Theoretical Design for a Zero Energy House in the Middle East

And analysis of design features and technologies present

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Abstract — Renewable energy and sustainable systems are of increasing importance in the current age of shifting away from fossil fuels, with a higher emphasise on green housing being given in the last 5 years. It is understood that truly sustainable housing is idealised as a Zero Energy house, i.e., one that produces as much power as it consumes in a given year thereby being able to completely sustain itself separate from the local power grid. This paper highlights the design philosophies and basic steps of designing a ZEH house for the hot and harsh climates, with deep focus on improvements to the building envelope by use of insulation, low thermal mass building materials, reflective coating and active technologies such as solar water heaters and VRF systems. A theoretical analysis of various technologies available for use will also be carried out.

Key Words — *ZEH, Insulation, ICF, U.A.E, Energy System, Reflective Coating.*

INTRODUCTION AND BACKGROUND

The current energy system is ever evolving worldwide; several sectors in the government, industry and society are generally aware of the negative impact greenhouse gases emissions and ill-thought material wastage deals to the environment, as well as the economic risks associated with dependence on non-renewable fossil fuels in the coming years. They are also aware of the business opportunities available with sustainable energy developments and green buildings. Those are the key motivations for this project, which aims to reduce the carbon footprint in the residential sector

Energy in the building environment can share upwards of 40% of the energy consumption of a country. However, in UAE the energy requirement is higher than 45%, reaching up to 75% in summer due to heavy reliance on air conditioning. In addition, real estate building have become a core business venture in the developing world as well as increased investment into energy production away from fossil fuels. Since buildings are the most consistent energy consumers, it is quite obvious we will have to focus on this sector for our energy savings, but without compromising on comfort and living quality as it is where 90% of our time is spent.

This project is based on “Trias Energetica” approach; first, a passive design is developed to reduce the cooling load to a minimal value, by the use of insulation, radiant panels, reflective coatings on windows, with special focus given to windows as they are a key design element of modern buildings given their aesthetically pleasing nature. After that, an active design is done based on solar energy, an obvious solution for the current geographical conditions. The objective of energy neutrality has to be achieved on this step. We will however not consider the third step of the “Trias Energetica” approach; which is to optimize the given energy system in relation to the power grid; as we plan on designing a house to be self-sustained, and not part of the main power grid.

Overview of ZEH

A zero energy building is one that produces the exact amount of energy it consumes in a specific duration of time (usually one year). There are various challenges faced when designing a ZEH as we have to consider the carious dynamic interactions between the building, the indoor and outdoor environments, and the climactic conditions that may influence the same.

Another major value to consider is the interaction of people with the internal conditions of the house, namely the comfort levels (Humidity, CO2, Dust or allergens) of the house as to maintain the standards set by the International Indoor Air Quality Association. Alongside the aforementioned, the interaction of the internal environment with the ambient atmosphere must also be considered, as well as use of various passive methods to increase the energy efficiency of cooling systems. These interactions will be factored in when selecting materials to help achieve energy neutrality.

BRIEF ON TECHNOLOGIES AVAILABLE

This section aims to give an insight into the various technologies that are used in this house design, and the various selection criteria used in material choice.

- **Building Materials:** The most important function of these materials is to keep the heat and moisture away from the house. The insulation alongside the reflective coating will effectively reduce the heat transfer along the roof and walls, double glazed windows and ground glass allowing translucent light blocking. Due to the high humidity in the UAE, a vapor barrier would generally be required to both prevent extra moisture from entering as well as to prevent the disruption of the radiant cooling system via in house moisture. But due to the use of ICF panels in construction, this step is already solved by the inclusion of a 2 inch polystyrene based vapor barrier within the structural material. Thermal performance and local availability, as well as health and fire safety are the main deciding factors for selecting building materials.

ICF is a system or formwork for reinforced concrete, usually made with a rigid thermal insulation that stays in place as a permanent interior and exterior substrate for the walls, floors and roofs. The forms are interlocking modular units that are dry – stacks and then filled with concrete. These unit lock together to for the structural walls or floors of a building. Alongside the higher structural strength, the inbuilt layer of insulation, usually consisting of Polystyrene foam, allows for very stringent energy efficiency standards to be met

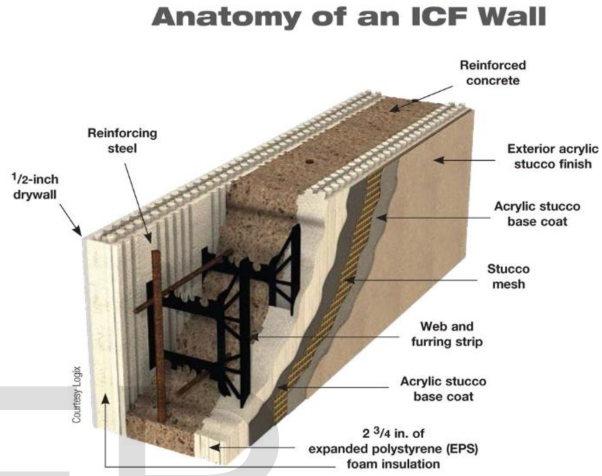


Fig 1. Cross Section of ICF wall

Major energy efficiency characteristics of this material include

(1) Minimal air leaks improves comfort and reduces heat loss as compared to walls without a solid air barrier built separate

(2) High thermal resistance results in a temperature difference of up to 70C along the thickness of the material

(3) Continuous insulation can be used without thermal bridges during construction

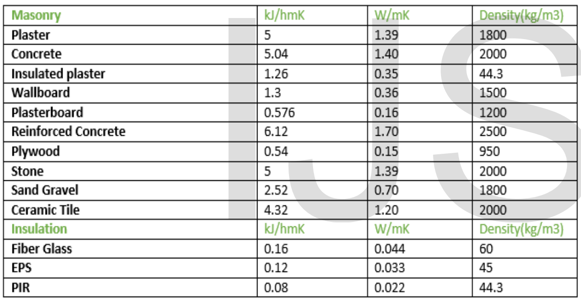
(4) Thermal mass, when used well and combined with passive solar design, can play an important role in further reductions in energy use, especially in climates where it's common to have outside temperatures swing above inside temperatures during the day and below at night.

- **Insulation Materials:** The aim of these materials is to reduce the heat transfer between the environment and the house. The heat can be transferred by conduction, convection and radiation. The insulating performance depends on the thermal properties, which depends on several operating conditions as well.

The thermal conductivity k (W/mK) is the one that define the performance of the material under heat conduction, which is the main heat transfer through the building envelope. A high k means a low thermal resistance, which indicates a poor thermal insulation performance.

To achieve values such as .32(W/m2K) (which is the standard set by ESTIDAMA) without insulation materials, which have a very small k value, huge thickness of masonry material would be needed (21 m thickness for a normal concrete with k = 2.1 W/mK to obtain U=0.1 (W/m2K)).

There are several types of insulation materials: wood, pulp and cork, polyethylene rubber, polystyrene, polyurethane, glass slag wool, fiber glass, mineral wool, calcium silicate, perlite and vermiculite



Masonry	kJ/hmK	W/mK	Density(kg/m3)
Plaster	5	1.39	1800
Concrete	5.04	1.40	2000
Insulated plaster	1.26	0.35	44.3
Wallboard	1.3	0.36	1500
Plasterboard	0.576	0.16	1200
Reinforced Concrete	6.12	1.70	2500
Plywood	0.54	0.15	950
Stone	5	1.39	2000
Sand Gravel	2.52	0.70	1800
Ceramic Tile	4.32	1.20	2000
Insulation	kJ/hmK	W/mK	Density(kg/m3)
Fiber Glass	0.16	0.044	60
EPS	0.12	0.033	45
PIR	0.08	0.022	44.3

Table 1; Building Materials Used

- **Thermal Breaks:** Thermal bridges are parts of the envelope of the house with a high thermal conductivity that connects the external environment with the interior of the house. It is common to find these bridges in the corners and columns of the house where structural steel is present, in the frames of the windows, or in internal roofs. Thermal bridges may cause a rise of 0.1 W/m2K in the conductivity of the wall

  Thermal breaks are insulation materials placed in the building envelope to reduce the thermal bridge effect. Thermal breaks are usually made of a rigid polymer, like rubber or polystyrene. If properly placed they can reduce in 50% the effect of thermal bridging

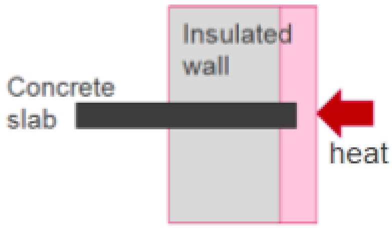


Figure 2; Thermal breaks in an insulated wall

- **Reflective Coating:** There are two main contributors to the cooling load of the building in this area, one of them is the ambient temperature, and the other one is the solar radiation. The solar radiation will reach the surface of the building and increase the surface temperature. A reflective coating can reflect part of the solar radiation that reaches the surface.

  SHGC or Solar Heat Gain Coefficient is the second major energy performance characteristic of windows and can be mostly controlled through glazing. The origin of this gain is the direct and diffuse radiation coming from the sun and the sky. Some radiation is directly transmitted through the glazing to the building interior, while some may be absorbed and indirectly admitted inside. The use of reflective coatings alongside tinted glazing, allow for up to 80% reductions in SHGC values as well as the added benefit of glare control and uniformity in exterior appearance.

  The reflective materials can be found as rolled foil or reflective paint, with aluminium foil being use as a common reflective material. White colour paint can provide a reflectance close to 50% a commercial product SOLACOAT can provide a reflectance of 70% and a new product developed in CSEM-UAE, has 86 %

- **Evaporative Cooling:** Evaporative coolers lower the temperature of air using the principle of evaporative cooling, unlike typical air conditioning systems which use vapour-compression refrigeration or absorption refrigerator. Evaporative cooling is the addition of water vapour into air, which causes a lowering of the temperature of the air. The energy needed to evaporate the water is taken from the air in the form of sensible heat, which affects the temperature of the air. Evaporative cooling therefore causes a drop in the temperature of air proportional to the sensible heat drop and an increase in humidity proportional to the latent heat gain.

Evaporative cooling is most effective when the relative humidity is on the lower side, as it greatly increases the moisture content within the house. A general effort as to not disrupt our radiant cooling system is to allow for the most amount of moisture to be removed beforehand, either by moisture condensers, or PCM absorbents.

Active methods include a mechanical evaporative cooler unit that uses a fan to draw air in through a wetted membrane or cooler pad. This principle is similar to directing exhaust air through double glazed windows, as it effective reduces the amount of heat radiated by the walls and ceiling of the house.

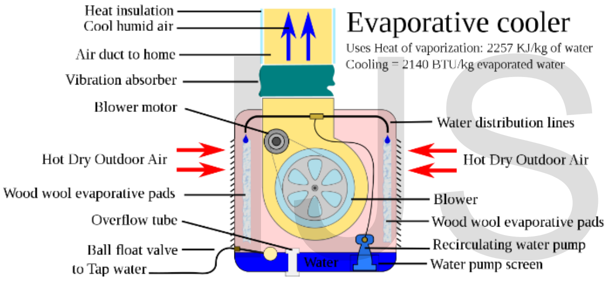


Figure 3; Evaporative Cooling Illustration

- **Variable Refrigerant Flow Systems:** Over the last 20 or 30 years, heat pump technology has continued to evolve, and present day we have a variety of different systems that can be installed to further enhance the cooling of residences. VRF technology is one such possibility, where it is mostly used in houses where installing a duct ventilation system is not an option. It is commonly known as a mini split heat pump or ductless heat pump, this system uses a single outdoor condensing unit to connect with multiple indoor air handle, through which the coolant is pumped. Each air handle can be further controlled via the sensors in each room to allow for more personalized temperature control based on comfort. As there is no duct system, there is close to a 30% reduction in energy loss as compared to conventional air conditioning systems.

  There are 2 system formats for VRF, namely the 2 pipe and 3 pipe systems. In a heat pump 2 pipe system, all regions have to be either in cooling or in heating. While Heat Recovery systems have the ability to simultaneously cool and heat separate zones at once, this is usually a feature of the 3 pipe system, where the working principle is the use of heat absorbed in cooling region to heat the zones that require heating. Albeit the high initial cost of a 3 pipe system, it allows for higher thermal control of the building.

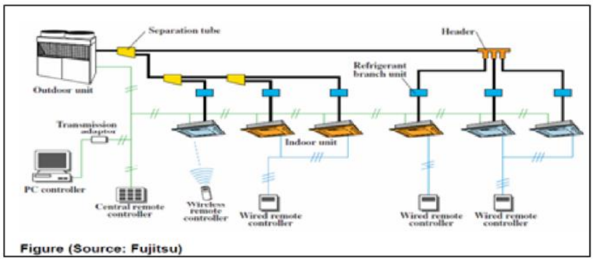


Figure (Source: Fujitsu)

Figure 4; Working principle of VRF systems

- **Solar Water Heater:** The average consumption of hot water is estimated to be 250 liters per day. In order to cover this demand, a solar water heater will be installed. Using simulations for the month of January where the solar irradiation is at the minimum, ESTIDAMA standards recommend covering 80% of the hot water requirements in winter in order to not oversize the system in summer. However, the objective of the ZEH is to cover the whole demand, and therefore we will not consider a backup water heater.

  The size of the collectors have been estimated using POLYSUN, and since we have to divide the roof space with the PV modules, a solar water heater with evacuated tubes, which gives the highest yield per surface area has been chosen. The alternative flat plate collector system can be used in conjunction with the PV array if the former model is deemed insufficient.

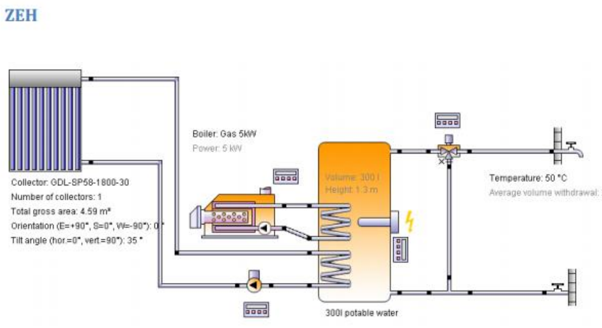


Figure 5; Diagram of solar water heater system

- **Windows:** Conventionally, windows in hot or cold climates are glazed, typically two or three layers of glass with an air gap between them. The air acts as insulation; however other fluids with lower thermal conductivity can be used, like CFCs, inert gases, like Argon or Krypton. The U value (W/m2K) of the window is in function of the glazing and the inner fluids. Values around 0.5 W/m2K are possible to reach with triple glazing. ESTIMADA indicates a minimal value of 0.4 in SHGC to reach the PVRS RE-R1.

  The windows can have films as well, applied inside or outside glass, which reduces the amount of UV and infrared radiation; however they normally reduce visible light. The state of the art are low emissivity films, they are selective spectral reflective coatings, which avoid heat and UV passing through the window and allow only visible light. A parameter that defines this thermal performance is called SHGC, which is the solar heat gain coefficient, and it measures the rate of heat that passes through the window compared to the total amount of irradiation that reaches the window. Recently some windows can improve the relation between SHGC and visibility, by allowing lighter or heat entering into the building in response to an external signal. Another important part of a glazed window is a spacer and a sealant; it will provide part of the support of the structure and keep the air or gas inside away from humidity. Polyurethane or silicon can act as sealants. One of the most innovative concepts is to convert windows in electricity producers, a polymer based solar cells, can be adapted to the window, depending on the type of crystal, dark or clear, the level of transmittance ranges between 30 to 70%; and the efficiency of conversion is around 5%. Another innovative technology is the integration of a PCM material in a glazed window, which will make the windows to work together with thermal mass to regulate the thermal inertia of the house. There are commercial examples like Delta Cool-28® or GlassX®, however the PCM has low visible transmittance in the solid state. From the table below, we find the optimal choice is option 8, a triple gazed low emissivity glass combination.

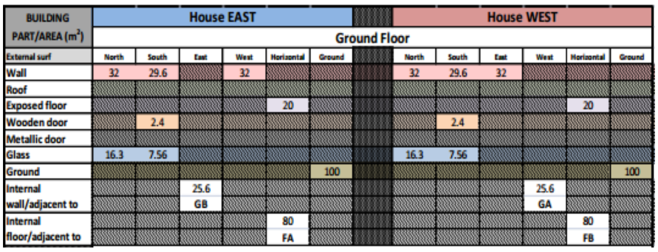
window	Glazing	U (W/m2K)	SHGC	VT (%)	Cooling load contribution North (kWh/m²K)	Cooling load contribution South (kWh/m²K)
0	2	1.4	0.58	70	123.14	215.90
1	2	0.97	0.334	66	47.14	90.36
2	2	0.97	0.256	50	44.83	84.03
3	2	1.01	0.387	65	49.64	95.97
4	2	0.98	0.533	71	75.47	155.72
5	2	1.29	0.333	66	55.03	103.33
6	3	0.59	0.402	67	47.83	97.06
7	2	1.26	0.212	50	49.92	94.14
8	3	0.7	0.22	50	38.61	74.25

Table 2; Cooling load contribution of different window types based on direction of solar irradiation in the UAE

COOLING LOAD OPTIMIZATION

UAE has some of the harshest hot and humid weathers in the world, with high ambient temperatures and humidity levels. Solar irradiation was measured for 5 years in the meteorological station of CSEM and this information was input in the simulations in TRNSYS

The average solar irradiation was found to be 550W/m2 (considering 10 hours of radiation per day) and the average ambient temperature at 28C. Although this figure varies during the summer, where the averages stretches to around 35C and can hit a maximum of 52C. The relative humidity is always about 53% and this along with the constant sand storms and wet winds from the coast reduces the possibility of using traditional natural ventilation methods during most of the year.



BUILDING PART/AREA (m²)	House EAST							House WEST					
	Ground Floor												
External surf	North	South	East	West	Horizontal	Ground		North	South	East	West	Horizontal	Ground
Wall	32	29.6		32				32	29.6	32			
Roof													
Exposed floor					20							20	
Wooden door		2.4							2.4				
Metallic door													
Glass	16.3	7.56						16.3	7.56				
Ground						100							100
Internal wall/adjacent to			25.6 GB								25.6 GA		
Internal floor/adjacent to					80 FA							80 FB	

Table 3; Zones in the ground floor, TRNSYS file

Since the house is designed to have a relatively simple HVAC system, a simplified model was chosen, where a zone for TRNSYS Calculations corresponds to one story in the house. The cooling load for each zone is calculated based on the extent of heating each zone receives, be it from internal or external sources. The external gains are due to solar radiation, ambient temperature and outdoor air that enters when opening a door or window. The air enters into the house by infiltration and ventilation, where infiltration is a feature that cannot be controlled, and is generally undesirable. Ventilation is required for comfort conditions and a healthy environment (internal temperatures of 24C and relative humidity of 40% is the standard comfort zone), and it is assumed that the current design covers the ASHRAE standards for minimal ventilation rate and the standard air flow changes (ACH) expected per zone. Ventilation rates defined are based on outdoor air flow exchange, in order to keep the CO2 levels in the room below 1000 ppm. For a residential house ASHRAE recommends a minimal flow of fresh air of 5.5 liters per second per person. This value is equal to 0.153 ACH, when the building is at a full capacity of 5 people. The ventilation system is designed based on mechanical ventilation and natural ventilation, wherein the latter as we discussed is not applicable for majority of the year due to climatic conditions.

Activity of the residents and their use of devices create negligible contributions to the internal gains. The table below will summarize the heat gains in the house.

Heat gain	Description
Solar radiation	The solar radiation will reach the building envelope and increase the surface temperature. This heat gain affects more transparent surfaces
Ambient temperature	The heat gain is driven by temperatures difference , if the inside temperature is fixed, the higher the exterior temperature, the higher the heat rate
Infiltration	Exterior air which is no conditioned brings heat and humidity to the building. Openings and leaks are the main enter
Ventilation	Exterior air which is conditioned. A proper ventilation is needed for a healthy environment, and it should not be compromised this factor for energy saving
Internal gains	It is caused by people and home devices that emits heat, a value between 2-3 W/m2 is typical for a residential building (20)

Table 3; Heat Gains in the house

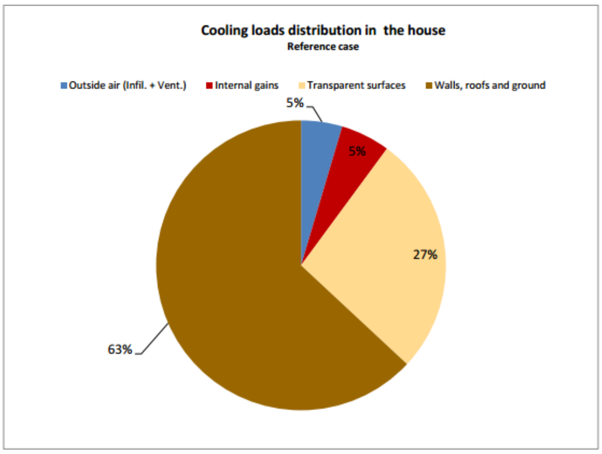


Figure 5, Cooling Load Contributors in a standard house

Another aspect of optimizing the ZEH is to calculate and control the amount of electricity spent in cooling the house. Considering the harsh weather of UAE, nearly 70% of the electricity consumption per year goes towards Air conditioning alone. But with the use of all previously mentioned technologies and methods, we can now improve our AC system. The current air conditioning units have a COP of 2.8 which is equal to an EER = 9.55. ESTIDAMA requires for the PVRS an air conditioning with a minimal EER= 11 (COP of 3.22). A cutting edge technology can have an EER performance between 13 and 21. Considering that the harsh climate conditions of the region affects the performance of the units, a minimal value of EER =13 (COP=3.8) is chosen. In the end, a VRF ductless system, alongside a 1TR capacity AC unit was found to be more than enough to completely take care of cooling requirements.

ENERGY SYSTEM

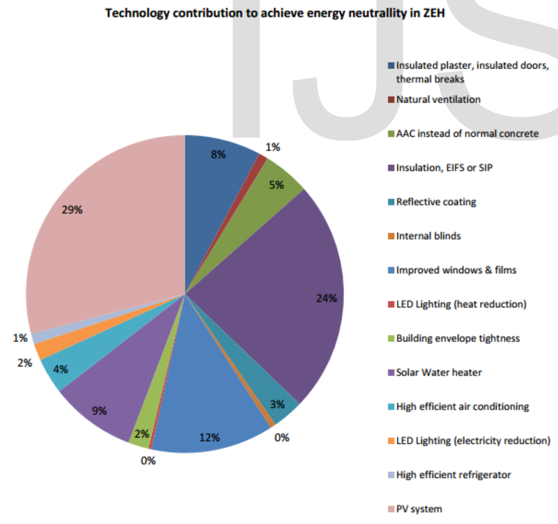
By applying the energy system as discussed, the energy neutrality condition of ZEH is achieved and the zero energy house has been designed. This electrical load is entirely covered by the PV modules. Locational priority is on the top of the roof, where the solar collectors are located. An array of 345 W PV mono-crystal modules were chosen, with each module covering an area of 1.6m2. The optimal orientation of the PV is the latitude of the place where they are located, which will vary based on the actual location of the constructed house. However, as aesthetics are also an important value of the house, we will incorporate a tilt angle as low as possible.

Considering the case of houses already existing in the Sustainable City of Dubai, we consider a house with a 5 degree orientation for the roof, and 90degrees for the south wall. The annual energy yield for a 5 degrees orientation has been calculated to be 342.5 kWh/m2 and for the vertical orientation is 197.6 kWh/m2.

As per the requirements for a standard house design optimised to ZEH standards in the UAE, we get a cooling load of 9.3443MW per annum, which can be covered by a total 19 PV modules generating a total 11.492MWh. The excess 2.1477 MW correlates to the 18% transmission losses. In the unlikely case of insufficient solar irradiation, a battery system capable of storing 2 days of peak demand will be designed, leading to a valve regulated lead – acid battery bank of 50 units is required, working at 12 V, 200Ah, 85% and with minimum state of charge of 30%, capable of storing 64kWh.

The final figure below shows the contribution of all technologies used to achieve the energy neutrality condition for a ZEH

Figure 6; Technology Contribution in ZEH



CONCLUSION

A zero energy house for a family in the UAE region was designed. The basic concept is applicable for any region with similar climate worldwide.

All the technologies used are commercial products. Some methods and systems applied can be considered free is installed in new buildings, and adding basic improvements to the envelope and use of blinds reduces the cooling load by 11% at the least. Focusing to improve the envelope further by use of insulation materials, reflective coatings and improved window panels help reduce the demand for air conditioning by up to 80%.

The largest contributor for performances as always, the use of proper insulation in the roofs and sunlit facades. PV technology is moving toward cheaper more efficient means now, and the cost of running houses entirely off the grid will be greatly comparable to the standard house model.

Energy storage technologies can also be improved, and considering houses are empty for majority of the day, the storing of this energy can prove indubitably useful. It is also easier to convert a cluster of houses to ZEH rather than a standalone, as the use of a district VRF system, or a centralized solar water heater will have higher overall efficiency. Also the use of a solar array to power multiple houses makes transmission losses much more bearable as well as allows for an entire model similar to the Sustainable City Dubai to be established

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