# Modeling, Construction and Monitoring of a Plus-Energy Building in Dubai

**Giuseppe Franchini, Giovanni Brumana, Antonio Perdichizzi**

Department of Engineering and Applied Sciences, University of Bergamo, Dalmine (Italy)

**Ali Shaheen, Mohammed Bin Neshooq, Shaikhah Alfalasi**

Mohammed Bin Rashid Space Centre, Dubai (UAE)

**Abstract**

This work presents the performance analysis of the very first Energy+ building in Dubai certified by the German Passive House Institute. The analysis is presented as comparison between numerical predictions and the first available monitored data. Trnsys is the software used to create the energy model, including both thermal envelope and HVAC system. The use of highly insulating materials, together with a design aimed to reduce the solar heat gains, allows for minimizing cooling loads. A 40 kW PV field, coupled to a 25 kWh battery storage and to a high-efficiency air-cooled electric chiller, fulfills the electric and cooling demand, making the building energy-autonomous. The study demonstrates the high accuracy of the energy model, able to predict precisely the building cooling loads, the energy production and the cooling system performance. The Energy+ building, inaugurated in November 2016, is a pioneering pilot-project and it represents an advance in the field of sustainable construction for all Arabic area.

*Keywords: energy+ building, solar cooling, PV, monitoring system, dynamic simulation*.

## 1. Introduction

In many developed countries, buildings and their use are responsible for approximately one-third of the total primary energy consumption and carbon emissions. Governments and scientific communities are aiming for new paradigms for energy-efficient buildings: the goal is to reduce the environmental impact of the construction sector (Nejat et al., 2015). Many authors investigated the design principles for high-efficient buildings in cold climates (Thalfeldt et al., 2013; Justo Alonso et al., 2015). More recently, the interest in the development of passive buildings has grown also for hot regions (Fokaides et al., 2016; Schnieders et al., 2015).

The development of sustainable solutions goes through the construction of more and more efficient buildings. At this regard, new concepts have gained wide international attention, such as Passive Houses, Nearly Zero Energy Buildings, Net Zero Energy Buildings and Energy+ Buildings (Marszal et al., 2011). The first step in order to comply with all high-efficiency standards is to reduce the energy consumption in buildings. Passive design strategies contribute to improve the interior comfort conditions, reducing the requirement of energy supply from active systems (Rodriguez-Ubinas et al., 2014).

Besides the development of well-insulated thermal envelopes, an improvement of the building sustainability can be achieved by using high-efficiency cooling technologies coupled with renewable energy sources. Several types of solar cooling systems have been investigated in the open literature (Nanda and Panigrahi, 2016; Ghaith and Abusitta, 2014). Among the available technologies, 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 thermal solar cooling systems was done by Lazzarin (2014). The results show that the performance is today comparable but the PV has a greater adaptability. Recently, huge investments in the electric storage technology have led to the spread of batteries for building applications and to the development of off-the-grid or stand-alone houses (Okoye and Solyalı, 2017; Fara and Craciunescu, 2017).


doi:10.18086/swc.2017.15.02 Available at http://proceedings.ises.org

In the Gulf area, the United Arab Emirates is one of the most active countries in the promotion of actions aiming to ensure a sustainable development while preserving the environment. The UAE Vision 2021 National Agenda focuses on improving the quality of air, preserving water resources, increasing the contribution of clean energy and implementing green growth plans. The UAE Energy Plan 2050 is an ambitious strategic plan aiming to cut carbon dioxide emissions by 70 per cent, to increase clean energy use by 50 per cent and to improve energy efficiency by 40 per cent by the middle of the century. Within this framework, the Government of Dubai is implementing policies and strategies in order to promote the energy efficiency and the use of renewable energy resources (Al-Amir and Abu-Hijleh, 2013). Recently, in the construction sector the Mohammed Bin Rashid Space Centre (MBRSC), a Dubai government R&D organization working in various fields of the scientific research including aerospace projects, started a Sustainable Energy Program. The goal was to build an autonomous house representing a model for the real-estate sector in the region. This project is the result of the collaboration of different players: the team of MBRSC engineers and scientists, University of Bergamo (modeling, simulations and scientific supervision), Casetta & Partners (executive design) and Wolf System (builder company). The present paper reports the modeling and simulation activities carried out to dictate the design choices for the building construction. All technologies used in this house are presented and the preliminary results of the monitoring data are shown. The building construction was completed in a record time of less than 100 days and was inaugurated in November 2016 by H.H. Sheikh Mohammed bin Rashid Al Maktoum, Vice President and Prime Minister of the United Arab Emirates, and ruler of the Emirate of Dubai.

## 2. Building description

The building is a two-floor office structure, with geometry and orientation aiming to reduce as much as possible the primary energy consumption. To do that, the surface to volume ratio is minimized. The solar irradiation on the walls during the day and across the seasons is accurately evaluated. 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 a photovoltaic field (see Fig, 1), 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.

**Fig. 1: The Energy+ Building unveiled in November 2016.**

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 (see Table 1).

The prefab European timber platform frame technology made possible to realize the building in less than 100 days. The building envelope has been designed according to the Passive House standard and the energy systems have been 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.

**Table 1. Envelope thermal properties.**

| | 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 |

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 three 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.

## 3. Building model

The design of high-efficiency buildings in hot climates requires the accurate prediction of the cooling demand and of the energy plant performance. Fundamental is the development of simulation tools for assessing the building energy performance (Harish et al., 2016; Mihai et al. 2017). In a well-insulated building, the internal loads play a crucial role. The prediction of the energy consumption due to the electrical equipment is very important, as documented by Widen (2014). Moreover, Hoxha and Jusselme (2017) showed the relevance of using efficient lights and appliances adapted to new high-efficiency buildings. Furthermore, the analysis of occupancy reveals its relevant impact on the energy performance (Blight and Coley, 2013).

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 (Wang et al., 2017; Satake et al., 2016). Frequently the goal of a high level of comfort perception is achieved through radiant floor cooling systems (Zhao et al., 2016).

The models developed for the simulation of building envelop 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.

### *3.1 Envelope model*

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 comfort parameters are listed in Table 2.

**Table 2. Comfort settings and internal gains.**

| | unit | value |
|---|---|---|
| Set point temperature | °C | 24 |
| Set point RH | % | 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 |

In the computer model the technical data of all the construction materials have been included, 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 Trnsys model allowed to predict the cooling demand all over the year. This is crucial for a correct sizing of the energy plants. The simulation results 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% (Table 3). The total cooling load and the latent load are shown in Fig 2: the peak cooling demand is about 27 kW. The short load duration curve (limited to 4000 hours per year) testifies the high performance of the building envelope.

**Table 3. Building cooling loads.**

| Peak Load | | | Annual Load | | |
|---|---|---|---|---|---|
| | unit | value | | unit | value |
| Air Load - sensible | kW | 6.83 | Air Load - sensible | kWh | 7954.6 |
| Air Load - latent | kW | 20.49 | Air Load - latent | kWh | 11920.7 |
| Floor Load | kW | 8.42 | Floor Load | kWh | 13844.5 |
| Total Load | kW | 27.03 | Total Load | kWh | 33719.9 |

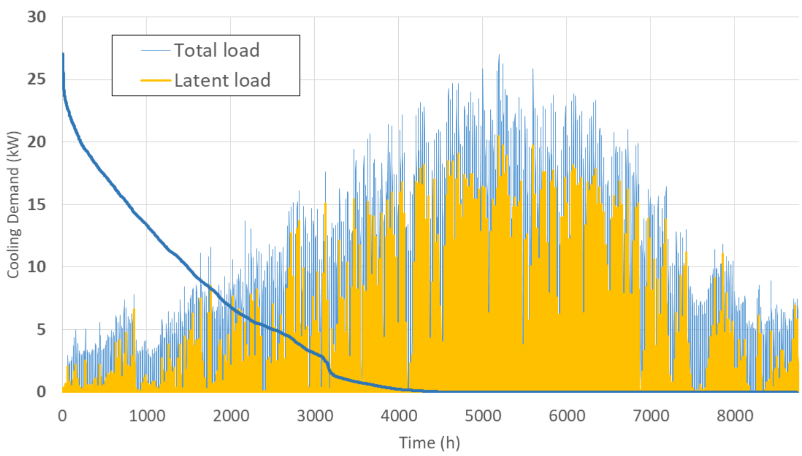


**Fig. 2: Cooling load and duration curve.**

In addition to the calculation of the global building performance, the Trnsys model permits to carry out detailed analysis of the thermal behavior of each single wall. For instance, Figure 3 reports for two consecutive summer days the temperature trends of a portion of flat roof not shaded by PV modules. It can be noted that, 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 predicted to be stable at 25°C.

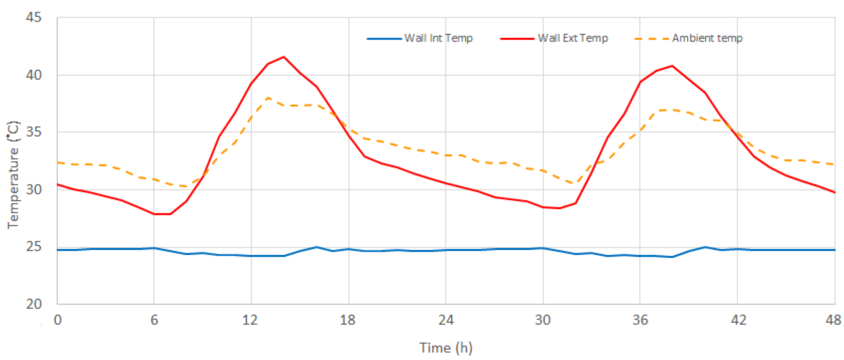


**Fig. 3: Roof temperature.**

Fanger's comfort parameters were also considered to improve the design quality. Table 4 shows the calculated comfort indexes: the excellent level is achieved thanks to the integration of different air conditioning systems. The predicted mean vote is very near to the ideal value (0) and the maximum deviation (0.27) is very small compared to the comfort region (-0.5 to 0.5) range. Furthermore, the value of the percentage of person dissatisfied is close to the minimum value.

**Table 4. 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 |

## *3.2 Energy system model*

The energy system is based on multi-crystalline PV panels coupled to a battery pack. Power PV-generated drives an air-cooled reversible heat pump and all technical devices. An electric energy storage (battery pack) has been designed to ensure the autonomous operation, assuring 24/7 power supply to A/C system, lighting and appliances. The electricity overproduction is exported into the grid when batteries are at full capacity. An additional small thermal energy storage (1 $m^3$ cold tank) compensates for cooling load fluctuations. The specifications of the PV system are reported in Table 5.

**Table 5. PV field and battery specifications.**

| | unit | value |
|---|---|---|
| Area | $m^2$ | 268 |
| Nominal efficiency | - | 14.9% |
| Efficiency modif. temp. | 1/°C | -0.0041 |
| Voltage at $P_{max}$ | V | 30.5 |
| Open circuit voltage | V | 37.6 |
| Battery capacity | kWh | 25 |

The cooling plant model includes the 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 chiller specifications are reported in Table 5.

**Table 6. Chiller specifications.**

| | unit | value |
|---|---|---|
| Chiller capacity* | kW | 27.51 |
| COP* | - | 2.38 |
| Power input* | kW | 11.55 |
| 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 the transient simulation carried out for a one-year period are shown in Table 7. 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 twice 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.

**Table 7. Electric production and consumption.**

| | unit | value |
|---|---|---|
| Chiller consumption | kWh | 11400.3 |
| Light and appliances | kWh | 11914.7 |
| Total electric load | kWh | 23315.0 |

| | unit | value |
|---|---|---|
| PV production | kWh | 56460.2 |
| Grid import | kWh | 0.0 |
| Grid export | kWh | 33123.7 |

The simulation results document that the battery charge level (see Fig. 4) is always above 60% of the full capacity (25 kWh), even in the peak periods. The power demand exhibits a daily peak of about 3 kW in the winter months, whilst the annual peak taking place in August (when the cooling demand is maximum) is 10 kW. The daily curves of power production and consumption are shown in Figure 5. The energy demand is met according to the following priority order: by PV (when available and sufficient), by batteries and, in the last case, by import from the grid (emergency only). Power consumption for appliances and lighting 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 6 shows the annual energy fluxes: PV production, total power consumption (heat pump, lighting 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%.

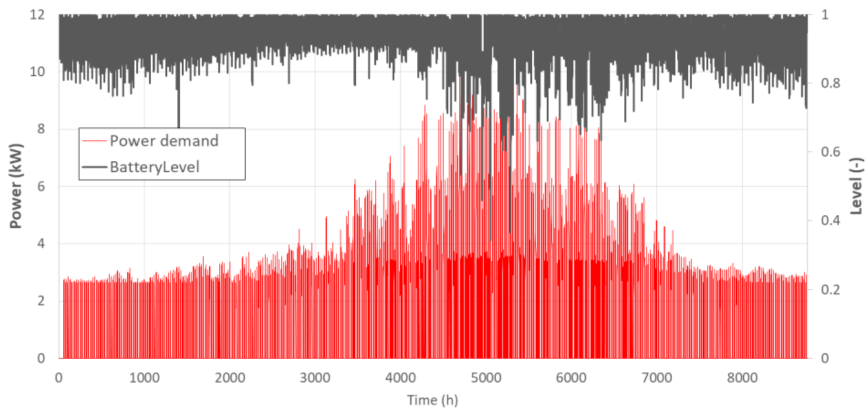


**Fig. 4: Power demand and battery level.**

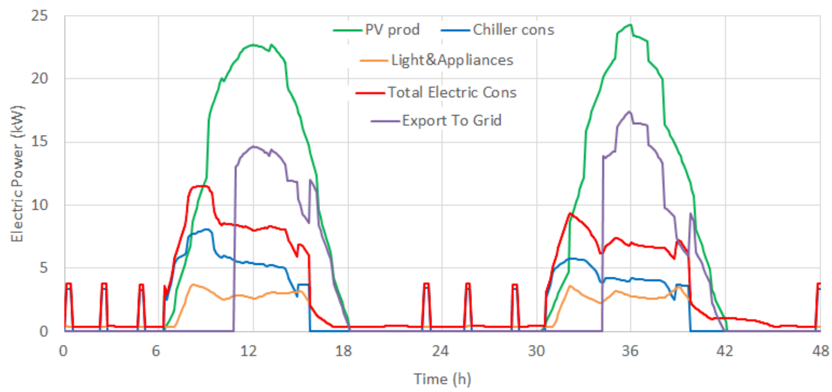


**Fig. 5: Power demand and production.**

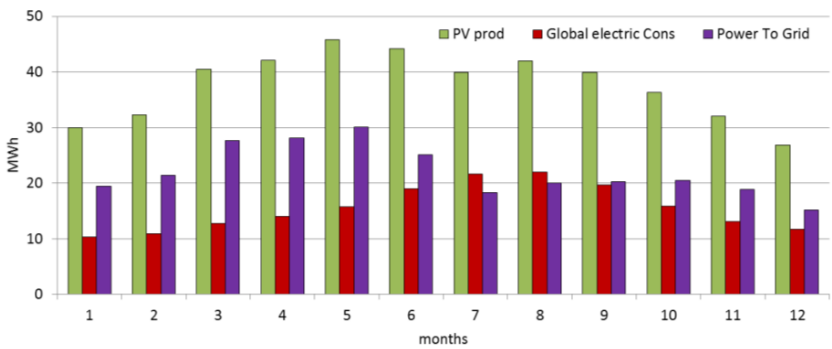


**Fig. 6: Monthly energy production, consumption and export.**

## 4. Comparison model prediction vs. monitoring data

The Plus-Energy building has been fully instrumented. A monitoring system has been installed for a remote real time access to all collected data (with a frequency of 1 sample per second). This equipment makes possible to monitor with high level of detail the building energy performance under real operating conditions. The monitoring system includes thermocouples in the wall layers, thermo-hygrometers in the rooms, power meters on the PV field, the battery package and all electric boards, temperature and flow rate sensors in all circuits of the HVAC system. Table 8 summarizes the main monitoring data.

**Tab. 8: Monitoring System Equipment**

| | |
|---|---|
| Weather | Ambient temperature, Ambient humidity, Global solar radiation |
| Building Envelope | Room temperatures, Humidity, $CO_2$, External/Internal side Walls/Roof temperature |
| PV Field & Grid | PV production, Grid Import/Export, Appliances and auxiliary consumption |
| Cooling Plant | Cooling production, Chiller electric consumption, AHU in/out temperatures, Floor cooling in/out temperatures |

It has to be reminded that this building is a pioneering pilot-project. The goal is to prove that new sustainable construction standards are possible in the UAE and that this is a viable solution to reduce the carbon footprint in the region. The monitoring activity is fundamental to demonstrate that the predicted performance is confirmed under real operating conditions. Moreover, the measurement campaign is important also for the model validation. Currently, the monitoring activity is going on and some weeks of collected data are available for analysis. This paper reports the comparison between the model predictions and the first available data.

Figures 7-10 show the simulation results and the experimental data for two consecutive days in September. Figure 7 refers to the cooling demand. The curves related to the model prediction (dashed line) and the measurements (solid line) exhibit a very good superposition: the model appears able to estimate the peak values, the hourly trend and the daily integral value. As mentioned before, in addition to the overall thermal loads the Trnsys model can predict the trend of detailed parameters, like wall and roof temperatures. Figure 8 shows the trend of internal and external temperatures for the well-insulated roof. The daily pattern for the outer side temperature (influenced by the incident solar radiation and the ambient temperature) is well predicted, in spite of a small time shift. The inner side temperature is perfectly estimated.

Moving to the energy systems, Figure 9 reports the 48-hour trend of the PV production and the power consumption due to light and appliances and for the chiller operation. The chart shows a small underestimation of the PV power output (-9.5% as integral value), whilst the power consumption for lighting and electrical equipment is very well predicted. A far as the chiller consumption is concerned, the monitored data show slightly different patterns during the day and higher peak levels. The hourly variation of the power input is related to the trend of the real cooling demand documented in Fig. 7, while the higher peak levels and the higher daily integral values indicate a lower-than-expected chiller efficiency (-12.8%).

As mentioned in the previous paragraphs, when the batteries are full charged the electricity surplus is supplied to the grid. Figure 10 shows the power export compared to the PV production. The model exhibits a good capability to predict the amount of electricity delivered to the grid and the time interval of the power exchange. When the battery package is full (at 11.30 a.m.) the model predicts an instantaneous shift to the exportation mode, whilst monitoring data show a soft ramp starting 2 hours before achieving the full capacity condition: this is due to the control system of the electric storage that is not implemented in the model. Nevertheless, the integral value of the exported electricity is well predicted: the error model vs. monitoring is only 2.0%.

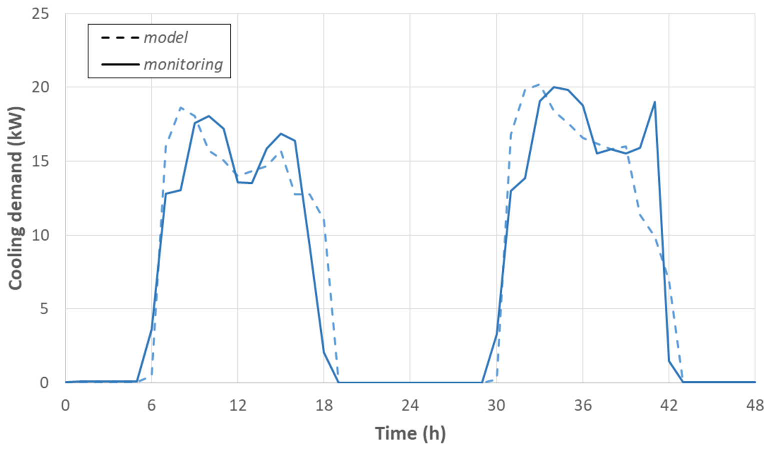


**Fig. 7: Cooling demand (model vs. monitoring).**

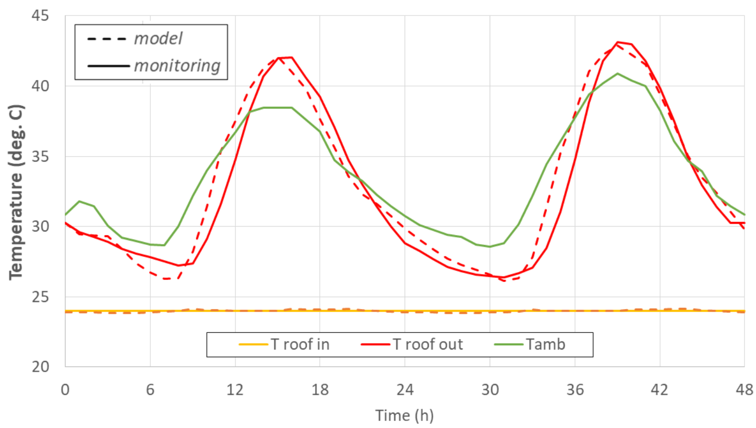


**Fig. 8: Roof temperature (model vs. monitoring).**

.

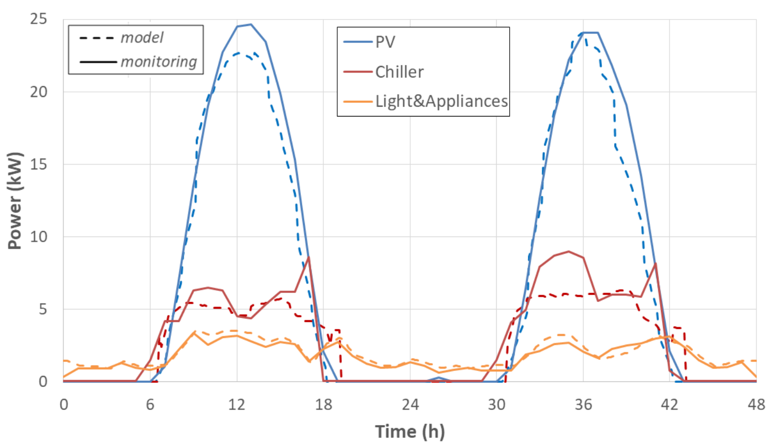


**Fig. 9: Power production and consumption (model vs. monitoring).**

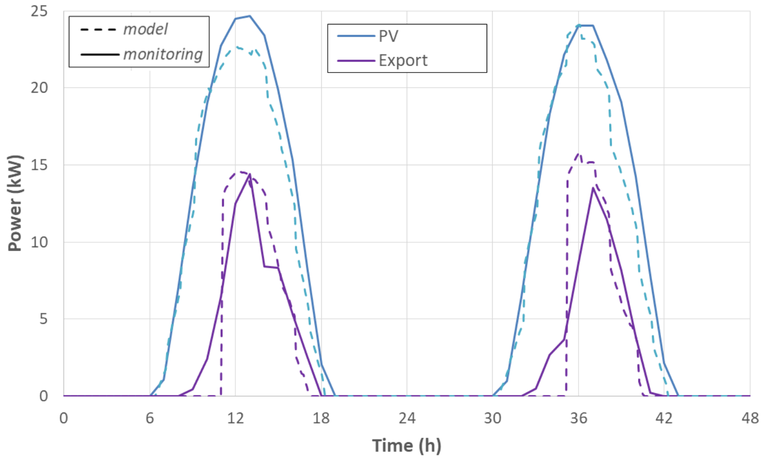


**Fig. 10: PV production and electricity export (model vs. monitoring).**

## 5. Conclusions

This work presents the very first Energy+ building certified by the Passive House Institute in the Dubai area. The building is a pioneering pilot-project aiming to prove that high comfort levels can be achieved by using solar energy as unique energy source. A 40 kW PV field, coupled to a 25 kWh battery storage and to a high-efficiency air-cooled electric chiller, fulfills the electric and cooling demand, making the building energy-autonomous. A preliminary activity of modeling and simulation dictated the design of the building envelope and of the energy systems. Trnsys is the software used to create the energy model and to predict the building performance. Starting from its inauguration, the building has been monitored to measure the actual performance under real operating conditions. The first available measurements confirm that the model predictions are very accurate and very close to the monitoring data. Therefore, it can be concluded that the expected targets in terms of energy savings and carbon footprint reduction have been successfully achieved.

## 6. References

Nejat P., Jomehzadeh F., Mahdi Taheri M., Gohari M., Majid M.Z.A., 2015. A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). Renewable and Sustainable Energy Reviews 43, 843-862.

Thalfeldt M., Pikas E., Kurnitski J., Voll H., 2013. Façade design principles for nearly zero energy buildings in a cold climate. Energy and Buildings 67, 309-321.

Justo Alonso M., Liu P., Mathisen H. M., Ge G., Simonson C., 2015. Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries. Building and Environment 84, 228-237.

Fokaides P. A., Christoforou E., Ilic M., Papadopoulos A., 2016. Performance of a Passive House under subtropical climatic conditions. Energy and Buildings 133, 14-31.

Schnieders J., Feist W., Rongen L, 2015. Passive Houses for different climate zones. Energy and Buildings 105, 71-87.

Marszal A.J., Heiselberg P., Bourelle J.S., Musall E., Voss K., Sartori I., Napolitano A., 2011. Zero Energy Building – A review of definitions and calculation methodologies. Energy and Buildings 43, 971-979.

Rodriguez-Ubinas E., Montero C., Porteros M., Vega S., Navarro I., Castillo-Cagigal M., Matallanas E., Gutiérrez A., 2014. Passive design strategies and performance of Net Energy Plus Houses. Energy and Buildings 83, 10-22.

Nanda A. K., Panigrahi C. K., 2016. A state-of-the-art review of solar passive building system for heating or cooling purpose. Frontiers in Energy 10(3), 347-354.

Ghaith F. A., Abusitta R., 2014. Energy analyses of an integrated solar powered heating and cooling systems in UAE. Energy and Buildings 79, 117-126.

Lazzarin R. M., 2014. Solar cooling: PV or thermal? A thermodynamic and economical analysis. International Journal of Refrigeration 39, 38-47.

Okoye C. O., Solyalı O., 2017. Optimal sizing of stand-alone photovoltaic systems in residential buildings. Energy 126, 573-584.

Fara L., Craciunescu D., 2017. Output Analysis of Stand-alone PV Systems: Modeling, Simulation and Control. Energy Procedia 112, 595-605.

Al-Amir J., Abu-Hijleh B., 2013. Strategies and policies from promoting the use of renewable energy resource in the UAE. Renewable and Sustainable Energy Reviews 26, 660-667.

Harish V. S. K. V., Kumar A., 2016. A review on modeling and simulation of building energy systems. Renewable and Sustainable Energy Reviews 56, 1272-1292.

Mihai M., Tanasiev V., Dinca C., Badea A., Vidu R., 2017. Passive house analysis in terms of energy performance. Energy and Buildings 144, 74-86.

Widén J., 2014. Improved photovoltaic self-consumption with appliance scheduling in 200 single-family buildings. Applied Energy 126, 199-212.

Hoxha E., Jusselme T., 2017. On the necessity of improving the environmental impacts of furniture and appliances in net-zero energy buildings. Science of The Total Environment 596, 405-416.

Blight T. S., Coley D. A., 2013. Sensitivity analysis of the effect of occupant behaviour on the energy consumption of passive house dwellings. Energy and Buildings 66, 183-192.

Wang Y., Kuckelkorn J., Zhao F. Y., Spliethoff H., Lang W., 2017. A state of art of review on interactions between energy performance and indoor environment quality in Passive House buildings. Renewable and Sustainable Energy Reviews 72, 1303-1319.

Satake A., Ikegami H., Mitani, Y., 2016. Energy-saving Operation and Optimization of Thermal Comfort in Thermal Radiative Cooling/Heating System. Energy Procedia 100, 452-458.

Zhao K., Liu X. H., Jiang Y., 2016. Application of radiant floor cooling in large space buildings–A review. Renewable and Sustainable Energy Reviews 55, 1083-1096.