Innovative Concepts for a Set of Net-Zero Energy Houses in the Middle East (Dubai)

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ABSTRACT

The Middle East is a booming market, and during the last years many buildings were built under the local energy code, the requirements of which are not at all comparable to those of European or American standards (see Table 1). As a result, the energy demand for cooling and dehumidification is usually very high. According to the local municipality, in Dubai 40% of the total energy consumption is used for air conditioning. Dubai is one of the hottest and most humid cities in the world. Therefore, not only cooling but also dehumidification are major issues.However, there is a lot of room for improvement. Due to the steep increase of energy costs in recent years, energy-efficient building concepts take an increasing and important role in the design of new buildings.

The goal of the investigation is a master plan with focus on a whole net-zero energy concept for a total of 32 individual buildings, each of which has a net floor area of more than 300 m², located on an island about 8 km off the coast of Dubai. While achieving a comprehensively planned and integrated community with a sense of luxury, the project also is expected to set new standards in environmental design. This means that the building energy demand is balanced over a year by renewable energies for typical Dubai climate conditions. The concept is based on two parts, the optimization of the building envelope and the development of an innovative efficient building service system with use of renewable energy; both are optimized with regard to a reduction of building energy demand. The use of passive means of climate control such as building orientation, shade structures, natural ventilation, and operable façades will provide the development with a very strong environmental meaning.

For the first part, hygrothermal building simulations with WUFI-Plus and TRNSYS have been conducted in order to analyze the useful energy demand of the buildings for cooling and dehumidification, which is the prevailing building energy demand due to the hot and humid climate conditions at site. In this respect, the building envelope was initially based on the local building standard Degree 66 and was further optimized (i.e., wall insulation, window shading by obstructions and blinds, high-performance lighting, partly different occupancy times). This was completed by useful energy demand calculations for hot water and electricity for plugs and appliances.

The second part of the concept comprised the development of an energy-efficient building services system, which has to provide the useful energy calculated before. A standard system for residential houses in such climates is the use of local split units with air circulation, which are typically installed in each room; natural ventilation due to openings like windows and cracks defines the air change rate. According to the problems that arise from a standard system, an efficient and aesthetically convincing (i.e., invisible for the occupants) "lean" building concept has been developed. Since only a relatively small hygienic air flow rate is required for each villa, dehumidification and sensible cooling have been realized by two separate systems: an air-based system is used to dehumidify the air, and a water-based system is used for sensible cooling (since water contains a higher heat capacity than air).

CLIMATE-SPECIFIC DESIGN

Modern architectural concepts often break the basic rule of climate specific design and as a consequence thermal-physically wrong decisions are then compensated by HVAC systems (with mostly high energy demands and often uncomfortable air conditioning systems). In many countries, buildings are being designed following western archetypes despite the fact that some of them show thermal-physical problems

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Table 1. Comparison of Different Requirements

	Dubai Municipality Decree 66	ASHRAE 90.1-2007	ASHRAE 189.1-2009	UK "Part L" 2010	Germany PassivHaus
Roof U-factor	0.44	0.27	0.23	0.25	0.15
Wall U-factor	0.57	0.36	0.36	0.35	0.15
Window U-factor	2.1	2.7	1.4	2.2	0.8
Window G-value	0.35	0.4	0.35	N/A	N/A
Infiltration rate (ACH at 50 Pa)	N/A	N/A	N/A	2.0 [2]	0.6
Energy recovery rate	N/A	50%	60%	N/A	80%

even in their country of origin. Transferred to locations with warmer climates, the energy consumption of a building which is already inappropriate for European or North American climate conditions increases considerably due to the high energy demand of cooling. Table 1 outlines requirements of standards in various parts of the world.

A climate-specific design reduces the solar gains and helps to provide a comfortable indoor climate while also saving a big part of the necessary energy. Climate-specific design is based on taking heed of local climate parameters. For this purpose, the basic rule should be followed:

> First climate-specific designing, then building-specific air conditioning!

Figure 1 shows the step-by-step approach to minimize energy demand. A stepwise optimization allows for an easy evaluation and quantification of single actions and permits a simple cost-benefit ratio.

The significant factors affecting the energy demand of a building are

- Air temperature
- Relative humidity
- Intensity of solar radiation

Other factors of importance may be precipitation and wind. Especially in hot climates, the possibility of enhancing the interior climate by natural ventilation and evaporative cooling should be considered. This means that, first of all, the in-situ climate conditions and the consequence of the usage emerging factors (unclear) have to be carefully analyzed. Adjusted to these boundary conditions, a building and its technical equipment are to be designed that meet the expectations of a preferably zero-energy concept for the conditioning of the indoor climate as well as the further interior energy demands (e.g., electricity).

To size the HVAC system, the wet-bulb temperature of the exterior climate and the global radiation (Figure 2) are especially relevant. In summary, it can be stated that the temperature level of the outdoor climate does not require any heating during the whole year, while air conditioning in summer seems to be inevitable. Concerning the building concepts, attention must be paid to minimize both heat and radiation gains as far as possible.

Step 1: Reducing Energy Demand

Various measures are proposed to minimize the energy demand for cooling of the buildings. For the first part, preliminary thermal building simulations have been conducted to analyze the energy demand of the buildings for cooling and dehumidification, which is the dominant building energy demand due to the hot and humid climate conditions. This was completed by energy demand calculations for hot water and electricity for plugs and appliances. The energy saving potential of the measures was checked and evaluated. The main measures to minimize the cooling load of a building are

- Low surface-to-volume ratio (favorably large, multi-story objects)
- Building orientation preferably in north/south direction, whereas here, the value of solar gains through radiation is minimized.
- Possibly small window area with double and triple glazing, avoiding windows facing east or west
- Preferably automatic shading devices as well as low SHGC values of the windows
- High level of insulation, especially on the roof
- Light-colored exterior surfaces
- Low air change rates and ventilation system with heat recovery
- Small alleyways and close building arrangements to provide mutual shading and reduce convective heat loss

In this respect, the building envelope was initially based on the building standard *Decree 66* (i.e., base case) and was further optimized (i.e., wall insulation, window shading by obstructions and blinds, high-performance lighting, partly different occupancy times). Figure 3 shows the monthly distribution of the heat flows for the design according to the local energy code. This was done by subsequently improving the thermal insulation of the different parts of the envelope as reducing the solar gains through the windows. For the windows, for example, the effectiveness of a smart windows

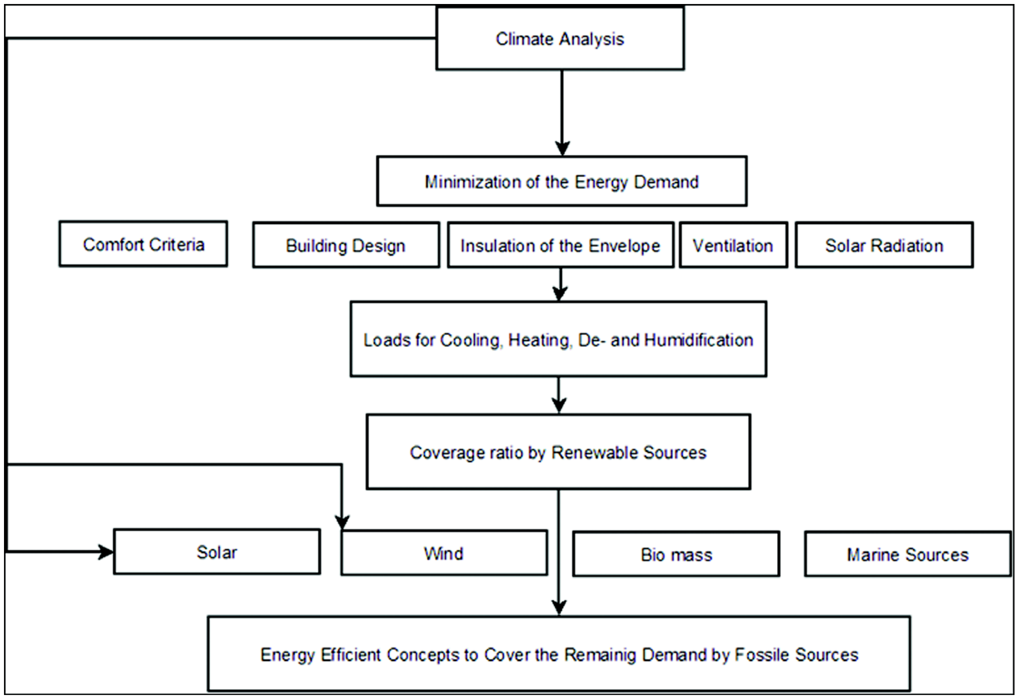

Figure 1 *Procedure to minimize the energy demand required to condition the interior climate.*

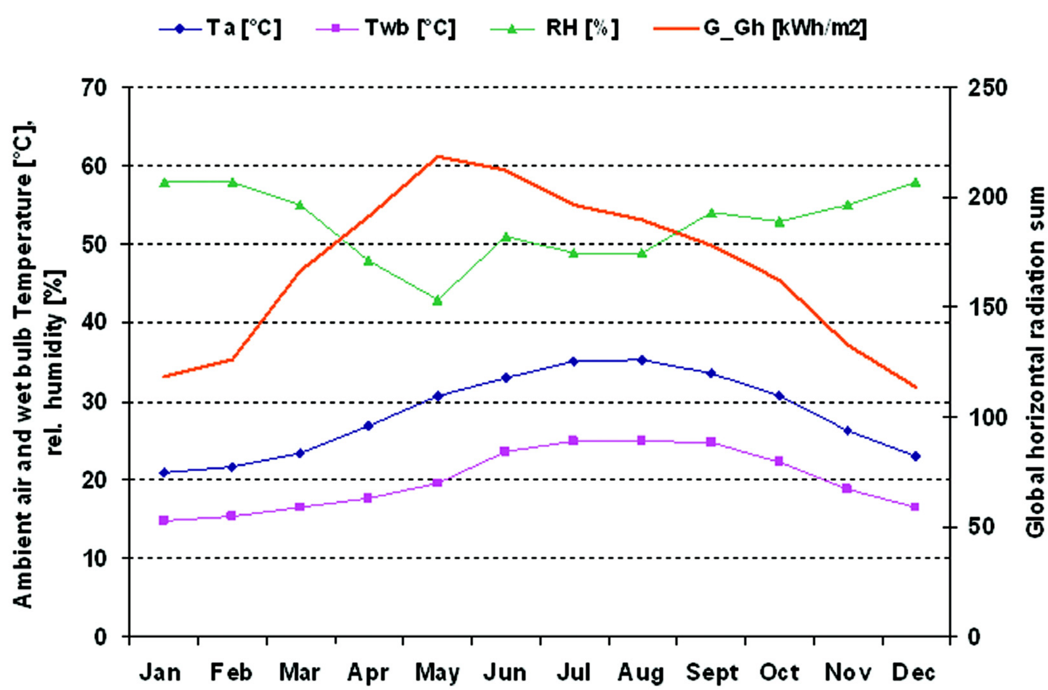

Figure 2 *Monthly averages of air and wet bulb temperature, relative humidity, and global radiation on a horizontal surface in Dubai.*

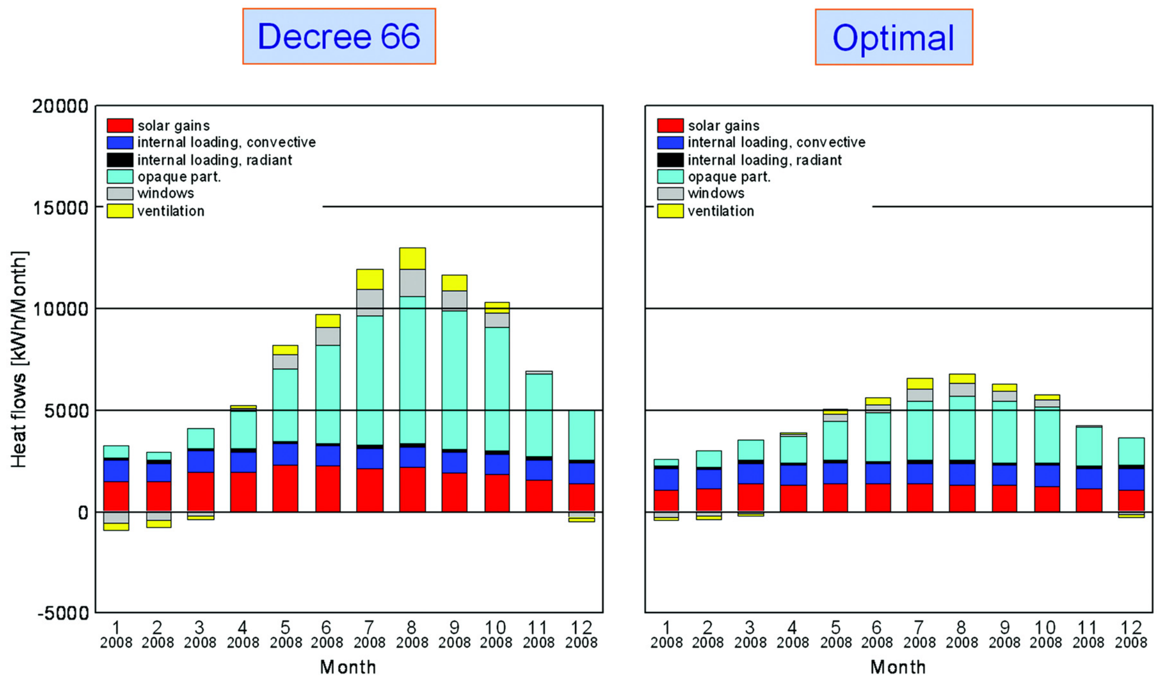

Figure 3 *Monthly heat flows for the design according to the local energy code (left) and for the optimal design (right).*

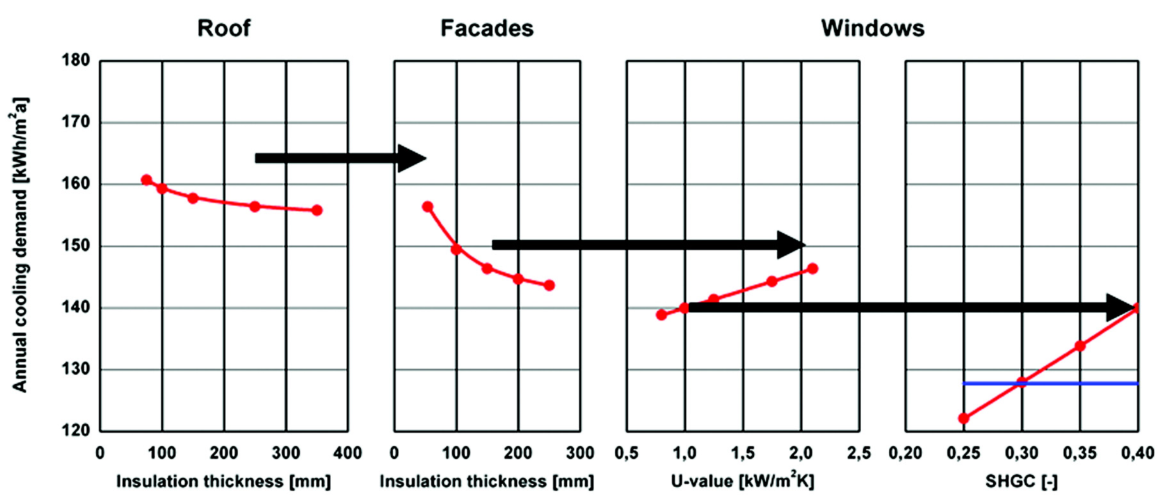

Figure 4 *Impact of the different thermal improvements on the annual cooling demand.*

system with a smart SHGC (varying from 0.25 to 0.4) also was studied. The results of this optimization process can be seen in Figure 4. By finding an optimal tradeoff between cost, constructability, local availability, and energy efficiency of the envelope, the windows (Figure 3), and the ventilation system a drastic improvement was achieved.

Due to the hot and humid climate at site, energy is required for air cooling and dehumidification throughout the year. Figure 5 shows the monthly dehumidification and sensible cooling rates for the optimized building design. In this case, the cooling load is comparable to the dehumidification load (which depends mainly on the ventilation rate). This indicates that typically split refrigeration systems cannot be used to cool and dehumidify the room air at the same time, because the drastic reduction of cooling demand means that either the split units will be overpowered (in order to dehumidify the air) or the relative humidity in the building will be too high.

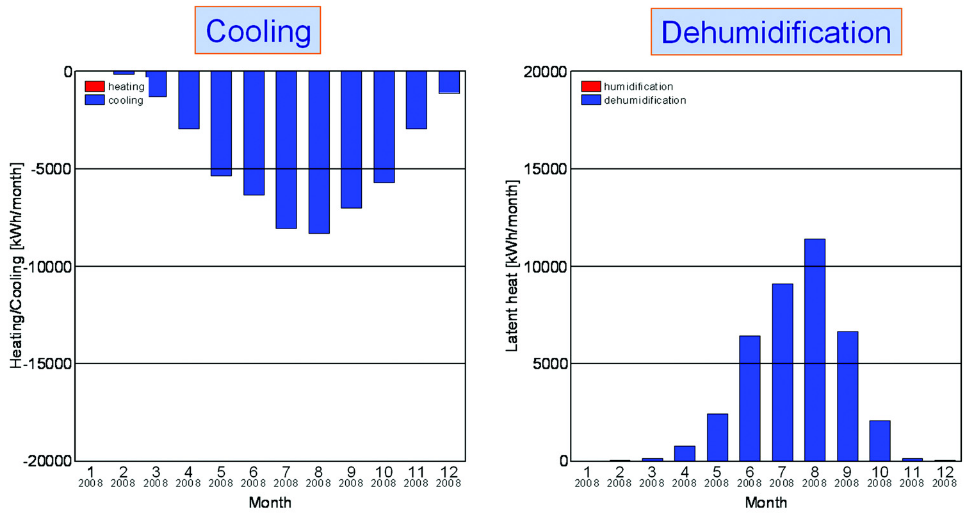

Figure 5 *Monthly sensible cooling dehumidification rate.*

Step 2: Development of an Energy-Efficient Building Services System—Solar-Assisted Building Conditioning

The second part of the concept consists of the development of an energy efficient building services system to provide the energy demand calculated in step 1. The standard cooling system for residential houses in such climates are split-unit air systems, which are typically installed in each room; natural ventilation through openings like windows and cracks provides fresh air. However, due to the small heat capacity of air—an index for the potential to store and transport cold or heat—high airflow rates would be required to meet the total cooling demand of the building. This potentially leads to high draft risks, high operation energy demands, and dissatisfying noise levels from the local compressor and fans; the local units and pipes are visible. Moreover, the required hygienic air change rate cannot be guaranteed by the self-regulating natural ventilation system. According to the problems that arise from a standard system, an efficient and aesthetically convincing, "lean" building concept has been developed. Since only a relative small hygienic air flow rate is required for each villa, dehumidification and sensible cooling has been realized by two separate systems. An air system is used to dehumidify the air, and a water system is used for sensible cooling (since water contains a higher heat capacity than air).

The net-zero energy houses contain mechanical ventilation systems. The air-handling unit (AHU) contains a heat recovery component with a heat recovery rate of up to 80%; this significantly reduces the cooling energy demand due to ventilation. The unit includes an adiabatic cooling component at the exhaust side, which cools the air before it enters the recuperator (evaporator?) to further increase its efficiency. Condensed water from the cooling coil of the inlet side is recycled and used by the adiabatic cooling component. The ambient air, which had been cooled below its dew point during the dehumidification process, is naturally reheated by an air-based thermo-activated ceiling (i.e., air tubes within the slab). The air approaches nearly room temperature before it enters the room at the inlets. This concept is efficient from the energetic and thermal comfort points of view. Sensible cooling of the rooms is realized by a water-based thermoactive building system (TABS). Chilled water flows through pipework in the ceiling and cools the surrounding concrete. The cool surface subsequently cools the room through convection and radiation. Due to the large area of the ceiling, the surface temperature can be close to the room air (i.e., low-exergy system) and still provides sufficient cooling. Thus, the chilled-water temperature can be higher than would be required for a typical air-conditioning system. This concept is advantageous from the energetic and thermal comfort points of view. As a consequence, a lean building concept has been realized according to the use of the AHU (with features like heat recovery, dehumidification, and natural reheating) and the TAB system. The concept is also aesthetically convincing, since the system is mainly invisible to the occupants: the system components are hidden within the building construction and plant room.

In order to supply the AHU and the TABS with chilled water, a cold production system is required. Various technologies have been discussed in terms of their feasibility on site. The final concept makes use of solar-assisted vapor compression chillers. A parametrical study for different operation strategies has been carried out with regards to the energy performance efficiency: the high thermal mass of the thermally activated ceiling concrete is similar to a huge heat sink (i.e., cold storage). The room heat gains can be stored during the day and released during nighttime operation of the TABS. Since the ambient air temperature is lower at night than during daytime, the chillers can release the heat and therefore produce cold more effectively through nighttime operation. The high chilled-water supply temperature level (e.g., 15°C)

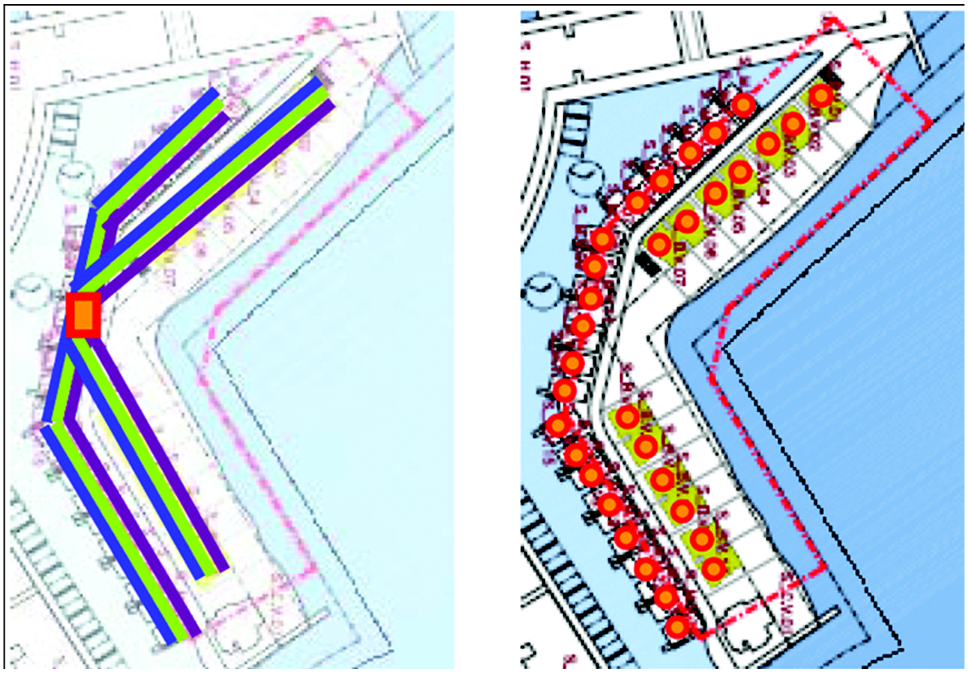

Figure 6 *Semicentral supply system: chilled water is produced on two temperature levels and stored in a central plant room for all villas (left); the water is then distributed to each villa and led back to the central place afterwards. The air-conditioning system (i.e., the air-handling unit) is installed (decentralized) in each house (right).*

helps to improve the chiller performance (seasonal performance index [SPI] > 4). In conclusion, nighttime operation of the chiller is considered for supplying chilled water to the TABS. In contrast, the AHU does not contain any thermal mass and therefore requires a huge cold storage or 24-hour operation. To provide chilled water for dehumidification, its temperature must be below the dew point of the air (e.g., 6°C), which reduces the chiller performance (SPI ≈ 3.7). A 24-hour chiller operation mode with supply temperature at 6°C is thought to be more economical than nighttime operation.

Basically, two design strategies are possible for the building services system: decentralized and centralized systems. In the case of a decentralized system, the components are implemented locally in each house, while for a centralized concept the main components for cold and heat production and air conditioning are provided in a central plant room. In the latter case cold, heat and conditioned air are distributed to the houses by a pipe and duct system.

A centralized system has the advantage that the energy performance of components is high and high reliability exists for operation and maintenance. Furthermore, high noise levels from local chillers (e.g., split units) next to the house do not exist. The slight increase of heat losses due to the distribution of cold to the villas is considered to be negligible compared to the advantages of the central system described before. Therefore, a central plant room is recommended in which the chilled water for cooling and dehumidification is produced and stored. Hygienic sensible components should be realized by a decentralized concept. Thus, air-handling units are installed in a plant room in each house separately. Cooling for dehumidification is provided by the central plant room. In conclusion, a semicentralized concept is recommended whereby the air conditioning is realized in a decentralized and the cold production in a centralized method.

A decentralized (i.e., in each house) and a centralized (i.e., a central plant room for all villas) chiller system have been compared to evaluate their energetic performances. The centralized system showed a significantly better performance. As a consequence, a semicentralized concept (Figure 6) has been considered: cold is provided by a central system, and hygienic components such as the AHU are installed decentrally within each house.

The distribution concept of the main building services in each building is illustrated in detail in Figure 7. Preconditioned ambient air from the air-handling unit (orange rectangle) flows into the building through a duct system (green rectangle), which is installed in the concrete ceiling (i.e., air-based thermoactive building system). The exhaust air is extracted from the building (red rectangles) and led back to the air-conditioning unit. The cold, which is required by the unit, is supplied from the central plant room. The central plant room also provides the cold supply and return flow (purple and green rectangles) for the thermoactive slab (blue circles). A PV system (brown rectangle) is installed on the roof and provides the electricity for the building services, plugs and lights. Figure 8 compares the total energy demand for all buildings with the energy provided by the PV system.

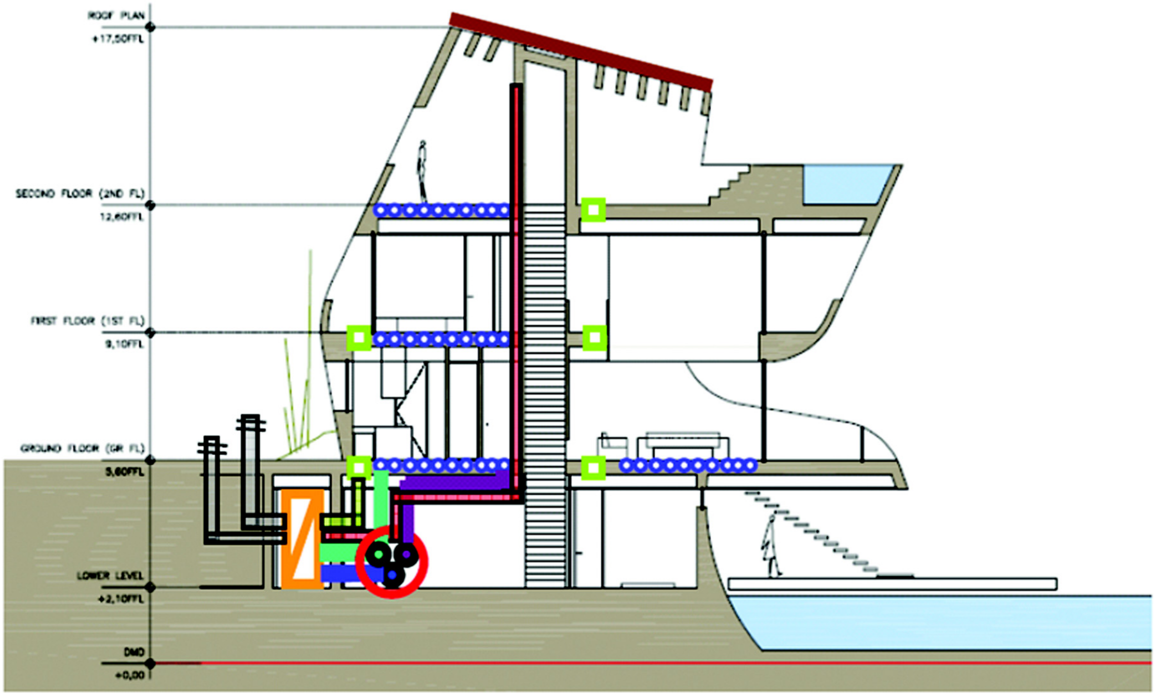

Figure 7 *Distribution of building services: cold water for the air-handling unit and thermoactivated concrete slab is distributed from the central plant room to a small decentralized plant room. The air-handling unit is also installed here. Due to this lean building service system, the services are mainly invisible to the occupants.*

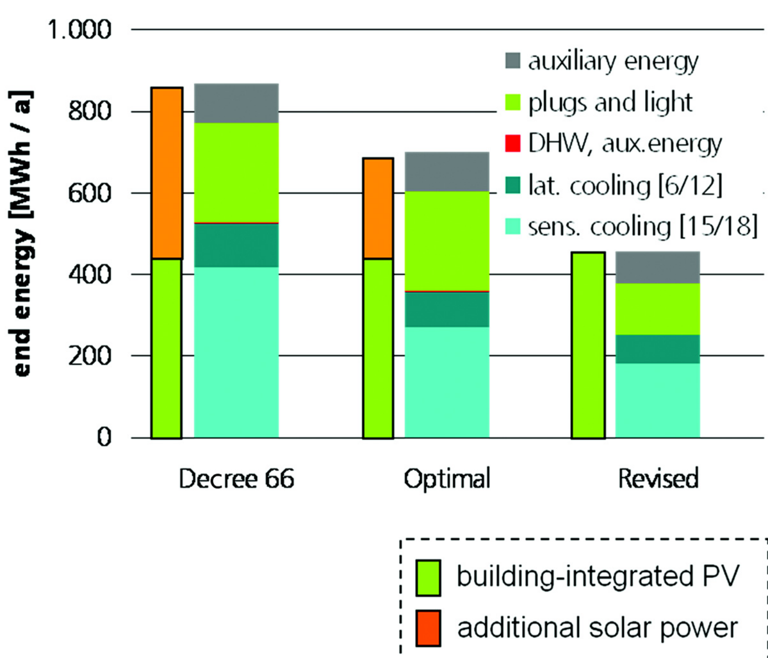

Figure 8 *Total end energy demand for all buildings in comparison with renewable energy provided by the building-integrated PV system and the additional solar power required to achieve the aim of a net-zero-energy concept.*

SUMMARY AND OUTLOOK

A building services and energy concept has been developed and reported with the aim to achieve a net-zero-energy villa concept. Calculations were carried out based on dynamic hourly simulations and simplified hourly and monthly methods.

Future work should contain a further verification of the plausibility of the results, particularly the SPI of the chillers under part load conditions which have a great impact on the total energy demand of the villas.