EFdeN Signature - a case study of a zero-energy house prototype optimized for Middle East climate

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Abstract. When talking about the urban challenges we face today at a global level, population growth and urbanization ranks high in the charts. Both challenges can be found in the Middle East and especially in Dubai, one of the fastest growing cities in the world - a rapidly developing urban settlement supporting an ever-increasing human population. With a very warm climate, the United Arab Emirates are struggling to develop strategies and solutions to decrease energy consumption. Among the major consumers in Middle East are the buildings therefore an integrated approach using renewable sources is mandatory. Within the Solar Decathlon competition the Romanian team of students proposed a house prototype to answer Middle East challenges. In this paper we present the developed model, its structure, systems and we demonstrate its potential as a positive energy balance building using numerical simulations.

1. Introduction

High-rise buildings in Dubai are a result of the aggressive development the city has been undertaking for decades, facilitated by the visionary goal, strong leadership, high quality infrastructure, an expatriate friendly environment, zero tax on personal and corporate income and the drive to diversify the economy. This had significant impact on building environment density and height, to the detriment of open spaces, public facilities and mobility. To answer Dubai’s dramatic sprawl and development of its urban area over the last four decades – from the urban origin before 1971, to the contemporary stage of Cities within the city mega projects - the Dubai Masterplan for 2020 [2] proposes the compact city as a solution to its associated challenges. This involves a web of centers encompassing diverse functions, from homes, offices, education, healthcare facilities to commercial, and leisure centers, among others. Each center would function as a self-sufficient micro community. As buildings are the core of Dubai there is a high interest in the optimization and reduction of energy consumption. Among the best measure to decrease cooling demand is the natural ventilation. Taleb [1] has used CFD analysis to test different ventilation strategies in low-energy houses in Dubai. Brumana et al. [3] conducted simulations using Trnsys software with a computer model of a two floor office in Dubai. Using simulations they have revised and validated the architectural prototype. Integrating solar energy is another important aspect on achieving low energy buildings in Middle East. Elshurufa et al. [5] performed a technoeconomic analysis on a 124 kW PV system commissioned in 2017 on a mosque rooftop in Riyadh, Saudi Arabia, under a net metering mechanism. In order to achieve Zero Energy Building (nZEB) standard, the principles we followed during the integrated design process regarding energy efficiency are those of Trias Energetica [7]. Other authors mentioned the Gulf Cooperation
Council (GCC) specific considerations regarding the design and construction of energy-efficient houses and recommendations for future research [4]. According to the first step of our strategy, energy waste had to be reduced to a minimum. To attain that, we first focused on both a comprehensive climate analysis for Middle East, and on the comfort conditions we wanted to reach, keeping in mind the energy efficiency principles. Based on the results and because there are big differences between European and Middle East climates, an extensive research on existing and developing solutions that address the issues we have encountered has been done and this led to the initial design and simulation of the house which became a reference for our further analysis. Our guiding points at this stage became existing solutions for green buildings in UAE (United Arabian Emirates). The next step consisted in simulating and comparing different design and systems solutions that we have considered with the one that we took as reference. If the energy demand was lower for the analyzed solution, it became the new reference for our further studies. Else, we discarded the results and went on to next design or system. After we found the lowest-energy strategy, the following step was to consider how achievable it is in terms of affordability, accessibility and interference with other house’s systems. Therefore, we must rethink and the prototype every time one of these conditions fail to be reached.

The prototype was presented during world solar competition Solar Decathlon Middle East 2018. Solar Decathlon is the most prestigious international competition for solar architecture and technology integration. It was initiated by the Department of energy in the year 2002 and its main scope is advocating for the widespread adoption of photovoltaic energy. The competition challenges the student’s teams to design very efficient and solar houses for two years, then build it fullscale, where the competition takes place. The teams prototypes are then evaluated by 10 contests such as: architecture, engineering and construction, energy efficiency, comfort conditions, sustainability, innovation and urban mobility. The 2018 edition of solar Decathlon was the first one to be taking place in the Middle East and it was intended to promote ideas like sustainability and energy efficiency in an area where these are not priorities. The house prototypes had the challenge to adapt to the harsh Middle Eastern climate, defined by extreme air temperature, high humidity and sandstorms, to tot to a more sustainable and comfortable living in the region. Over time Romania had several participating teams at Solar Decathlon: Team Prispa in Solar Decathlon Europe 2012, Team EFdeN in Versailles in 2014 and Team Over4 in Hungary, 2019.

2. Prototype presentation

Overlapping the city’s vision with our belief that nature is the key factor of creating sustainable development, the proposed prototype involves scaling up a self-sustainable urban organism, creating a super-organism, where all of its components act as generators, collectors, and concentrators of local resources and renewable energy. Aiming to develop places and destinations, we intend to create livable neighborhoods, where buildings preserve specificity in terms of height, density, integration of communal and recreation spaces, as well as to preserve the local characteristics of the urban form (reinterpreted mashrabiya and windtowers). The main reason why we integrated in the prototype’s design such generous sheltered terrace is that of land being used for building construction rather than for development of open spaces, especially protected ones - from solar radiation and sandstorms, which makes it harder for the inhabitants to ever spend time outside. The prototype reflects the values we aim to integrate in this type of urban community, envisioned on a smaller scale. The simple geometry of the proposed housing unit was purposely conceived to facilitate its replication, reshaping, overlapping. We integrated biophilic patterns into our prototype, reflected through nature analogues in our indoor space, as well as principles of biomimetic architecture, through architectural features and passive strategies reflecting natural mechanisms. We were inspired by a cell structure to design a multi-layered skin for the nucleus of the house, which acts as a protective barrier from the harsh environment. At the same time, we noticed that all of the elements that make up the cell, while they each have very specific and well defined functions, are in constant communication with one another. This led us to explore a more radical kind of space organization, based on functional distinctions and
fluidity. Each of the house’s three protective layers plays a specific role in creating a pleasant interior space as follows:

- The 1st element (Cell’s wall) - highly perforated panels - filters the harsh light and provides protection for the green terrace.
- The 2nd element (Cytoplasm) - vegetation barrier filters the air and balances the temperature and humidity.
- The 3rd element (Nucleus wall) - well-insulated envelope - ensures a cooled and pleasant interior, using passive strategies.

If we were to describe the house in two words, as far as architecture is concerned, it would be “singular experience”. The completely open floor plan, with all the different functions and layers of the house integrated into such a compact area, challenge the user to experiment space in a completely new way, both in its simplicity and its complexity at the same time. The space’s fluidity also enhances the relationship with nature, with large glazing’s that allow you to establish a visual connection with the surrounding vegetation, making it an integrated part of the interior’s scenery. The communication between the indoor and the outdoor becomes seamless, breaking the formal barriers between them (see Fig. 1).

The elevated surfaces and volumes, aside from dividing the space into functions, also create intrinsically functional spaces. The house size and occupancy assumptions are as it follows: the liveable area is 74 m², the conditioned surface area is 66 m² and the conditioned volume is 205 m³. The house is to be occupied by two people, according to an occupancy scenario. Designing for the extreme Middle Eastern weather was a great for designing a house intended to be both sustainable but also comfortable. The glazing of the house is designed so that the gentle north light enters the house entirely, while the more intense east light is refined by two layers: the perforated facade panels and the vegetation layer. The tower windows insert a clearer, unfiltered light into the house, that creates a skylight effect. Furthermore, we can harvest daylight in the kitchen area, living, dining and office by using 4 sensors, which measure the illuminance level, value which is used to automatically adjust dimming or to even switch off the light in the case of sufficiency.

Artificial light is another mean we used in order to border different areas in the house - the position of the luminaires communicate harmoniously with the ceiling’s silhouette. Vegetation areas are the only ones to break the rhythmic geometrical patterns that the rest of the house is made up of - much like the way our biophilic house would break the standardized patterns of residential buildings that exist today. The green wall breaks the rhythm of the equally divided 3-segment curtain wall, while the ground planted area soothes the rigidity of the terrace decking. Their organic shapes mix with the clean lines of the facade and glazed surfaces, giving the illusion of nature making its way inside the house. Local
architecture inspired us to use traditional elements in a modern way, which resulted in the multifunctional towers and the perforated facade. The elevated volumes follow basic principles from Middle Eastern wind towers to enhance natural ventilation by stimulating air circulation and hot air evacuation through the high-placed openings. The traditional mashrabyia inspired the patterns on the outer shell that filter light, while shading the outdoor private space. The pattern also acts as a customizable element, as it can be changed according to the user’s preferences. We used the house’s orientation and a compact floor plan to minimize solar and radiated heat gains from the external factors, while maximizing natural light intake. The multi-layered skin, together with the house nucleus gradually diminish the house’s energy consumption and increase the comfort level. Windows’ placement and size adjustment according to house’s orientation minimize energy demand, because a great deal of the thermal energy is lost at window joineries. For that reason, the technical room, kitchen, office and bathroom face west, because they do not require generous glazed surfaces. Also, the fact the the glazing’s are placed within the external wall’s thermal insulation leads to great reduction of thermal bridging. The façade panels are made of a highly reflective aluminum composite, which gives us double the advantage - reduces excess heating by Redirecting solar radiation and lowers outer wall temperatures by using air circulation through the ventilated facade to cool it down. This first barrier ensures significant protection for the green terrace. The planted areas help filter the air on the terrace and cools the air in its immediate proximity. The terrace acts as a shaded transition area between the harsh exterior conditions and the indoor cool temperatures. The well insulated walls of the house made of structural wooden panels and 25 cm of rockwool help maintain a proper temperature inside the house. Mohamed et al. [6] have demonstrated that also traditional mud architecture can reduce the need for cooling during summertime. Low thermal transmittance is also ensured by glass configuration, while the solar control coatings applied on glass ensure protection for interior spaces and maximize daylight.

3. Structural, electrical and HVAC engineering of the prototype

The structural system combines prefabricated modules for slabs, load-bearing walls and beams for added resistance. It was specially tailored to an open and continuous architectural space. In order to create imperceptible transitions between the modules we used consolidation beams that allow for very large structural openings, without the need of pillars or walls, which would divide the space. We used prefabricated elements as much as possible, achieving an almost entirely dry assembly process, reduced carbon emissions from transportation, minimal manufacturing time, better waste management, and overall lower construction costs stemming from fast fabrication and assembly (2-3 months), reduced costs for heavy-duty equipment rental and for workforce. The advantage of this kind of structure is that it can be assembled in under 3 days, closing the house and opening 3 different workfronts (interior finishes, exterior finishes, outer shell), speeding up the process even more. Our floor plan is a big open space, and this was the greatest challenge in structural design. No central pillars or interior walls can be used as supports for horizontal elements. So the structural solution is an optimized mix of three structural systems:

- Cross Laminated Timber, in the shape of ErgioWall
- Timber Frame (TF)
- Glued Laminated Wood (Glulam)

Fresh air is supplied through a heat and humidity recovery unit. The mechanical ventilation is controlled by air quality sensors, which ensure that the CO₂ concentration is below 800 ppm and that humidity is between 30% and 60%. Unlike usual enthalpic recovery units, the model used in the prototype is not of the rotary type, but plate heat exchanger made of desiccant fibers, thus reducing sound output. Other contaminants which might get indoors such as fine dust and small particles are filtered out by the advanced filtration integrated in the AC indoor units. As the active cooling source, a multi-split system with two indoor units is be used. Two cooling solutions were analyzed, chosen for fitting best to the Dubai climate - the multi-split and a solar powered absorption chiller. We decided to
go with the multi-split option, because despite the absorption system consuming 9% less electricity (3.81 MWh/year compared to 4.19 MWh/ year), it costs 9.7 times more and requires more maintenance, therefore requiring additional care and long-run costs from the user. One of the main energy efficiency strategies is being able to minimize consumption by interrupting functioning during unoccupied periods, so being able to reach nominal functioning parameters fast is necessary. The usual inconveniences of air-based systems – lower thermal comfort compared to radiant solutions are resolved by the technology integrated in the units. The infrared sensor maps radiant temperatures in the rooms and directs airflow where is needed, evening out temperature distribution, while also avoiding direct airflow towards people. Furthermore, low sound levels and air velocity during operation virtually eliminate downsides associated with air conditioning, while preserving advantages such as affordability, ease of operation and reliability.

All water fixtures have an efficiency of at least 30% less water used than standard ones. A smart meter is installed on the main supply line and has 2 purposes, one is measuring and providing statistics in order to make the inhabitants more aware of their water usage, and the other acts a safety measure, cutting the water supply when leaks or pipe bursts are detected. Grey water is collected from the bathroom washstand, shower, laundry washing machine and the rainwater drainage system and is mechanically filtered using sand layers in order to eliminate residues and is reused, fully covering irrigation needs. As concerns the indoor acoustics the reverberation time has been decreased to a measured value of 0.6s, thanks to using sound absorbent cork tiles on the ceiling and some walls. Sound emittance of mechanical equipment has been one of the determining decision factors. The heat recovery unit emits 17-27 dB depending of fan speed, while the indoor air conditioning units have sound pressure values as low as 19 dB while running on silent mode. During testing and monitoring procedures followed construction completion in Romania, a facade airborne sound insulation and an indoor reverberation time test have been conducted, in order to further optimize acoustic performance.

4. BMS and electrical engineering

The design of the electrical panel is quite simple, tidy and well organized, divided into three main zones:

- The upper part (4 rows) which consists in terminal units that deliver electrical energy to and from the main panel, as well as terminal units used for monitoring or communication protocols;
- The mid part (4 rows) The first two rows have contactors and relays which helps us control how the energy is delivered in the entire electrical panel; The last two consist in the automation system equipment (PLC and the communication modules with an entire row dedicated to the lighting system solution).
- The bottom part (4 rows) houses protection devices (circuit breakers, fuses, separators) and meters on every major branch circuit to monitor: general consumption (or production, depending on flow), photovoltaic production, lighting, sockets, appliances, HVAC, plumbing, electrical charging station and low currents.

Powered by the sun the PV System is designed to cover the house consumption requirements in order to get a positive energy balance. This goal is accomplished by planning our energy strategies using passive and active systems conscientiously. The system consists of 4 PV strings with 8 polycrystalline 280 Wp solar modules each, which make a total peak power of 8.96 [kWp]. These four strings enter 2 by 2 in the string inverters. We integrated one of the strings into the house shell in order to create an efficient design that will facilitate the production of electricity as well as a pleasant effect of natural light. For the storage system we opted for LiFePO4 as technology because it has the highest discharging capacity (close to 100%), so the storage capacity (13.8 kWh) can be used almost integral. The main strategy that we adopted is self-consumption, which is the act of consuming only the energy that you produced. In this sense our system stores the excess produced energy during the day for use...
during the night and supplies it to the grid when the storage system is full. This strategy works best when you have a positive balance, and overall, for the entire year the energy balance is positive, which is consistent with our strategy. Building a futuristic house is a difficult task which requires a clear strategy to maintain owner’s comfort without jeopardizing energy efficiency and cost effectiveness. To achieve this goal, we designed a network mapping of the entire house, a network consisting of sensors and actuators managed by an electric-logical brain (a programmable logic controller - PLC).

In our search for quality, we ended up with 4 communication protocols (Modbus RTU-TCP, KNX, EnOcean, DALI), 4 direct connection modules (Analog/Digital Inputs and Analog/Digital Outputs) and a complex, redundant (if one bus line fails, a major part of the house’s functions are still active) and scalable system (new physical added devices are easy to be identified on the bus and implemented in the source code). However, the process to integrate all protocols to act as a whole entity under our self-developed application wasn’t easy. For example, one problem we faced was to establish the direct control for a non-open source protocol such as DALI. To solve this issue, we had to use KNX as a gateway between the PLC and DALI needed, we take it from the grid. The ventilation system and the cooling system will operate based on the CO₂ level and humidity level, interior and exterior temperature values (read from the sensors all around the house) in correlation with low consumption strategies. In other words, the system will determine the best action to ensure house required comfort conditions:

- start ventilation fans
- switch to a more powerful level of the heat recovery unit
- open the motorized windows
- increase/decrease multi-split system temperature setpoint.

The irrigation system will provide the water necessary for the prosperity of the garden using data from the moisture sensor. Technical equipment integrity is taken into consideration. Solar system overheating will be avoided by operating the shading system based on temperature sensors placed on the roof. Flood sensor, smoke alarm and preset devices’ integrated error alarm will warn the owner about faulty processes. House accessibility is ensured by a door entry system able to open/close the door smart lock. When it comes to house safety, magnetic contacts will provide information about doors and windows status. The lighting system provides a complete dimmable control for almost every light fixture. Furthermore, daylight harvesting is also made possible in the living, kitchen, dining and office areas by 4 sensors which measure illuminance level, value which is used to automatically adjust dimming or to switch off lights when there is enough natural light. This method together with motion sensing assure energy savings and provide a constant and uniform light level.

5. Energy efficiency and simulations

To maintain system stability in the face of extreme environmental factors, a series of building envelope solutions were implemented:

- a wooden structure - unlike other building materials like concrete and steel, wood has much more similar thermal conductivity values to insulation materials, so it helps to reduce thermal bridging;
- a compact floor plan with no protuberances that would create an outer wall heat exposure;
- a 2-layer exterior barrier made of etalbond (an aluminum composite material) panels - the shell and the façade - for solar radiation protection/scattering; According to technical specification, it is proved that the material behaves excellently at temperatures of up to +80°C.
- 3-layered glass panels, Cool-lite Xtreme 60-28 II coating glazed surfaces with 2-16 smm 90% Argon buffers, one of the latest innovations in high performance solar control coatings, with a solar factor of 0.28 (EN410) and the U value of 1.0 W/m²K
- Passive House certified joineries system were used mineral wool insulation (thermal conductivity value of 0.035 W/mK) is combined with thermal bridges limiting strategies such as mounting insulation between orthogonal mullions;
For the house and HVAC simulations we used Design Builder version 5.2. It is comprised of a core 3D modeler and 10 modules, amongst which are Energy Plus, Visualization, Daylighting, CFD, HVAC, Optimization and Scripting, that we used for our simulation purposes. The user-friendly graphical interface is of great aid for beginners compared to other existing programs, thus simplifying Energy Plus thermal simulations.

For the DesignBuilder simulations, the climate data file provided by SDME Organizers was used. Furthermore, we conducted deeper climate analysis as to get a better understanding of the context in which our prototype will be adapted. Geographical location: South-West Asia, Arabian Peninsula, Persian Gulf, United Arab Emirates Geographic coordinates: 25° 15’8” N, 55° 16’48” E Altitude in the coast area: ~ 2 m The United Arab Emirates experiences a tropical desert climate and is located near The Tropic of Cancer that causing a longer exposure to sunlight leading to a dramatic increase in temperatures throughout the year reaching its maximum high by June to August, so the extreme values of temperature approaching 50°C. Under clear skies, incident solar radiation fluxes of 1000 W/m² are measured by inland surface stations.

The location has influenced the climatic characteristics of the United Arab Emirates is influenced by some environmental factors, making it arid and unique in humidity, because near the surface RH is often surprisingly high (70-90%), particularly in the coastal cities like Dubai. Temperature and rain quantity characteristics are also different compared to other arid climates, because these factors have special characteristics: geographical location, area topography, water cover, pressure distribution points and air masses.

Average sunshine (sunshine hours/day): maximum differences between June (maximum sunshine) and January (minimum sunshine) result into an watt pick of 3.4 hours throughout the year. Medium annual value - 9.8 hours/day. Thermal peak is reached in July and August (36.5°C). June and September also show a high thermal potential, with average temperatures above the threshold of 30°C; the thermal minimum is reached in January (17.6°C); the annual average is 27.8°C. Warm hours are characterized by higher wind speeds than the rest of the day. The same tendency is noticeable in the warmer months than the coldest, with maximum at 16:00. Dust storms are considered as one of the common weather phenomena in this region and have a significant effect on climate, on human activities as well as on buildings. The location of the UAE is affected by dust storm, of different durations and intensities, this can also be seen in the representation below. Trendline for this diagram shows the presence of an increasing tendency in the occurrence of dust storms over the years. Especially during the summer season, a low-pressure area develops over Dubai forcing strong north-westerly winds to blow from Saudi Arabia. These winds, also known as Shamal (north) in Arabic, become gusty and unpredictable on reaching Dubai. Shamal boost up the desert sand and reduce visibility and the sandstorms may last for several days.

First and foremost, basic conservative passive strategies have been applied - ensuring a well-insulated, airtight building envelope. All building construction elements follow Passive House thermal resistance recommendations. Also, an airtight envelope layer is designed towards reaching a maximum of 0.6 ac/h at 50 Pa. For this, a combination of air/vapor barrier foil and airtight adhesive band is used. Then, knowing that the largest electrical load is air conditioning, strategies are directed at reducing the cooling load and air conditioning consumption, while also balancing other criteria such as natural lighting. The most important strategy is the building “shell”, a permeable second building envelope which reflects most of the direct solar radiation and creates buffer spaces around the house. Its degree of transparency is achieved by perforating aluminum composite panels accordingly. The green terrace and glazing’s except that facing North are covered by shading 25 to 30% perforated, while the rest is 0-5% perforated, acting as a ventilated facade. Also, in order to improve both indoor comfort and energy efficiency, raised ceilings above the bedroom and kitchen have been implemented, the two “towers”. They provide natural lighting without that much direct solar radiation in the habitable area below. Also, they serve as spaces where hot air rises and is evacuated through the automated operable windows in the
upper side. They also provide a higher channel for air circulation and can be used for “chimney effect” ventilation when outdoor conditions are favorable. Another strategy is the high reflective index of the building facade and of the shell, which we modeled by color and surface optical properties of the outer layer of building elements.

Among the scenarios in terms of occupancy, the house will be inhabited by a married couple with no children, both working adults. During weekdays, it will be unoccupied from 8:00 to 18:00 and during weekends the house will be fully occupied. In terms of environmental control, during occupied hours we considered a setpoint temperature of 24 degrees Celsius for cooling and 23 degrees Celsius for heating and for the unoccupied hours we considered a setback temperature of 28 degrees Celsius for cooling and 20 degrees Celsius for heating. As we pursue Passive House standard airtightness - 0.6 ac/h at n=50 Pa, under normal differential pressure conditions - 4Pa, we consider the house virtually airtight. Thus, zero infiltration. Mechanical ventilation is taken into consideration, with airflows sized to maintain carbon dioxide levels under 800 ppm. A constant outdoor carbon dioxide concentration of 400 ppm was modeled.

Building envelope elements have been modeled as to closely match the real ones, both as thermal resistance and inertia. A mean U-value of 0.13 W/m²K was used for walls and roof slab and 0.19 W/m²K for the floor slab. The total glazing surface of 33.15m² has a Ug (W/m²K) of 0.5 and a SHGC of 0.26.

Table. 1 Building envelope U-values

| Building envelope element | U-value (W/m²K) |
|---------------------------|----------------|
| Wall type 1               | 0.126          |
| Wall type 1               | 0.133          |
| Wall type 1               | 0.123          |
| Wall type 1               | 0.127          |
| Floor slab                | 0.193          |
| Roof slab                 | 0.126          |

The modeled HVAC system consists of an air loop which represents the mechanical ventilation system with heat recovery, a zone group which is the indoor conditioned space. Air conditioning is modeled as a VRF system, without the heat recovery options, as the actual air conditioning equipment is a multisplit unit. The ductless indoor unit recirculates indoor air. For the heat recovery unit, a constant air volume template was used, but variable speed motors option has enabled as to model our variable speed heat recovery unit. As it recovers both sensible and latent loads, heat transfer efficiency were manually introduced as to match the unit - 85% for sensible and 75% for latent gains. The heat exchanger is plate-type, made of desiccant material. Unit control is done by carbon dioxide level. The air conditioning equipment was modeled with the real unit characteristics - nominal cooling capacity of 8.5 kW and a seasonal cooling COP of 3.7. Figure 2 presents the energy simulation for one hottest day.
The cooling design capacity was calculated to be 6.64 kW for the Middle East weather climatic conditions.

We used PVSyst simulation software for the electrical energy balance simulation, using the solar radiation and the temperature data, gathered from Al-maktoumiap, Canada EPW.

For the electricity demand we made simulations for a whole week in each season.

- Spring week: April 1st-7th
- Summer week: July 1st-7th
- Autumn week: October 1st-7th
- Winter week: January 1st-7th

The annual average consumption is based on these seasonal profiles.

Table. 2 Appliances, HVAC and other electrical consumption equipment’s

| EQ  | Description                  | Installed power [W] | Demanded Power [W] |
|-----|------------------------------|---------------------|--------------------|
| EO  | Electric Oven                | 3100                | 2900               |
| EH  | Electric stove               | 7400                | 1200               |
| KH  | Kitchen hood                 | 268                 | 167                |
| DW  | Dish washer                  | 1930                | 414                |
| RF  | Refrigerator + freezer       | 100                 | 24.2               |
| WM  | Washing machine              | 2000                | 300                |
| DM  | Drying machine               | 670                 | 563                |
| PC  | Computer / Laptop            | 90                  | 25                 |
| TV  | Television                   | 71                  | 71                 |
| LL  | Living room lighting         | 208                 | 208                |
| DL  | Dining room lighting         | 152                 | 152                |
The total installed power is calculated to be 30.53 kW while the PV system consisted of 8.96 kWp installation with 32 photovoltaic panels, 280 W each, grouped in 4 strings with 8 panels each. The string inverter has a power of 8.2 kWp, 8 kVA battery inverter and 13.8 kWh battery bank made with 2 x 25.6 V 287.5 Ah batteries, series connected. The calculation takes into consideration: Global irradiation (for Dubai, United Arab Emirates); Photovoltaic array: slope (0 degrees), orientation (0 degrees azimuth), installed power (8 960 Wp) and efficiency (around 15%); Array losses (5.3%), Inverter losses (3%) and Wiring losses (0.2%). As the outdoor temperature is higher during spring compared to winter, the AC consumption is increased. Most of the electrical energy is used by the AC and the charging station. Table 3 presents the average and normalized summer electrical consumption while table 4 summarize the energy demand.

**Table. 3 Average (A) and normalized (N) summer consumption**

| Day | App&Dev | Light. | AC | Vent. | Plumb. | BMS | e-Charge |
|-----|---------|--------|----|-------|--------|-----|----------|
|     | A   | N  | A | N  | A | N  | A | N  | A | N | A | N |
| Mo  | 1.80 | 5% | 1.03 | 3% | 16.63 | 63% | 0.15 | 0% | 3.20 | 2% | 1.09 | 3% | 7.40 | 22% |
| Tu  | 2.18 | 6% | 1.03 | 3% | 17.71 | 64% | 0.15 | 0% | 3.20 | 2% | 1.09 | 3% | 7.40 | 21% |
| We  | 4.70 | 12%| 1.03 | 3% | 18.20 | 60% | 0.15 | 0% | 3.20 | 2% | 1.09 | 3% | 7.40 | 20% |
| Th  | 12% | 3% | 60% | 0% | 2% | 3% | 20% |
Annual energy consumption fluctuates according to the seasons and the biggest factor to the energy consumption is the outside temperature. The energy consumed scales almost proportionally with the temperature. Thus during summer we observe the highest percentages. That is due to the increased energy required to maintain appropriate temperature levels, because of the high delta between the outside temperature value and the desired one. At the polar opposite there is winter where there is the least energy required. And spring and autumn with the their respective results being between the winter and the summer ones.

**Table. 5 Annual energy consumption**

| Appliances & Devices: 1396 kWh/year | SPRING | SUMMER | AUTUMN | WINTER | TOTAL (per system) |
|-----------------------------------|--------|--------|--------|--------|-------------------|
| Lighting: 424 kWh/year            | 110.58 | 102.95 | 107.01 | 103.22 | 423.76 (4%        |
| AC: 4195 kWh/year                 | 863.87 | 1785.9 | 1419.0 | 126.05 | 4194.87 (41%      |
| Ventilation: 65 kWh/year          | 16.45  | 16.45  | 15.92  | 15.74  | 64.56 (1%         |
| Plumbing: 1354 kWh/year           | 344.31 | 342.41 | 333.21 | 333.10 | 1353.03 (13%      |
| BMS: 398 kWh/year                 | 101.32 | 101.32 | 98.05  | 96.96  | 397.65 (4%        |
| e-Charge: 2316 kWh/year           | 589.89 | 589.89 | 570.86 | 564.51 | 2315.14 (23%      |
| TOTAL                             | 2381.93| 3294.43| 2888.12| 1579.81| 10144.29          |
Looking at the total annual energy consumption we can see that the AC is the biggest consumer. As shown in the simulations we have a positive balance for most of the year period. As seen in the chart below (see Table 6) most of the time the system works as follows: the energy produced is greater than the one required, as a result the surplus energy is stored or placed into the grid when the storage system is fully charged. For the rest of the time when the energy produced does not meet the demands, the rest of the energy is provided by the grid.

**Table. 6 Monthly energy produced versus energy needed**

| Available solar energy | Energy needed by the user | Energy balance |
|------------------------|---------------------------|----------------|
| E Produced (kWh)       | E Load (kWh)              |                |
| JAN                    | 908                       | 549.97         | 358.03         |
| FEB                    | 982.84                    | 497.02         | 485.82         |
| MAR                    | 1168.59                   | 789.15         | 379.44         |
| APR                    | 1454.47                   | 778.2          | 676.27         |
| MAY                    | 1654.76                   | 785.55         | 869.21         |
| JUN                    | 1594.07                   | 723.54         | 870.53         |
| JUL                    | 1599.77                   | 756.45         | 843.32         |
| AUG                    | 1608.81                   | 740.04         | 868.77         |
| SEP                    | 1335.39                   | 973.25         | 362.14         |
| OCT                    | 1170.72                   | 989.36         | 181.36         |
| NOV                    | 870.64                    | 650.24         | 220.4          |
| DEC                    | 858.09                    | 555.4          | 302.69         |
| TOTAL                  | 15206.15                  | 8788.17        | 6417.98        |

The CO₂ content electricity mix for Dubai is 0.56 tCO₂/MWh. For a photovoltaic system that produces 15,206 kWh/year, and taking a lifespan of 30 years of photovoltaic panels, the total reduction of carbon dioxide emissions would be 253.32 tCO₂ or 28.27 tCO₂/kWp

6. Conclusions

Building energy simulations were used during the whole design stage to assist in decisions such as choosing and sizing equipment, optimizing shape and orientation, architectural features as well as building elements layers and construction. The energy factor contributed in the decision making, alongside cost-effectiveness, reliability, comfort and context integration. By performing simulations in early design stages offered insights about the main heat gains and their factor, giving us the best directions for improving energy efficiency. As the most important heat gain category was solar gains, shadings were implemented and further optimized until reaching its final design, the “shell”. In more advanced design stages, when house shape, size, main architectural features and building envelope design were final, passive simulations were used to size air conditioning systems. Furthermore, two conditioning systems were analyzed, concluding that the most energy and cost-effective option is an efficient multi-split system. Finally, building energy simulation offered estimates regarding energy consumption of the built prototype, giving an insight on the long-term living costs related to energy in the prototype and demonstrating its viability.

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