrofitting through the utilization of solar energy if the BIPV is to succeed in offering reliable energy outputs. While providing electricity from a renewable and pollution-free source, and unlike the limited application of rooftop PV panel systems in the UAE, the BIPV has the advantage of avoiding the limitation of having to place the PV panels on the roofs of the houses. It rather depends on integrating the PV panels with the architectural elements of the envelope of the house. Thus, it frees the roof space for various domestic uses, such as roof gardens, for family gathering, BBQs, etc. In addition, the BIPV systems are easier for the households to maintain and clean with simple cleaning tools when compared with rooftop PV panels.

Concerns about the limitation of achieving the optimal tilt angles for the PV panels in the BIPV systems could be compensated for when these systems are associated with other implemented passive measures for decreasing air conditioning demands, the main source of energy consumption in the housing sector in the UAE. These passive measures, which are out of the scope of this research, include, for example, increasing thermal insulation of the house envelope, implementing evaporative cooling techniques, etc. Besides their role in generating electricity, the BIPV systems also work as climate screens for the outer building envelope. Therefore, the BIPV systems could provide extra savings in air conditioning loads, in addition to reducing electricity costs [11]. On the other hand, the BIPV market, as a segment of the overall PV market, is experiencing rapid growth worldwide, which has caused a reduction or redefinition of national support schemes for the utilization of solar energy in buildings in many countries [12].

In the literature, utilization of the BIPV systems has been advocated as a reliable renovation technique of apartment blocks where their energy efficiency and economic value proved suitable in temperate climates (see, for example: [13]) and cold climates (see, for example: [14]). BIPV systems were also analyzed from both the construction and performance aspects when vertically fitted on simple modern façades of high-rise buildings (see, for example: [15]). Other research work tackled the utilization of urban BIPV in the new residential construction industry (see, for example: [16]). Still other research concentrated on cost analysis of the BIPV rooftop systems in the residential sector (see, for example: [17]). Accordingly, this research attempts to add to this scholarly work, albeit on a pilot scale, through considering BIPV retrofitting that, while having the potential to generate energy, integrates well with relatively complex architectural features to preserve the architectural identity of the existing public housing and will be accepted by the Emirati residents.

The main objective of this research is three-fold. First, to develop a customized BIPV system that integrates carefully selected PV panel types, in terms of efficiency, cost, and appropriateness, with the architectural features and motives of an existing and frequently developed single-family model house of the UAE's public housing projects in a way that preserves the architectural identity of the house. Second, to investigate the efficiency of the suggested BIPV system in meeting most, if not all, of house electricity consumption demands. This would make the house self-sufficient in energy through meeting its electricity demand from its own BIPV sustainable and clean energy system. Third, to conduct a pilot survey to investigate the Emirati residents' acceptance of the architectural identity after implementing the suggested BIPV system on the façades of the model house. In addition, the research aims to briefly and roughly estimate the expected savings in the electricity bill of a selected house due to the installation of the suggested BIPV system.

2. Research Method and Procedures

This research is mainly a pilot study that deliberately utilizes simple but valid simulation tools to be easily replicated on other exiting housing models in order to give indications as to the expected potential of the energy outputs from the BIPV systems. The simplified energy consumption and output simulation tools include Building Information Modeling (BIM) for the existing model house in Autodesk Revit [18], use of the Insight plugin [19] to estimate Energy Use Intensity (EUI) in kWh/m^2/year for the house before the BIPV retrofitting, and PVWatts Calculator, a reliable PV electricity output calculator developed by the National Renewable Energy Laboratory (NREL) of the US Department of Energy [20] for estimating the expected electricity output of the suggested BIPV system for the selected model house. Despite the availability of more advanced simulation packages and tools including, for example, Design Builder, SAM, etc., these simple and user-friendly simulation tools and the suggested application method here could provide an example that might be easily replicated in municipalities and housing institutions for conducting preliminary retrofitting studies of existing (and new) public housing designs. For more scientific in-depth research, other advanced simulation tools could be applied.

Furthermore, the focus of this pilot study is not only on the potential energy output of the suggested BIPV system, but also on preserving the architectural character of the model house after applying the system and to briefly explore the Emirati community acceptance of the resulting architectural form after application of the BIPV system. It is believed that the local community acceptance of the retrofitted model house form after installing the BIPV panels will encourage them to contribute to the initial retrofitting cost and welcome the responsibility for maintaining the PV panels. Such acceptance will likewise help widen the implementation of the BIPV retrofitting of existing public housing all over the UAE.

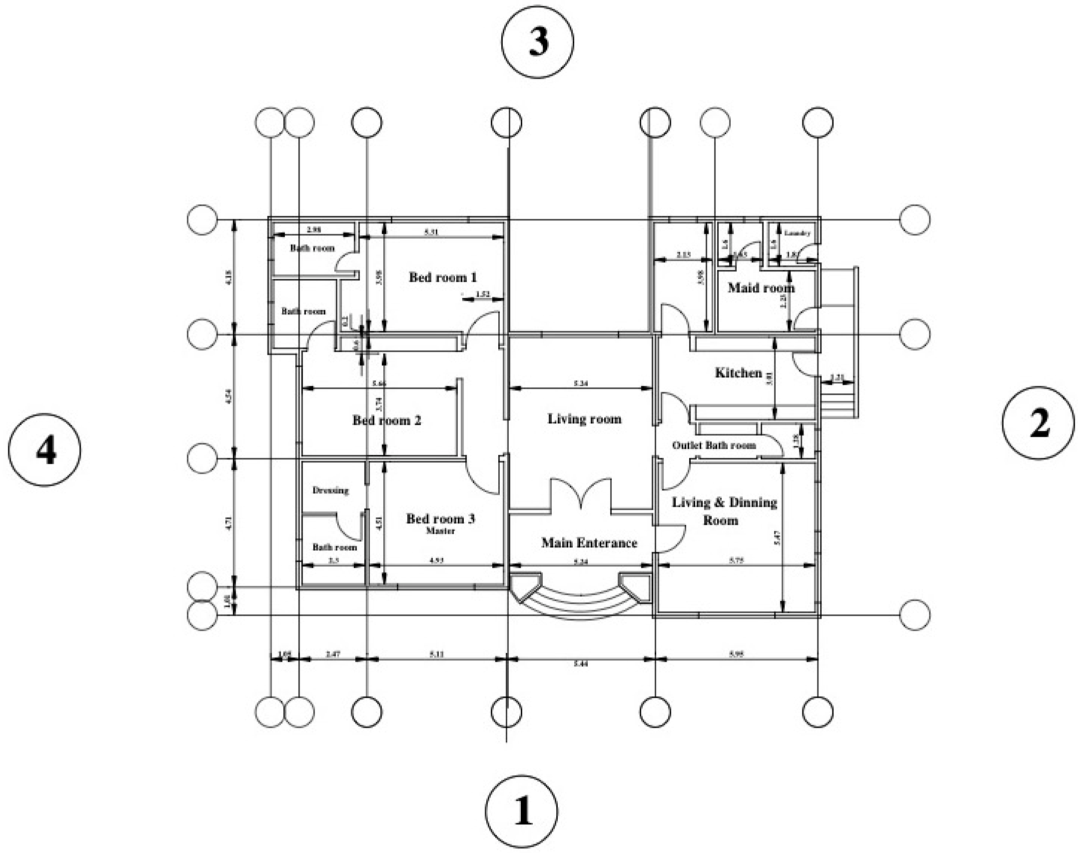
A commonly developed one-floor single family model house by the Sheikh Zayed Housing Program (SZHP), the chief federal social housing provider in the UAE, was selected to integrate the PV solar panels into its façades, producing a customized BIPV system. The built-up area of this three-bedroom house is approximately 220 m^2 and it is designed to achieve thermal insulation requirements as set by Estidama. In fact, while there is still room for passive energy conservation enhancements through, for example, increasing the thermal insulation of the house envelope by added thermal insulation cladding, the original design of the house has already achieved the U-values required for its envelope by Estidama through using 20 cm self-insulated Concrete Masonry Unit (CMU) external walls, a thermally insulated roof by 5 cm rigid thermal insulation, double-glazed windows, and the use of window overhangs.

The inner spaces of house are designed to achieve traditional functions and a spatial distribution that respond to Emirati socio-cultural values. Externally, a traditional architectural identity was created through using architectural motives such as arches and canopies. Figure 1 shows simplified CAD drawings for the Ground Floor plan and the four façades of this model house, as developed by the authors.

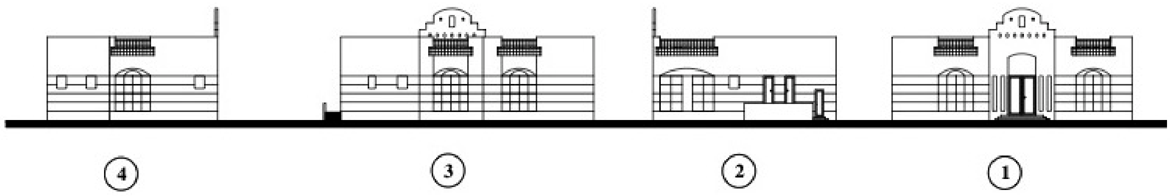
2.1. Developing the 3D BIM Model of the House

After developing the plan and the façades into to-scale CAD drawings, a 3D BIM model of the house was developed including all house construction materials and systems. This permitted undertaking electricity consumption simulations for the house through the Insight plugin in Revit software and, later, the integration of the BIPV panels with its four façades. Figure 2 shows rendered views of the developed 3D BIM model of the house.

In this 3D BIM model, the specifications of the used construction materials of the walls, the roof, and the windows of the house were accurately defined. The 20 cm thick self-insulated hollow core CMU with added 2 cm thick external and internal cement plastering layers give external walls a total thickness of 24 cm with a cumulative U-value of 0.11 $W/m^2{\cdot}K$. Meanwhile, the total thickness of the roof reached 30 cm, including a 5 cm thermal insulation layer, giving a U-value of 0.09 $W/m^2{\cdot}K$. The windows were modeled as double glazed with aluminum metal framing, giving a U-value of 2.80 $W/m^2{\cdot}K$. Table 1 shows the specifications of the components of the house walls, roof, and windows.



(**a**)

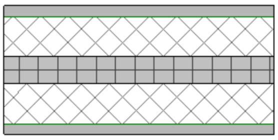
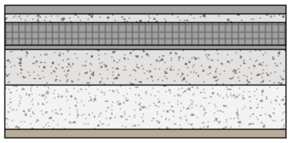


(**b**)

Figure 1. The Ground Floor plan (**a**,**b**) the four façades of the selected model house.

Figure 2. The 3D BIM model of the house before integrating the solar panels.

Table 1. The specifications of the components of the envelope of the house (from Autodesk Revit).

	Wall	**Roof**	**Windows**
U-Value (W/m^2·K)	0.11	0.09	2.80
Layers	*Outer finishing:* - Plaster + paint (2 cm) *Structure core:* - Concrete Masonry Unit (CMU) (7.5 cm) - Thermal layer: rigid insulation (5 cm) - Concrete Masonry Unit (7.5 cm) *Inner finishing:* - Plaster + paint (2 cm)	*Outer finishing:* - Cement tiles (2 cm) - Cement mortar (2 cm) - Thermal rigid insulation (5 cm) - Water damp-proofing (dpm) (1 cm) - Lightweight concrete (LWC) (8 cm) *Structure core:* - Cast in place concrete slab (10 cm) *Inner finishing:* - Plaster + paint (2 cm)	Double panes of glass with aluminum metal framing
Total thickness	24 cm	30 cm	
BIM Cross-Section			

The above-mentioned thermal conductivity values of the model house envelope are automatically generated in the 3D BIM model in Revit where they are fed into the simulation process of the electricity consumption of the model house through the Insight plugin in Revit software. In this process, the house plan is divided into zones to compute the amount of electricity needed for operating the HVAC, lighting, and other electrical equipment in the house. The Insight plugin simulates the electricity consumption of the 3D BIM model of the house taking into consideration its architectural form, climatic conditions of its geographical location, the specification of the envelope's materials, and the anticipated energy consumption by other electricity consuming systems. Energy analysis via the Insight plugin is undertaken through reliable simulation engines, including DOE 2.2 and EnergyPlus, that analyze the building energy performance relying on the building materials and systems data integrated within the 3D BIM model of the house [19]. With its consideration of the architectural form of the model house and its integration with the 3D BIM modeling, Insight is a reliable, simple and user-friendly simulation tool that is suitable for accomplishing the objective of this pilot study.

2.2. Developing the BIPV BIM Model of the House

The most suitable architectural elements of the envelope of the selected model house were defined to accommodate the integrated PV solar panels of the customized BIPV system in a way that preserves the original architectural identity of the façades. These architectural elements included the canopies above the windows and the horizontal ribbons around the four façades and above the main entrance (Figure 3). The original inclined shading canopies above the windows were extended around the four facades of the house to maximize the collected solar energy while still preserving the architectural motive of the original design. The inclined angle for these canopies was adjusted to 24°, as the best inclination angle for the fixed PV panels that matches the latitude angle of Al Ain city in the UAE, where the selected model house was mostly developed. The horizontal ribbon of the PV panels has a 90° (vertical) inclination angle to also preserve the architectural style of the façades, despite the consequent expected decrease in efficiency. Consequently, a complete set of to-scale BIPV panel designs for these defined architectural elements of the selected model house was prepared. As discussed below, the detailed dimensions and areas of the PV panels and their type were defined in these designs for each of the four façades of the model house. Furthermore, by virtue of the accurately detailed 3D BIM model of the house and the Revit software showcasing the expected self-shading during all times of the day along the 12 months of the year, the proposed depth and heights of both the peripheral tilted and the vertical BIPV panels were adjusted as much as possible to prevent the negative effect of self-shading on the PV panels (see Figure 3).

Figure 3. The 3D BIPV BIM model of the selected model house after integrating the solar panels.

The selection criteria of the PV panel type included, besides its nominal maximum power (Pmax), its efficiency, cost, weight, Nominal Module Operating Temperature (NMOT), and Temperature Coefficient related to Power. Cost is a vital factor for public housing retrofitting initiatives due to the typically tight budget, while the PV panels' weight is critical, because in the suggested BIPV system, several PV panels will be mounted on the existing 20 cm thick hollow core CMU walls. Hence, the weight of the PV panels should be as light as possible to avoid damaging the wall or the panels if they fall down as a result their heavy weight. The high temperature in Al Ain city and the UAE in general makes the NMOT and Temperature Coefficient related to the nominal maximum output power of the selected panel crucial selection criteria as well. After a brief market survey at the time of undertaking the research in early 2021, three main products were defined. Table 2 shows the decision matrix of the selected PV panel type. Despite its lower Pmax value of 100 w, the SPR 100_46 Mono Solar module was selected because it has a much lower price and unit weight and the best NMOT, if compared to the other two types, as shown in Table 2. It also gives almost the same efficiency and a close Temperature Coefficient (affecting Pmax) as the other two types. It is still worth mentioning that with the ongoing rapid changes in the PV industry, and the associated raised efficiency and decreased cost and weight of the PV panels, other current/future PV types might be more appropriate for BIPV retrofitting of public housing than those mentioned in Table 2. Still, the PV panel selection criteria applied here are believed valid in this and any future similar housing retrofitting process.

The standard dimensions of the selected panels were considered in the developed BIPV BIM model (Figure 3) and were also used in calculating the total areas of both the 24° tilted and the 90° vertical PV modules. The total calculated areas of the PV panels on the vertical elements (external walls at 90°) of the four façades of the model house reached almost 40 m^2, while the total area of the PV panels on the 24° inclined elements (shading canopies) was about 165 m^2.

Table 2. The decision matrix for selecting the solar PV panels.

PV Panel Type	LG Solar LG345N1C-V5 NeON 2 *	SPR 100_46 Mono Solar Module **	LG Solar LG365Q1C-A5 NeON R ***
Efficiency (%)	20.1%	20%	21.1%
Nominal Maximum Power (Pmax)(W)	345	100	380
Nominal Module Operating Temperature (NMOT) (°C)	42 ± 3	46 ± 2	44 ± 3
Temperature Coefficient-Power (Pmax) (%/°C)	−0.36	−0.38	−0.30
Size (mm)	1686 × 1016 × 40	1037 × 527 × 46	1700 × 1016 × 40
Weight (kg)	17.1	7.20	18.5
Price (USD)	490.00	279.43	411.00

* https://www.lg.com/us/business/solar-panels/lg-lg345n1c-v5 accessed on 12 December 2021. ** https://ocatcdn01.azureedge.net/media/documents/phaesun/products/3100/310054_DS_EN_lrg.pdf accessed on 12 December 2021. *** https://www.lg.com/us/business/solar-panels/lg-LG365Q1C-A5 accessed on 12 December 2021.

2.3. The Calculation Measures for the BIPV Electricity Output

After selecting the PV module type, the PVWatts Calculator [20] was used in this pilot study for simulating the expected electricity output of the suggested BIPV system. The PVWatts Calculator uses hourly typical meteorological year (TMY) weather data and a PV performance model to estimate annual electricity production. The PVWatts Calculator considers the geographical location of the house, the orientation (azimuth) of the solar panels and their tilt angles, the expected system losses (%), the DC system size (kW), and the module type. The calculations were conducted for the four façades of the model house in the four possible orientations for each of them, in the north, south, east, and west, as well as the overall average electricity output.

As discussed earlier, the geographical location was selected to be Al Ain city, and the tilt angle 90° for the vertical panels on the external walls and 24° for the tilted panels on the spandrel shading canopies. The system soiling, wiring, connection, and availability losses were estimated to be about 11% based on the weather of Al Ain city and the type of connection wires [21,22]. The weather in Al Ain city is mainly sunny but also frequently dusty with occasional sandstorms causing dust accumulation on the surface of the PV modules, especially the tilted ones. The dust layer deployment on the surface of the PV panels causes a significant power drop for the PV panels if they are not cleaned for a period of 10 days. This makes the suggested BIPV system in this research more efficient in terms of ease of dust removal (about twice a week) when compared with the rooftop PV installations.

On the other hand, the high temperature in Al Ain city was another concern. The performance of the PV module is inversely proportional to the module's temperature. For example, a 1 °C increase in a crystalline module temperature above its Standard Testing Condition (STC) will typically result in a decrease in its power output by 0.5%. On a polycrystalline panel, the effect of the temperature on the efficiency can be around 0.45% for each 1 °C increase. In a monocrystalline panel, like that selected in the research (Table 2), the effect is a bit lower [23]. Natural ventilation behind the PV modules is an important solution for the improvement in power performance associated with temperature. As for the appropriate ventilation gap, an experimental test was conducted to assess the effect of natural ventilation on the efficiency of the PV panels in which three PV models were examined, the first without ventilation, the second with a 10 cm ventilation gap from the supporting surface, and the third with a 50 cm gap. The comparison results indicated that the best solution is to leave a small gap between the building surface and the PV panel [23].

Therefore, it is not beneficial to have a bigger gap between the surface and the PV panel for the provision of natural ventilation as the effect of heat transfer by radiation between the two surfaces can be neglected, the only problem being air circulation in the gap if it is not well designed. Leaving a wider gap would also increase the cost of the installation of the BIPV system due to the higher deadloads and the increase in required construction materials [23]. Accordingly, in this research, a gap of 10 cm between the PV panel and both the canopies and the external wall surfaces was considered for the designed BIPV system. This simple natural ventilation technique would help avoid overheating problems and, hence, allow more electricity production which makes the BIPV system more profitable, albeit with a slight increase in investment cost due to the considered 10 cm ventilation gap while supporting the PV modules.

On the other hand, the DC system size was calculated twice for each façade of the house; first, for the tilted panels on the canopies and second, for the vertical panels on the walls, based on the following equation:

$$\text{Size (kW)} = \text{Array Area (m}^2\text{)} \times 1\ \text{kW/m}^2 \times \text{Module Efficiency (\%)} \quad (1)$$

Finally, the solar PV modules are assumed to be 'Connected in Series', where the output voltage is the sum of all modules' Maximum Power Point (MPP) voltages, and the output current remains as the module's MPP current. This is because the aim is to achieve a higher voltage grid connected system [24].

In addition to the professional design of the BIPV system to preserve the original architectural identity of the model house, the local Emirati residents' acceptance of the architectural identity of the suggested BIPV retrofitted house was assessed through a pilot questionnaire administered online for two weeks in March 2021. Responses from 1080 Emirati citizens living in public housing schemes that have the same selected model house or close to its architectural design were received. The responses came from both males and females almost equally (48% male and 52% female). As for age groups, the majority of the respondents were 25–45 years old (44.84%), followed by 18–24 years old (39.91%), those below 18 years old (7.76%), and 45–65 years old (7.21%). Meanwhile, 65-year-old and above respondents made up only 0.27%.

Only two questions were posted. The first was "Would you accept retrofitting your house with solar PV panels that you will be responsible for their maintenance and cleaning?" Meanwhile, in the second question, two 3D images were shown to the Emirati respondents of the model house, before and after installing the suggested BIPV modules, and then they were asked "Do you find that the external façades of the house after installing the solar panels are architecturally acceptable to you?" The simple frequency analysis of the responses to the two questions was analyzed in Excel.

3. Results

3.1. EUI and Annual Energy Consumption of the Selected Model House

As illustrated in Figure 4, the average annual EUI is about 265 kWh/m^2/year for the selected model house. Therefore, the total energy needed for the house equals this EUI value multiplied by the house total floor area of 220 m^2. This results in an estimated energy consumption of about 58,300 kWh per year. As expected, most of the energy is consumed in cooling (57%).

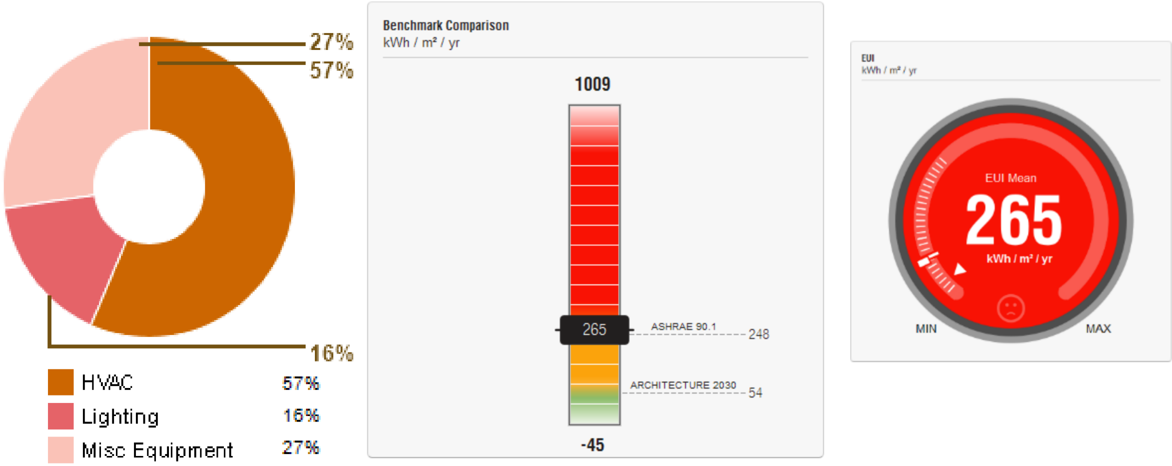


Figure 4. The EUI result for the house from Insight simulation.

3.2. BIPV Electricity Outputs

With a DC to AC ratio equal to 1.2 and inverter efficiency of 96%, PVWatts calculation results of the estimated yearly electricity output (in kWh) of both the tilted (24°) and the vertical (90°) modules of the BIPV system for the four different possible orientations of the model house main entrance's façade (N, S, E, and W), besides the tilted and vertical DC System Sizes (in kW), are shown in Table 3. The electricity output of the BIPV modules was recorded for the different architectural configurations (Figure 3) in each of the four façades of the model house four times, once for each of the four possible façade's orientations. The BIPV modules on the four façades of the model house collectively produced close values of the total electricity output when measured in each of these four possible orientations. The total yearly electricity output from the four façades was 60,070 kWh/year with the entrance facing north, 59,690 kWh/year facing south, 60,300 kWh/year facing east, and 60,720 kWh/year facing west. The total average electricity output of the BIPV system reached about 60,196.5 kWh per year.

Most of the electricity generated was from the BIPV modules in the south façade, followed by those of the west façade. As expected, the 90° modules mounted on the house's facades produced the lowest electricity power and showed wide variations. These vertically mounted PV modules obviously do not produce an electricity output as high as the latitude-tilt modules because of the higher angle of incidence of solar irradiation. Meanwhile, the variation in the results for different façade orientations came from the seasonal changes of the solar altitude in Al Ain city. But on the other hand, the soiling losses on the vertically mounted modules are usually lower than 1% where dust does not accumulate on them as it does on the tilted modules and when the modules are regularly cleaned each 10 days [25]. As the total average of the estimated electricity output from all of the BIPV modules reached about 60,197 kWh/year, it 'theoretically' exceeds the estimated 58,300 kWh/year yearly average electricity consumption of the tested model house.

The selected model house in existing public housing projects was developed in plots with generous setbacks of 3 m to 4 m from the sides and the back, and 4 m to 6 m from the front edge of the plot. This means that the space between the side and the back façades of the two neighboring houses will range between 6 m to 8 m, while the front façades will be 8 m to 12 m before adding the width of the street (around 12 m in average). These wide setbacks associated with the low rise of the house have minimized the possible negative effect of mutual shading on façades that would decrease the efficiency of the proposed BIPV system.

Table 3. DC system sizes and yearly AC electricity output of the BIPV arrays for the four house façades in the four different orientations of the house entrance.

Façade	Tilted DC System Size (kW)	Vertical DC System Size (kW)	Tilted AC Output (kWh)	Vertical AC Output (kWh)	Total AC Output (kWh)
House Orientation 1: Entrance at North					
North	8.30	3.28	11,251	1398	12,649
East	6.80	1.35	10,930	1226	12,156
South	10.40	2.09	19,258	2098	21,356
West	7.80	1.26	12,727	1178	13,905
Total (kWh)			54,166	5900	**60,066**
House Orientation 2: Entrance at South					
North	10.40	2.87	14,097	890	14,987
East	7.80	1.26	12,537	1145	13,682
South	8.30	3.28	15,370	3296	18,666
West	6.80	1.35	11,095	1260	12,355
Total (kWh)			53,099	6591	**59,690**
House Orientation 3: Entrance at East					
North	7.80	1.26	10,573	537	11,110
East	8.30	3.28	13,341	2980	16,321
South	6.80	1.35	12,592	1355	13,947
West	10.40	2.08	16,969	1951	18,920
Total (kWh)			53,475	6823	**60,298**
House Orientation 4: Entrance at West					
North	6.80	1.35	9217	575	9792
East	10.40	2.87	16,716	1897	18,613
South	7.80	1.26	14,444	1267	15,711
West	8.30	3.28	13,543	3064	16,607
Total (kWh)			53,920	6803	**60,723**
Overall AC Output for Each Entrance's Orientation and Total Average					
Entrance at East	**Entrance at North**	**Entrance at South**	**Entrance at West**	**Total Average Output (kW/h)**	
60,298	60,066	59,690	60,723	**60,196.5**	

3.3. Community Acceptance of the BIPV Retrofitting and Its Resulting Architectural Style

As for the community acceptance of the suggested BIPV system, the responses to the first question "Would you accept retrofitting your house with solar PV panels that you will be responsible for their maintenance and cleaning?" were overwhelmingly positive, where 89.95% of the 1080 Emirati respondents, from both genders (male and female) and from the age groups between 18–45 years old specifically, accepted. As for the second question, after seeing the two 3D images for the model house before and after installation of the suggested BIPV modules, the majority of the respondents (76.66%) found that the external façades of the house after installing the solar panels successfully preserved the original architectural identity of the house.

4. Discussion

The results of the estimated average yearly electricity output of the designed BIPV system for the selected model house obviously indicate the 'theoretical' efficiency of this BIPV system. This efficiency is expected to increase further in the future when considering the on-going enhancements in the power output and efficiency of the PV panels and the future decrease in their initial costs, which have already fallen over 20% over the past 5 years and is expected to drop further in the near future [26]. Moreover, the promising results of this pilot study are expected to encourage the local authorities in the UAE to include the BIPV systems in the existing governmental applications and webpages allocated for solar PV retrofitting of residential buildings and houses that are currently only considering rooftop systems [27].

From the economic perspective, the proposed BIPV system with its passive and simple maintenance techniques would help achieve the building sustainability agenda in the Emirati public housing sector in Abu Dhabi, and other Emirates in the UAE. Using renewable and clean energy resources would keep the energy consumption rates in the Abu Dhabi Emirate at the defined Green Band level that reflects the ideal average consumption for locals by setting a daily allowance consumption of 400 kWh. Emirati residents are currently charged only 6.7 fils/kWh within this allowance daily limit, but if they exceed it, they will be charged based on the Red Band with a higher rate of 7.5 fils/kWh [28]. As discussed earlier, the expected electricity consumption in the selected model house reached about 58,300 kWh per year, i.e., about 160 kWh per day, so it is still in the Green Band for electricity consumption for Emirati citizens. At this average yearly electricity consumption, the estimated cost for locals would equal about 3906 AED per year, when calculated at the subsidized rate of 6.70 fils/kWh. This cost becomes extremely high if the house is inhabited by non-Emiratis with much less subsidization, if any, at a current rate of 26.8 fils/kWh, i.e., about 15,624 AED per year.

After applying the BIPV system, the cost of electricity consumption of the selected model house would dramatically drop as the house, in best-case scenarios, would not only satisfy its electricity energy needs, but might even supply some excessively generated electricity to the national grid. As calculated above, the expected output electricity from the selected model house equals about 60,196.5 kWh/year. If this is deducted from the assumed electricity consumption of 58,300 kWh/year, then the cost will be a negative figure of—127.0 AED/year ($-$1896.5 KWh/year $\times$ 6.7 fils) when this excessive amount of 1896.5 kWh is sold to the electricity provider at the same subsidized rate.

On another important front, the evident success of the proposed BIPV system in preserving the architectural identity of the original house while achieving the anticipated energy benefits is supported by the noticeable acceptance of the Emirati citizens of the architectural configurations of the façades after the BIPV retrofitting. Hence, this opens a new door to engaging the local communities in the design of the BIPV retrofitting of their existing housing where they will become key players in preserving the efficiency of the PV models integrated with the façades of their houses by keeping them clean to avoid soiling losses, as much as is possible.

5. Conclusions

A simply designed system of PV modules carefully integrated with the architectural components of the external envelope of a commonly constructed single-family public housing model in the Abu Dhabi Emirate indicated the plausible success of BIPV retrofitting, especially as an alternative to the limited current rooftop PV solutions, in providing a renewable clean energy resource for covering the electricity consumption of the large existing stock of public housing in the UAE. The customized BIPV system managed to 'theoretically' produce electricity that slightly exceeded the expected yearly energy consumption of the model house. Even with the vertical 90° positioning of some PV panels in the suggested BIPV system, the overall performance was satisfactory.

Therefore, the BIPV solution could be practically considered a better choice if compared with the conventional rooftop PV panels solution, even despite the fact that the rooftop PV panels would technically perform better. Besides the proved satisfactory technical performance in generating electricity and compensating for the electricity demand, the preference of the BIPV retrofitting solution over the rooftop one might be attributed to three reasons. First, it clears the house's roof for other domestic activities, such as green roofs, social gathering, BBQs, kids' play areas, etc. Second, it enables the residents to easily clean the PV panels of accumulated dust that used to be a major problem in increasing the PV system soiling losses in the UAE. Third, it is the community-accepted architectural form of the facades of the model house after integrating the PV modules with the traditional architectural design motives of the façades in a way that might inspire and encourage other Emirati residents to similarly transform their houses, especially if some governmental assistance is provided through, for example, partial covering of the capital cost of the BIPV system, payment for it in easy installments, and/or exempting the BIPV systems from the applied Value Added Taxes (VAT).

On the other hand, the suggested BIPV system could be integrated with the existing Dubai and Abu Dhabi PV simulation applications that are available for the Emirati public in the two Emirates to give the residents opportunity to select between the rooftop PV retrofitting solution and the BIPV one, instead of the rooftop solution that is the only one currently available to them. The BIPV system could also be applicable to new single-family public housing projects with the same applied method in this research that takes different possible orientations of the house façades into consideration.

Mutual shading from surrounding houses should be considered in the design of these new housing projects, especially if the setbacks from the sides and the back of housing plots decreased compared with the existing public housing schemes. This, in addition to the evident acceptance of the Emirati residents to have BIPV systems, and preserve the original architectural identity of their houses, make the suggested BIPV retrofitting of the existing public housing stock a viable step towards meeting the challenges associated with the UAE's sustainable development initiatives and its 2030 SDGs Local Agenda, especially in the areas related to clean renewable energy and sustainable communities.

For further research, the results of the simulations and calculations conducted in this research are to be validated through actual transformation of an existing model house in one of the social housing projects. In addition, as most of the estimates for the capital cost for installing solar PV systems are for rooftop systems, more accurate supply/demand analysis and cost estimation through a detailed analysis of Levelized Cost of Electricity (LCOE), which defines the total cost of the BIPV system divided by the total amount of electricity it produces [29], are required and should be continuously updated to reflect the recent figures in the local and international PV markets.

Finally, while the Autodesk Insight plugin for Revit and the PVWatts Calculator are reliable and quick simulation tools that fit the scope of this pilot study, with its intentionally simplified method for exploring the potential efficiency of the BIPV system as an energy generation retrofitting strategy for the existing public housing in the UAE, the use of more scientifically accurate simulation tools such as Design Builders and SAM is still recommended when more accurate results are desired.

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