Form follows Zero Energy: Technological Design for Sustainable Housing in Extreme Climate Areas

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Abstract: Hot and humid Extreme Climate Areas, like the United Arab Emirates, pose unique challenges for architects and engineers seeking innovative technologies for energy and environmental efficient building designs; at the same time, these regions are characterized by an innovative spirit that pushes to develop and implement projects to test renewable building technologies and solutions.

The research team, which includes the Engineering faculty of The British University in Dubai, is working to develop design strategies that contribute to implementing low-energy and off-grid architecture in the UAE. The goal is to design a home balancing human comfort and efficient energy use, and to respond to the site's climatic and contextual variables. The research aims to design a water-conserving, net-zero energy single-family home that can be used as a prototype for new building developments in this area. The approach developed toward an energy-efficient design process includes both traditional bioclimatic elements and high-performance active technological systems. The experimental design process also aims to reduce the building's environmental impact while creating a comfortable and responsive living environment. In this way, efficient water use and renewable energy features can be aesthetically, economically and culturally integrated into the home's architecture to improve its residents' quality of life. The house design responds to the climate challenges and complements active systems reducing energy use and associated carbon emissions. At the same time, it aims to contribute to the development of appropriate architecture, a starting point for simple architectural expression in the UAE.

Keywords: Sustainable design, sustainable technologies, energy efficiency, on-site energy production, green energy, climatic resource, solar control, ventilation, passive cooling, natural elements, insulation.

INTRODUCTION

Today, the need to control the environmental aspect using technologies and renewable energy sources is a design priority, especially in places where comfort in constructed spaces needs to compensate for extreme climatic conditions. In this regard, the United Arab Emirates (UAE) provide an interesting case study: from being an oil exporter, the country is moving towards developing renewable energy sources for the 21st century.

Many cities in the United Arab Emirates have undergone rapid change; Dubai especially has been transformed in about 20 years from a small desert *enclave* of "*barasati huts*" into a "global city", a veritable "iconic and futuristic architecture laboratory".

Modernisation and globalisation have gone hand in hand with the growing global economy, initially with the discovery and exploitation of petroleum and subsequently with the launch of the tertiary and quaternary sectors, through a forward-looking design vision for the city that not only aims to participate in the global economy as an important link between east and west, but to attract its most important players as well.

The city has grown quickly, eliminating any dialogue with the social and environmental context. Following two decades of development, the United Arab Emirates, and Dubai in particular, has become one of the most desirable places for the transnational community, but also one of the most "energy hungry" countries in the world, with 70% of energy used in buildings, primarily for mechanical ventilation (air conditioning and heating) and artificial lighting [1].

Following a period during which it imported western building models unsuited to the local climate and culture, the UAE's inhabitants began to be more aware and respectful, and to appreciate cultural aspects more in the Nineties. The desire to create an architectural vocabulary better suited to Dubai's economic, cultural and social situation is now demonstrated in its buildings as a means of expressing the Arab identity, "*a living culture needs a constant reference to the collective memory that is amply embodied in the construction of shapes*" [2].

This interest in the "*perception of its inhabitants*" is clearly visible in the approval of new laws on architectural conservation, and in the facades, shapes, adaptations and interpretations of space in new buildings and new layouts. Attention to the context is reflected in the consideration of architecture of the past as a formal guide, seeking to look to local and regional history, the Bedouin culture and Arab/Islamic culture in

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Figure 1: Dubai skyline.

Figure 2: Wind tower in vernacular architecture in Dubai.

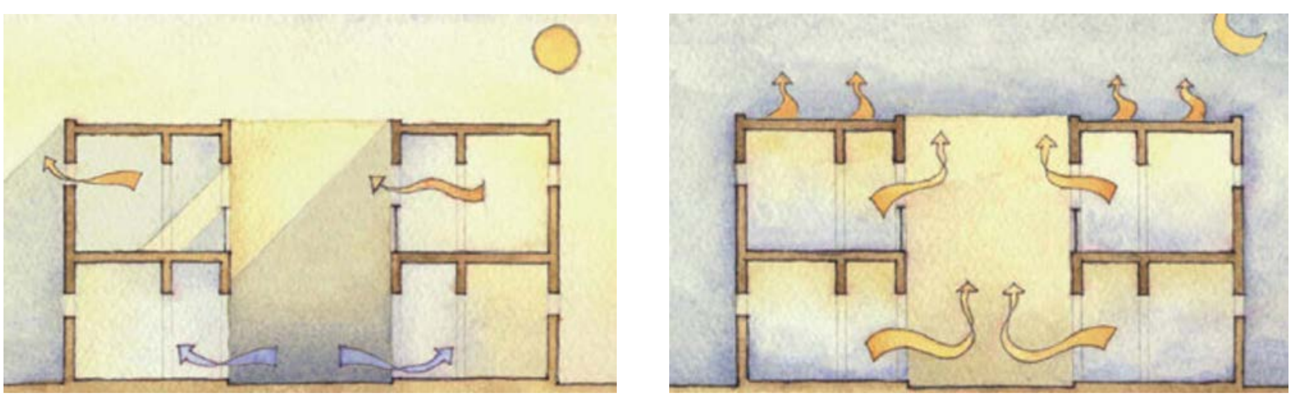

Figure 3: Natural ventilation system in vernacular architecture.

Figure 4: Dubai, *World Trade Center* di John Harris and Associates.

new architecture (the *Masharabiyyas* appears as an ornamental motif in many contemporary buildings, see the *World Trade Center* by John Harris and Associates, the *Deira* towers and the buildings on *Al-Maktoum* street); and in awareness of environmental issues. The decline in oil exports has created a need to diversify the economy and the goal of transforming the United Arab Emirates into a research, experimentation and development centre for energy efficient solutions in architecture and urban design. One of the first experiments is the *Masdar* project in Abu Dhabi (a zero-energy city) with its research centre designed by Sir Norman Foster [3], "*considered a prototype for the transition to a completely new economic sector for Abu Dhabi, that of renewable energy, with the goal of making the Emirates a regional and global centre for future energy solutions* " [4].

This strategic vision was born of a need to address the climate change caused by excessive greenhouse gas emissions, and carbon dioxide in particular, and the resulting increase in global temperatures (maximum temperatures have increased in the past 100 years by 0.5 - 1°C with respect to average temperatures between 1986 and 2005). This phenomenon, along with extreme weather events like flooding and heat waves, impacts the national economy, ecosystems, biodiversity and society. For example, the cost of desalination could rise because of warmer water with a higher salt content; there is likely to be a gap in energy demand related to increased demand for cooling caused by rising temperatures and humidity; and finally, future climate change conditions will hinder the barrier reef's ability to prevent coastal erosion and flooding. The World Meteorological Organisation (WMO) also expects increasing temperatures to cause unpredictable weather events in the Middle East, including more and more powerful cyclones and sand storms.

The document identifies active and passive design strategies that can help to develop "Zero Energy" architectures in the United Arab Emirates, starting with an analysis of the architectural heritage of Middle Eastern countries based, as always, on design that is sensitive to the climate, both with regard to the context with sophisticated passive cooling and heating techniques for urban spaces and buildings. The strategies derived from vernacular architecture are the starting point for an architecture that respects both the place and local lifestyles [5].

THE RESEARCH

The research team is working to develop design strategies that contribute to implementing low-energy and self-sufficient architecture in the UAE. The goal is to design a house that balances human comfort and efficient energy use, and responds to the climatic and contextual variables of the home's location.

Hot and humid climates like that of Dubai pose unique challenges for architects and engineers seeking to design energy efficient buildings. The approach developed in our team's studies implements design strategies that might contribute to low-energy architecture in the UAE. The goal is to design a water-conserving, net-zero energy single-family home that can be used as a prototype for new developments in this climate.

Climate data for Dubai

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	31.6 (88.9)	37.5 (99.5)	41.3 (106.3)	43.5 (110.3)	47.0 (116.6)	46.7 (116.1)	49.0 (120.2)	48.7 (119.7)	45.1 (113.2)	42.0 (107.6)	41.0 (105.8)	35.5 (95.9)	49 (120.2)
Average high °C (°F)	24.0 (75.2)	25.4 (77.7)	28.2 (82.8)	32.9 (91.2)	37.6 (99.7)	39.5 (103.1)	40.8 (105.4)	41.3 (106.3)	38.9 (102)	35.4 (95.7)	30.5 (86.9)	26.2 (79.2)	33.4 (92.1)
Daily mean °C (°F)	19 (66)	20 (68)	22.5 (72.5)	26 (79)	30.5 (86.9)	33 (91)	34.5 (94.1)	35.5 (95.9)	32.5 (90.5)	29 (84)	24.5 (76.1)	21 (70)	27.5 (81.5)
Average low °C (°F)	14.3 (57.7)	15.4 (59.7)	17.6 (63.7)	20.8 (69.4)	24.6 (76.3)	27.2 (81)	29.9 (85.8)	30.2 (86.4)	27.5 (81.5)	23.9 (75)	19.9 (67.8)	16.3 (61.3)	22.3 (72.1)
Record low °C (°F)	6.1 (43)	6.9 (44.4)	9.0 (48.2)	13.4 (56.1)	15.1 (59.2)	18.2 (64.8)	20.4 (68.7)	23.1 (73.6)	16.5 (61.7)	15.0 (59)	11.8 (53.2)	8.2 (46.8)	6.1 (43)
Precipitation mm (inches)	18.8 (0.74)	25.0 (0.984)	22.1 (0.87)	7.2 (0.283)	0.4 (0.016)	0.0 (0)	0.8 (0.031)	0.0 (0)	0.0 (0)	1.1 (0.043)	2.7 (0.106)	16.2 (0.638)	94.3 (3.711)
Avg. precipitation days	5.4	4.7	5.8	2.6	0.3	0.0	0.5	0.5	0.1	0.2	1.3	3.8	25.2
% humidity	65	65	63	55	53	58	56	57	60	60	61	64	59.8
Mean monthly sunshine hours	254.2	229.6	254.5	294.0	344.1	342.0	322.4	316.2	309.0	303.8	285.0	256.6	3,511.4

Source #1: Dubai Meteorological Office

Source #2: climatebase.ru (extremes, sun), NOAA (humidity, 1974-1991)

Figure 5: Climate data.

The approach to energy efficient design includes both traditional elements and modern technology. The research aims to reduce the building's impact on the environment while creating a comfortable, responsive living environment, and to merge the systems seamlessly with the architectural design so that efficient water and energy features can be incorporated aesthetically and economically in a single-family home to improve its residents' quality of life.

The house design intends to respond to the climate challenges and complements active systems reducing building energy use and associated carbon emissions. At the same, it aims to contribute to the development of appropriate architecture, a starting point for simple architectural expression in the UAE.

These objectives include other goals regarding the concept of sustainability in its components.

Social sustainability is pursued through the "*Universal Design*" approach [6].

The home environment must not only meet primary living needs, but also expectations of improved life and social relations and people's work. There is a growing need for living environments that meet the needs of users with different abilities, outside of standardization. Autonomy, independence and wellbeing are the result of spaces' true usability and adaptability. The project to improve living spaces' inclusiveness is an interdisciplinary process in which integrating specialized contributions adaptively customizes solutions and technological solutions that evolve with individuals' changing needs, functional capacities and abilities.

The design concept focuses on the user, such that the house serves the broadest range of people with no need for adaptation or specialized design regardless of their ability or mobility, age, gender or physical stature. So, through different configurations depending on the season, the house adapts to accommodate users of different ages and abilities. The concept is that of an "open building", seeking to guarantee maximal capacity to accommodate different needs over time [7].

Another important goal is to counteract aging of the building so that it has a long lifecycle. This is achieved by preventing building obsolescence and deterioration.

Today, designing housing systems is challenged by a highly uncertain context dominated by the rapid development of functional and technological obsolescence in inherited housing models. The design of housing systems should first and foremost optimize sub-system longevity and be able to offset the process of obsolescence which is concomitant with both the current use of materials and components designed to fail after a short period, and to rigid spatial models incapable of adapting to changes in the household's needs over time. This research examines flexibility as a fundamental requirement to be incorporated in the house's lifecycle, using strategies that affect both the form and the technological system governing its structure.

If flexibility is a system's ability to be modified easily and to respond to changes in the environment in a timely and convenient manner, then it can be considered the antidote to obsolescence (the characteristic of the system that guarantees slippage over time).

Design for flexibility and maintainability requirements aims to pursue environmental sustainability through the careful selection of building materials. Building technologies are chosen to guarantee safe and normal use throughout the building's lifespan and to extend the lifespan reasonably. Great attention is paid to technical solutions with easy maintenance, such as the open horizontal and vertical distribution of wires and pipes. Desert environments feature extreme weather events that require PV modules to be cleaned, as soiling has a major impact on a photovoltaic system's performance. Our design approach implements a rooftop array cleaning system.

Flexibility and Inclusiveness as Basic Requirements

One of the main problems affecting housing in recent decades has been the risk of technical or functional obsolescence in the short term, because building performance is no longer a competitive advantage on the housing market, nor does it satisfy users' needs. This inability to address the social-natural and cultural context and the various needs arising from different types of home use tends to render the housing system inadequate and reduces its lifespan. This suggests a need to rethink the concepts of obsolescence, lifespan and flexibility during the design phase in general, and particularly during renovation works.

Flexibility is defined as a system's ability to be easily modified and to respond to user needs in a timely and effective manner; this means that it can be considered an antidote to obsolescence and a system characteristic extending its life cycle over time.

We can then identify two strategies to ensure the extension of the life of the house, meaning that the same level of performance is guaranteed over time [8]:

- Spatial flexibility that, in the typological context, guarantees home modifiability, the target shift, due to the onset of specific user requirements. Then tied "to the possibility of preparing functional variables models, spatial configurations and technical alternatives and constructive intended to be implemented by users within different temporal thresholds" [9]; the implementation of spatial flexibility.

- Technological flexibility that, in the technology context, ensures ease of modification, allows all those operations that do not alter the original objective, but aim to improve the technological apparatus. And then tied to the relationship between maintainability and reversibility, ease of repair of any breakdowns, installation of new components, the upgrading of existing ones and the recycling of unused ones.

Instead of design homologation, which homogenises spaces and equipment based on standard users or the entire community, we should prefer a design culture that seeks solutions customizing housing space according to users' (biological, physical, behavioural, gestural, cognitive, social) needs at specific times in their lives in order to achieve an inclusive idea of real users. A flexible, adaptable and inclusive approach to design overcomes the idea of space optimization in relation to functions, first and foremost by pursuing the search for "equal, simple and safe" use (in compliance with the seven principles of universal design) while reading the specific needs of users through observation of their actions in relation to space, technological and functional objects (as urban furniture), and technical and constructive elements featured in the public space (such as roofing and flooring technology) [10]. Sizing the space must allow for usability notwithstanding the users' body size, posture or ability to move. Therefore, in addition to design strategies facilitating autonomy, such as providing an abundance of entrances into the home (facilitating possible autonomy of the assisted person through the development of independent but neighbouring or connected housing units) at the design stage, modular, replaceable and maintainable plant design (ductwork, equipped decking, controllable flooring to facilitate reconfiguration, transfer or increase in technical hubs), movable internal partitions (light-weight partitions facilitating resizing of environmental units), space customization and adaptability solutions are added, through the study of the ergonomic optimization of space to users' needs.

Figure 6: Spatial and technological flexibility.

Technologies and Design

The design approach is based on the principle of two skins: a "house within a house". The first skin envelopes the living area with all indoor functions contained within it. The second skin, formed by a canopy, serves two functions: to protect the house from the sun and wind, and support photovoltaic panels.

As a priority, the proposed design strategies define architectural and technological choices in relation with floor planning, façade design and orientation. For example, engineering solutions only help the architectural dimension in pursuit of wellbeing for users. Design strategies focus primarily on reducing cooling loads, the most significant energy issue in the UAE, where the cooling season is much longer than the heating season.

Architecture Design Criteria

House orientation needs to reduce cooling loads by minimizing solar penetration through windows and solar absorption through walls and roofs, and maximizing cross ventilation. The high insulation levels promote a strong preference for a north-south orientation.

To reduce the area of irradiated surfaces, the east and west walls are shorter than those on the north and south. East and west façades are opaque and serve as thermal mass buffers, given the low altitude of early morning and late afternoon sun.

As the side with the greatest solar exposure, the south is carefully controlled to be protected from direct sunlight and glare. The north façade, on the other hand, is more open, providing views and controlled daylight; on this side, a light shading system can manage late summer afternoon sun.

Because of high humidity levels, the orientation also takes advantage of prevailing wind directions. Even when breezes are not perpendicular to the facade, they are beneficial for cooling through cross ventilation. The orientation is also considered in the organization of interior spaces to benefit from ventilation.

Proper design of operable windows and doors promotes cooling breezes throughout the home; the size and location of openings improve and increase air movement from high pressure to low pressure areas, creating a breeze throughout the house. Air movement is also promoted taking advantage of temperature variations by incorporating openings in the top and

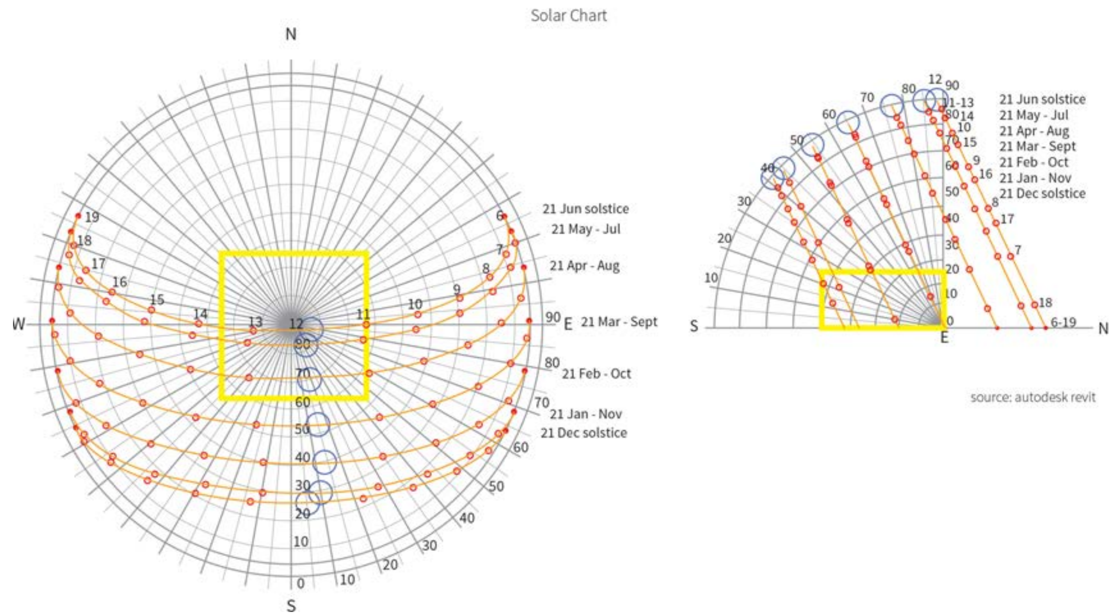

Figure 7: Solar chart.

bottom of the outer walls to expel warm air from the higher points and draw in cool air from lower.

Adding a secondary roof floating above the residence helps reduce solar heat gain while providing shade. The roof is raised above the house in a kind of canopy structure that provides enough airflow and cross ventilation to keep the house cool during the day. The detached horizontal roof shades the building below and supports the energy production system.

The facades' light colour can be chosen for thermal performance and to reduce maximum indoor temperatures, thus reducing the need for mechanical ventilation and cooling. In this way, external walls absorb less solar radiation. This is a simple and cost-effective strategy for reducing building energy use. To avoid glare, medium-to-light colours are used for internal and selected walls.

The design has a flexible floor plan with a compact shape: the changing space organization allows modifications for great exposure to the air. Windows are covered by shutters or opaque panels during the daytime and opened at night. The building envelope's changeable surface area both minimizes daytime radiant and conductive heat gains and maximizes the rate of cooling via cooler night-time air movement. The ability to open the plan more fully also provides benefits during periods of high humidity.

The interior living space extends outside and allows users to benefit from a shaded terrace. With the sliding doors open, the interior immediately becomes part of the exterior, and the inhabitants can fully enjoy the cool breeze.

A simple aggregation scheme can create arrays of houses taking advantage of opaque walls. Detached houses have a large envelope area in comparison with other building types, and so are highly susceptible to solar radiation. Therefore, the building envelope design includes a second structure shading the exterior surfaces of walls and roof depending on seasonal conditions.

Engineering

The roof is used to produce electricity from solar energy because it is in the most suitable position for optimal photovoltaic panel performance.

Solar power is fundamental to pursuing a high-quality and environmentally sustainable lifestyle because photovoltaic panels (PV) convert current solar energy into usable energy.

The photovoltaic (PV) cells convert solar energy into electricity and their design maximizes the effectiveness of the solar arrays.

The roof is also useful for collecting rain water and generating the energy necessary to produce drinking water.

The design is committed to retaining and collecting rainwater and grey water on site; promoting efficiency

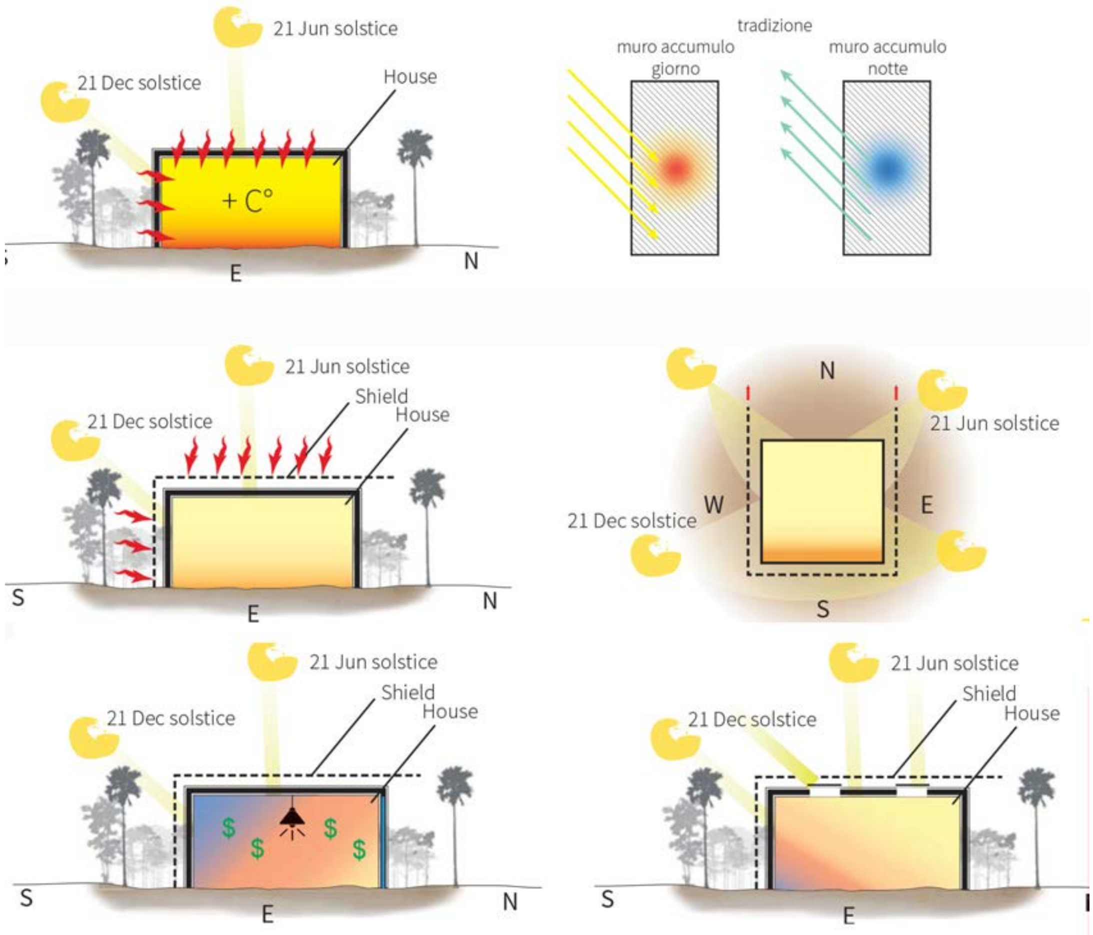

Figure 8: Sun and shadow studies.

by collecting rainwater, and reusing indoor wash water. Run-off from rooftops and other surfaces, as well as water from washing machines, dishwashers, bathtubs and sinks are collected and stored in a cistern. Grey water can be gradually filtered through a special planter bed and used to irrigate the land around the house.

Drinking water can be generated by a residential atmospheric water generator, which serves as an ideal water supply solution for homes in the EAU. The system produces 250-800 litres of potable water per day depending on temperature and humidity conditions. System efficiency improves with higher relative humidity, especially approaching 80 to 90 percent.

The concept is based on well-known laws of chemistry and physics; evidence of fog and dew collection systems on cool surfaces has been found in ancient Middle Eastern and South American civilizations. The National Aeronautics and Space Administration (NASA) uses atmospheric condensation in space stations, and has contracted for a system to condense water from the Martian atmosphere for a future Mars landing.

To control its environment, the house is equipped with an Adaptive Control System. This allows its occupants to interact with the home and monitor house conditions in real time so that adjustments can be made to optimize energy use, humidity, and light and water consumption. This system enhances the users' experience in the house.

The main choices adopted in developing the prototype are:

- Opaque envelope (vertical walls and roof) for incident solar radiation, with dynamic thermal behaviour during the summer and thermal and acoustic insulation (less thermal insulation and hygrometric performance for the ground floor);
- Transparent envelope (glazed walls) for incident solar radiation, solar shades (mobile and fixed) and thermal and acoustic insulation;

- Natural ventilation (opposite) for the layout of the openings and of the rooms;
- Controlled mechanical ventilation system (CMV system with high-efficiency heat recovery unit) with plant components installed in the side walls and the air treatment unit in an accessible compartment above the bathroom's usable volume;
- Summer air conditioning system (direct expansion air-air cooling system with heat recovery at the source to heat domestic hot water). By converting the operation of this type of cooling system into a heat pump, we can also meet any winter heating needs; in this case, the heat pump can be a variable refrigerant delivery system to better adapt to the building's heat loads;
- Domestic hot water production system (served by the cooling system/heat pump and connected to the thermal solar system or flat glazed collectors);
- Energy production system powered by renewable sources (e.g.: a heat pump for thermal energy and the thermal solar system for hot water, and the photovoltaic solar system in the envelope for electricity production);
- LED lighting with automatic on/off/dimmer control depending on the availability of natural light;
- Innovative home automation systems for automatic adjustment/control/monitoring of air conditioning systems based on external climatic parameters and interior comfort levels (depending on use profiles).

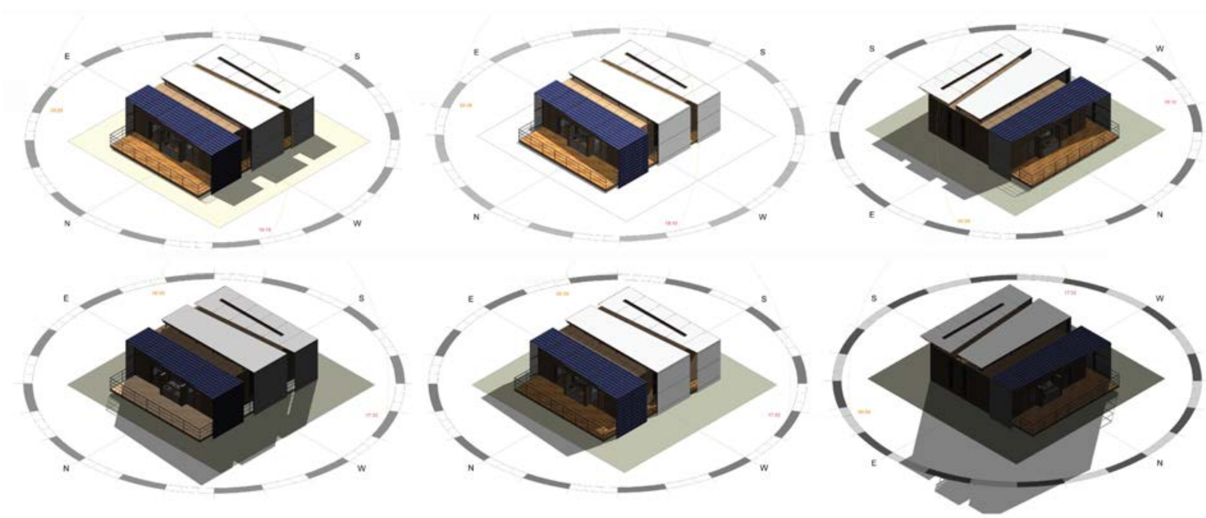

Figure 9: Prototype studies: sun and shadow.

Figure 10: Prototype studies: cross section with court.

CONCLUSIONS

Today, research into possible forms of evolution and innovation in housing projects in extreme climate areas like that of the United Arab Emirates is of topical interest to promote the development of new technologies and innovate the residential space concept, while also seeking economic feasibility.

Various levels have been analysed: the relationship between the building and the environmental context, the organization of space according to the criteria of maximum flexibility and accessibility to meet very large numbers of users, innovative materials and structure, and, finally, building use and management.

This paper summarizes the key points of the Pescara team's research for the design of a Zero Energy Building, describing the criteria for designing active and passive technologies that have been developed or chosen to create an efficient building prototype in a hot and humid area. We analysed fundamental variables such as shading, insulation, ventilation, cooling and daylight to improve the building’s climatic adaptability based on the climate and thermal comfort in coastal areas of the UAE.

Bioclimatic, energy and environmental research for housing in hot and humid climates is currently in the experimental phase; the design and building stages have been completed, and the test phase will be started soon. Measurements of the prototype’s environmental performance with respect to the various climatic conditions, in operation simulations, will help perfect the advanced technologies developed with component producers.

The primary objectives are to optimise natural bioclimatic aspects, maximise environmental comfort, drastically reduce energy demands and maximise the use of eco-sustainable materials

The results expected from the research activities, refer to the following aspects:

- development of design methodologies referring to spaces and furnishings, which can be easily applied for the autonomy and quality of life of users;
- development of a design process able to integrate the multiple aspects linked to the definition of the quality of the environmental system;
- development of a new framework of requirements for housing functions, which consider the needs for the reduction of living spaces and the need to control the extreme climatic conditions, such as those of the Emirates;
- development of innovative construction technologies for the accessibility, sustainability and flexibility of the houses in extreme climate contexts;
- develop an observation, analysis and measurement protocol, to verify the quality of the living spaces directly, by tests carried out in a pilot house;
- definition of design criteria that can guide the choice of the most appropriate technologies, in terms of adaptability and comfort of the domestic space. It could bases on the three main research actions: the strategic phase (based on the elaboration of product concepts), the tactical phase (based on the requirements definition, the operational phase (based on a measurement and verification of pilot interventions);
- development and testing of prototypes for performance verification;
- creation of families of building furnitures and products, suitable to meet the needs identified.

Further study will focus on more specific methods for active technologies improving the energy efficiency of off-grid buildings and detailing how they work cinematically by reacting to changing climate conditions.

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