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Design and Performance Prediction of an Energy+ Building in Dubai

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Abstract

The result of the joint efforts of University of Bergamo and Mohammed Bin Rashid Space Centre (a Dubai Government institute) is the first Energy+ building in Dubai, virtually off-the-grid and PassivHaus certified. The present work deals with the computer models developed to predict the energy performance and to guide the design choices of the two floor office building unveiled to the public in November 2016. Trnsys software has been used to revise and validate the architectural ideas and the energy design.

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Keywords: Energy+ Building, Trnsys model, Dynamic simulation, Solar cooling

1. Introduction

The severity of environmental problems is forcing the construction sector in hot climate regions to introduce new paradigms in the design and erection of energy-efficient buildings. The growing interest in the development of passive buildings for hot climates [1] is inextricably linked to the climatic conditions of the site as well enlightened by Schnieders et al. [2]. A critical issue is often due to the difficulty of obtaining data in particular areas of the world [3]. This process involves new energy systems and a new shell design [4], including efficient shading devices to reduce energy consumption [5]. The development of sustainable solutions goes through the construction of more and more efficient buildings, such as Nearly Zero Energy Buildings [6] and Zero Energy Buildings [7]. Fundamental is the development of simulation tools for assessing the building energy performance [8] [9], especially when they are

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coupled with experimental measures [10]. The difficulty of performing reliable predictions of the thermal behavior and the energy consumption of buildings is well illustrated in [11] by Song et al.

Besides the development of well-insulated thermal envelopes according to the Passive House standards, an important step for improving the building sustainability is the use of high-efficiency cooling technologies coupled with renewable energy sources. Several types of solar cooling systems are available (Nanda et Panigrahi [12]): among these, the option based on compression chiller driven by a PV field assisted by a battery pack is highlighted. A remarkable comparison between this solution and absorption chiller driven by solar collectors was done by Lazzarin [13]. The results show that the performance is today comparable but the PV has a greater adaptability. In this contest, the study of Viera et al. [14] evaluates the performance of a residential building equipped with photovoltaic modules and batteries. The growth of the self-production energy and battery capacity leads to the development of the buildings called off-the-grid or stand-alone [15] [16]. These buildings do not require connection to the grids, can supply the own energy needs and jointly maintain high standards of comfort. The management of the self-produced energy is another topical point, as illustrated by Chekired et al. in [17], especially when the overproduction is exported to the network [18] [19]. The importance of the consumption of electrical equipment in buildings is well illustrated by Widen in [20]. Moreover, Hoxha and Jusselme in [21] show the relevance of using efficient lights and appliances adapted to new low-impact buildings. Furthermore, the analysis of occupancy reveals its relevant impact on the energy performance as well documented by Blight and Coley [22].

In the energy-efficient buildings a primary interest is the comfort perception: predictive techniques for quantifying and qualifying the indoor comfort are included in several building models [23] [24]. Frequently the goal of a high level of comfort perception is achieved through radiant floor cooling systems [25].

Starting from previous researches on solar cooling systems for buildings in hot climates [26], the present paper deals with the modeling and the design of the first Energy+ Building in Dubai, virtually off-the-grid. The developed computer models aimed to predict the energy performance and the thermal comfort, and was used to dictate the design choices for the building construction.

Nomenclature

$G_{\text{-value,w}}$	windows solar factor (%/100)	U_{roof}	roof U-value (W/m^2/K)
HX	Heat Exchanger	$U_{\text{-value,w}}$	windows U-value (W/m^2/K)
PV	Photovoltaic	U_{wall}	wall U-value (W/m^2/K)

2. Building Design

Geometry and orientation of the two floor building aim to reduce as much as possible the primary energy consumption taking into account the irradiation on the walls during the day and across the seasons. The surface to volume ratio is minimized. A small patio shrinks the radiation on the glazed elements and keeps shaded the office areas. This solution allows for avoiding window shields even in daylight hours. The diffuse light naturally illuminates the 550 m^2 floor surface and – at the same time – the solar gains are minimized.

A timber trimmed structure is designed to support the photovoltaic field, to promote the ventilation on PV modules and to shade the flat roof. The outline elements of the windows are protruding to limit direct radiation.

A lightweight load bearing structure made by wood supports timber walls and roof. The walls are designed to reduce as much as possible the building cooling load. The balance between mass and insulation improves the energy performance: the insulation thickness is designed to minimize thermal transmittance and the phase shift is controlled by adding mass layers. Walls are painted with a special reflective paint to curtail the absorption of solar radiation on the outer layer. Similarly, the roof is treated with a reflective film and infrared reflector films are inserted inside the walls. Windows are specific for warm climates with very low U and G values to limit the solar gains.

The building envelope is designed according to the Passive House standard and the energy plants are selected to reach the level of Energy+ Building. Power supply is ensured by the rooftop PV field. A battery pack is available to store electricity during light hours and to supply electricity after sunset.

The building is virtually off-grid (power import is possible for emergency) and the electric overproduction is delivered to the grid.

A high-efficient air-water reversible heat pump - specifically designed for hot-humid climates - meets the cooling and dehumidification demand, and the production of domestic hot water. The cooling system is based on a combination of 3 different technologies: floor cooling, mechanical ventilation and fan-coils. The radiant floor cooling maintains a high level of comfort, the air handling unit with high-efficient heat recovery controls temperature and humidity of the inlet air, and the fan-coils fulfill the cooling peak loads. The integration of high-efficient technologies both in the thermal envelope and energy systems is the key of the project performance.

Fig. 1. The Energy+ Building presented in November 2016.

3. Building model and results

The models developed for simulation of building and solar cooling system performance are based on Trnsys® v.17. Weather data with hourly resolution have been provided by the Mohammed Bin Rashid Space Center.

The detailed architectural building model is based on Trnsys Multizone Building Type and developed by the 3D cad software Google Sketch Up®, with the plug-in Trnsys3D for geometry and shading. The building model includes 10 homogeneous thermal zones and all main building parameters are listed in Table 1. Technical data of the materials were selected in design phase and have been implemented in the model, thus allowing a realistic prediction of the building envelope behavior.

Internal loads due to lights and appliances have been carefully evaluated. The occupancy is considered as an average attendance including random occurrence of overload events.

The simulation results (Tab. 2) show the strong impact of latent loads due to high relative humidity levels. The dehumidification demand influences both the peak load and the annual demand respectively by 60% and 30%.

The total cooling load is shown in Fig 2: the short load duration curve (limited to 4000 hours per year) is due to the high performance of the building envelope.

Table 1. Comfort settings, internal gains and envelope characteristics.

Comfort & Gains		
	unit	value
Set point temperature	°C	24
Set point relative humidity	%	50
Mean ventilation ratio	Vol/hr	0.60
HX efficiency	%	80
Infiltration	Vol/hr	0.06
Lighting (peak)	W/m^2	5
Internal gains (peak)	kW	6
Occupancy	Nr.	20

Wall layers & Windows		
	unit	value
U_{wall}	$W/m^2/K$	0.063
Wall thickness	m	0.603
Wall solar absorptance	%/100	0.3
U_{roof}	$W/m^2/K$	0.061
Roof thickness	m	0.566
Roof solar absorptance	%/100	0.2
$U_{-value,w}$	$W/m^2/K$	0.7
$G_{-value,w}$	%/100	0.294

Table 2. Building cooling load.

Peak Load		
	unit	value
Air Load - sensible	kW	6.83
Air Load - latent	kW	20.49
Floor Load	kW	8.42
Total Load	kW	27.03
Total Load / Net Floor Area	kW/m^2	0.065

Annual Load		
	unit	value
Air Load - sensible	kWh	7954.6
Air Load - latent	kWh	11920.7
Floor Load	kWh	13844.5
Total Load	kWh	33719.9
Total Load / Net Floor Area	kWh/m^2	82.24

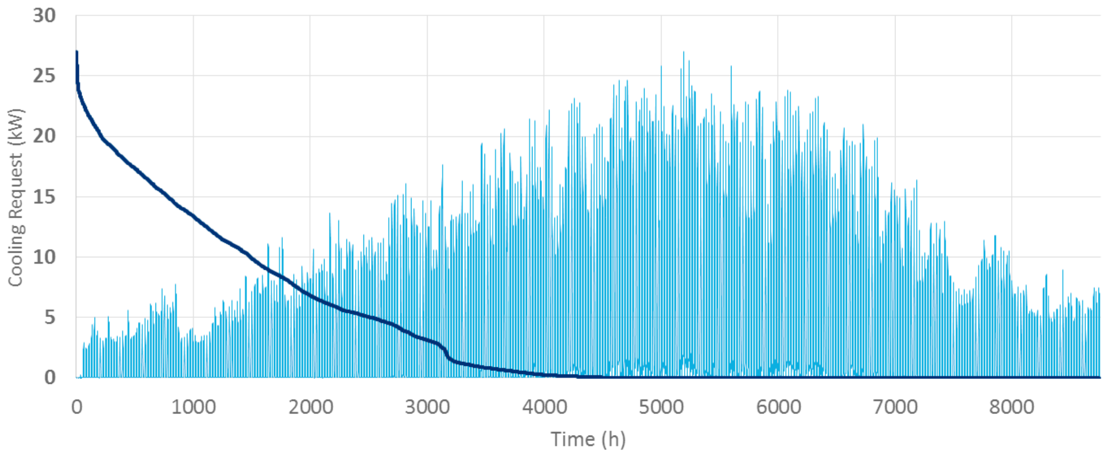

Fig. 2. Building cooling load and load duration curve.

The light color of the walls, coupled with the reflective film, limits the absorption of solar radiation. Fig. 3 reports for 2 summer days the temperature trends of the part of flat roof not shaded by PV modules. In spite of a strong temperature variation in the external side (with peak higher than 42°C), the temperature level on the internal side is stable at 25°C.

Fanger's comfort parameters were also considered to improve the design quality. Table 3 shows the calculated comfort parameters: the excellent level is achieved thanks to the integration of different air conditioning systems. The predicted mean vote is very near to the desired value and the maximum deviation (0.27) is very small compared to the comfort region (-0.5 to 0.5) extension. Furthermore, the value of the percentage of person dissatisfied is close to the minimum value.

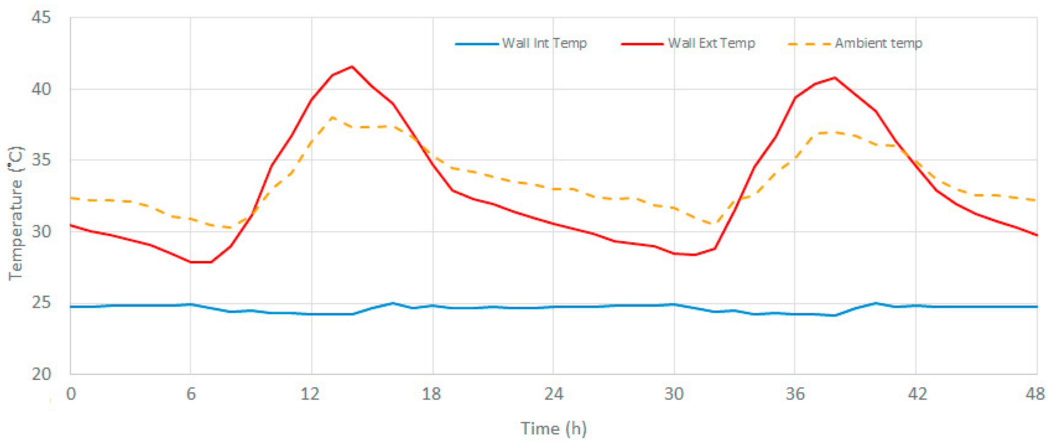

Fig. 3. Roof temperature patterns

Table 3. Building comfort parameters.

	Unit	Max	Min	Average
Mean Radiant Temperature	°C	24.23	22.34	23.66
Operative Temperature	°C	24.11	22.25	23.75
Predicted Mean Vote	[-3 ; 3]	0.26	-0.27	0.16
Percentage of Person Dissatisfied	% [5 ; 100]	6.51	5.00	5.69

4. Energy source and cooling plant models and results

The energy source model is based on multi-crystalline PV panels coupled to a battery pack. Power generated drives the reversible heat pump and all technical systems, and the overproduction is exported into the grid when batteries are at full capacity. The simplified block diagram in Figure 4 shows the operative scheme of the electric system.

An electric energy storage (battery pack) has been designed to ensure the off-the-grid mode operation, assuring 24/7 power supply to A/C system, lighting and appliances. An additional small thermal energy storage (1 m^3 cold tank) compensates for cooling load fluctuations.

The cooling plant model includes the air-cooled heat pump performance map provided by the manufacturer. The chiller is designed to operate with an outdoor temperature up to 50 deg. C and the cooling capacity was selected to fulfill the peak demand of the building. The specification of the energy models are reported in Table 4

Table 4. PV field and cooling plant characteristics

PV field and Battery specifications		
	unit	value
Area	m^2	268
Nominal efficiency	-	0.149
Efficiency modif temp	1/°C	-0.0041
P_{max} Voltage	V	30.5
Open circuit voltage	V	37.6
Battery capacity	kWh	25

Cooling Plant Data		
	unit	value
Chiller capacity*	kW	27.51
COP*	-	2.38
Power input*	kW	11.55
Cold Tank Specifications		
Cold tank volume	m^3	1
Tank insulation (EPS)	m	0.2

* Ambient temperature 30 deg. C; chilled water 7-12 deg. C.

The results of a transient simulation carried out for a one-year period are shown in Table 5. It can be seen that power consumption for air conditioning is about half of the total electricity consumption. The electricity production to meet the off-the-grid requirement results to be more than two time the Net-Zero Energy standard (export = import over one-year period). This has a heavy impact on the design of the photovoltaic field. Because the energy import must be zero at any time, PV system must be large enough to ensure the energy autonomy of the building. The simulation results document that the battery charge level (see Figure 5) is always above 60% of the full capacity (25 kWh), even in the peak periods.

Figure 6 shows the trend of the heat pump cooling production and power consumption for two typical summer days. The resulting COP (according to the chiller performance map) results to be strongly affected by the high ambient temperatures. The cooling load rises a few hours before the PV production and the energy is taken from the batteries. Chiller consumption is higher in the morning when internal temperature must shift from nighttime to daytime set point.

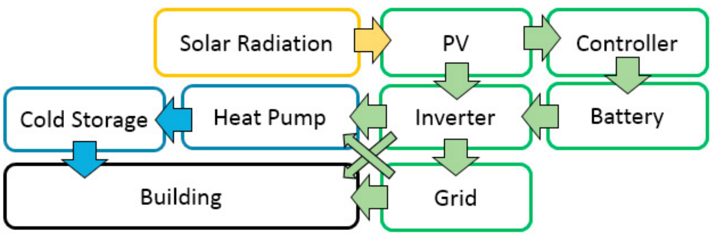

Fig. 4. Block diagram of the electric system

The patterns of power production and consumption are shown in Figure 7. The energy demand is met according to the following priority order: by PV (when available or sufficient), by batteries and, in the last case, by import from the grid. Power consumption for appliances and light depends on the occupancy and the activities in the thermal zones. The PV field drives the heat pump as priority and the surplus recharges the battery pack. The electricity overproduction, when the battery level is full, is delivered to the grid according to a net-metering scheme.

Figure 8 shows the annual energy fluxes: PV production, total power consumption (heat pump, light and appliances) and the export to the network on a monthly basis. In winter months, when the cooling request is low and the heat pump efficiency is high thanks to the low ambient temperature, the electric energy delivered to the grid is around 70% of the global PV production. During the warm season this ratio decreases to 50%.

Table 5. Electric production and consumption

Electric Consumption		
	unit	value
Chiller consumption	kWh	11400.3
Light and appliances	kWh	11914.7
Total electric load	kWh	23315.0

Electric Production and Grid Balance		
	unit	value
PV production	kWh	56460.2
Grid import	kWh	0.0
Grid export	kWh	33123.7

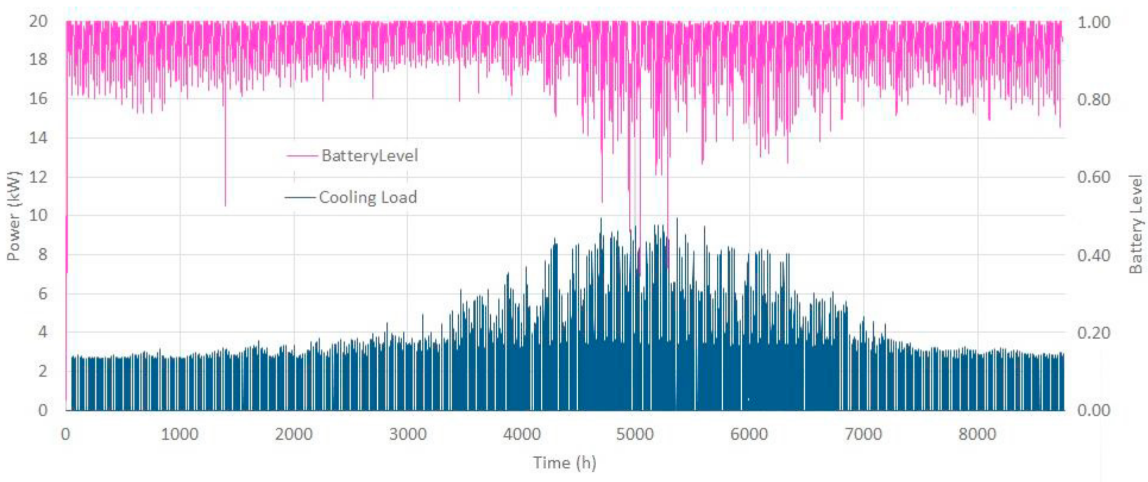

Fig. 5. Cooling load and battery level.

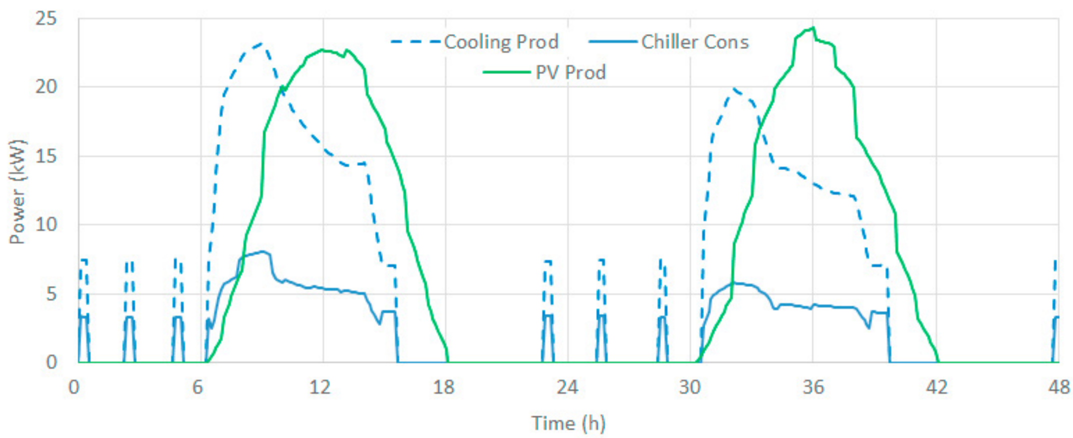

Fig. 6. PV and heat pump energy fluxes

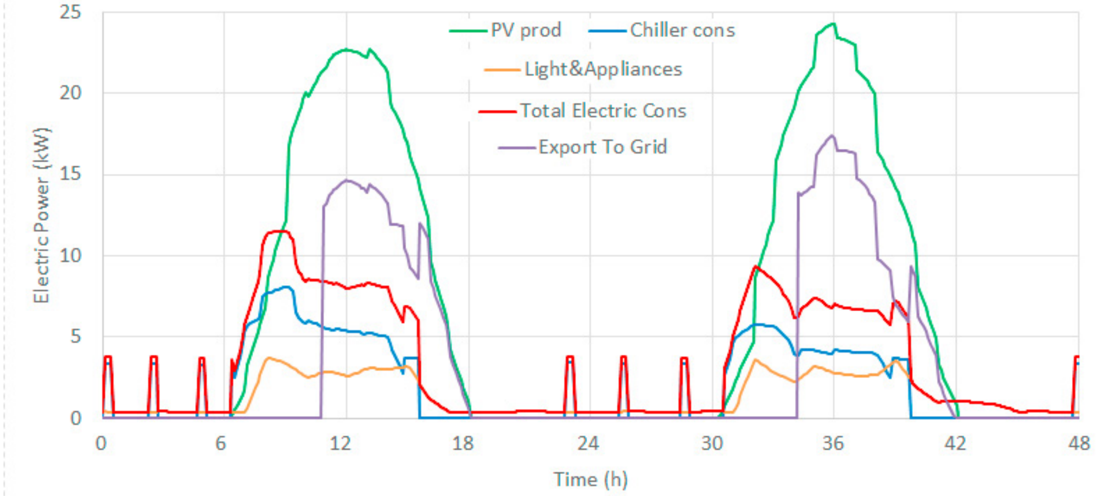

Fig. 7. Grid exchange and consumption details

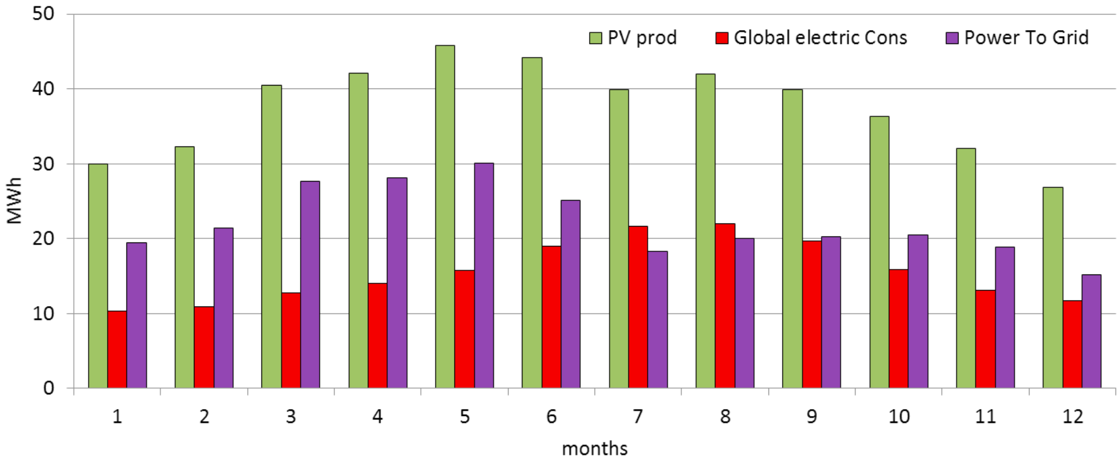

Fig. 8. Monthly energy production, consumption and export

5. Conclusions

The modelling and the design of the first PassivHaus Energy+ building in Dubai was developed to predict the energy performance and revise the project. The results show a perfect autonomy of the building even under severe load conditions: the PV field exports electricity to the grid for several hours, whilst importation does not occur all year round, making the house an Energy+ building able to operate also in Off-the-Grid conditions. Simulation outcomes have been used to size the PV field (40 kWp), the battery pack (25 kWh), the chiller capacity (27.5 kW) and all auxiliary components. The building has been fully instrumented and currently the monitoring system is collecting data, which in future will be used for the model validation.

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