The Passivhaus-concept for the Arabian Peninsula
(An energetic-economical evaluation considering the thermal comfort)

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1 From standard house to Passivhaus

The Passivhaus standard is a modern building concept, which was originally developed for European climate conditions under the demand of high energy efficiency and high comfort. Major elements of the Passivhaus concept are a high thermal insulation of the external walls, the use of heat and/or solar shading glazing as well as an airtight building envelope. Energy-efficient heating or cooling generators are also components of the technical building installations. And efficient energy-recovery systems are used in order to air-condition the Passivhaus by means of a ventilation system.

The objective on the partnership between Qatar Green Building Council (QGBC) and Solar-Institut Jülich (SIJ) was the evaluation of the Passivhaus-Villa compared with a reference building in standard design (Figure 1-1). Both buildings were constructed within the framework of Baytna-project in Barwa City (Doha, Qatar). The main focus of the simulation-supported analysis was not limited on energy- or cost-efficiency of the building air-conditioning, but also included the evaluation of the user comfort with view onto the thermal comfort. Therefore the simulation tools Carnot and Lacasa based on MATLAB/Simulink were used. Since the development at the SIJ for dynamic building and equipment simulations, these tools are continuously optimized as well as adapted onto new technical developments. The simulation tool „Carnot" is used worldwide by approx. 200 scientific institutions or commercial companies.

Figure 1-1: Reference building in standard design (left) and Passvhaus-Villa (right) in Barwa City (Doha, Qatar), Source: Qatar Green Building Council (QGBC)

2 Simulation model

2.1 Meteorological data

The cooling load of a building in the hot and humid climate of the Arabian Peninsula is influenced mostly by the structural heat and sun protection but also by the internal heat sources (persons, electrical devices, artificial lighting). This relates in particular the heat input into the building due to the heat and solar irradiation transmitted through the windows. If the building cooling load is supposed to be determined by means of a simulation, meteorological data as precise as possible are necessary. In order to guarantee this, meteorological data for the location Doha-Airport (Qatar) from the weather database Meteonorm 7 were used within this project. The used dataset includes data for ambient air temperature, direct / diffuse solar irradiation (horizontal) (Figure 2-1) as well as relative air humidity, air pressure and wind velocity in hourly time-steps.

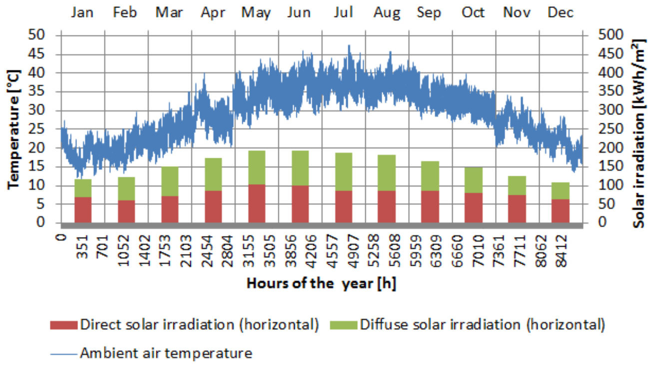

Figure 2-1: Ambient air temperature and solar irradiation (direct- / diffuse-horizontal) at the location of Doha-Airport (Qatar), source of data: Meteonorm 7

2.2 Dynamic building and equipment simulation

An essential part of the evaluation of the Passivhaus-Villa is the thermal building simulation to determine the cooling load. This was carried out by the use of a multiple-zone building model realized in the MATLAB/Simulink-Toolbox Lacasa, for both the Passivhaus-Villa and the reference building. Elements of the dynamic building simulation in Lacasa are the simulation of components (Walls, floor, roof, windows) as multi-layer-models, the consideration of the natural air exchange and the calculation of the long-wave radiation interchange between the internal surfaces as well as the distribution of direct or diffuse solar irradiation (short-wave) in the interior of the respective building zones (Figure 2-2). The calculation of heat radiation exchange and solar irradiation distribution depends on temperatures and radiation properties of the surfaces and is also based on view-factors between interior spaces (geometrical value). As a result of the dynamic building simulation for every zone of the buildings the particular cooling load, the operative room temperature the radiation temperature (temperature of enclosing surfaces) and the absolute / relative air humidity in the interior were calculated.

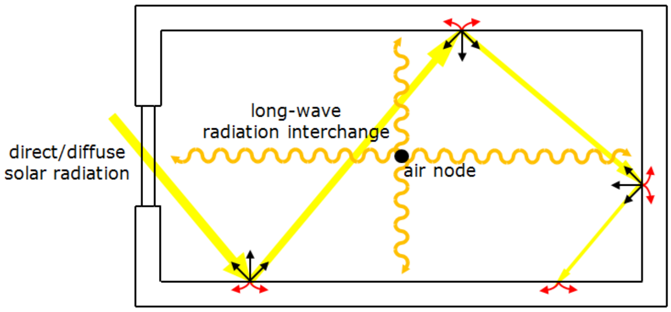

Figure 2-2: Schematic representation of the calculation of solar irradiation distribution and heat radiation exchange in the interior

In combination with the toolbox Carnot the dynamic building simulation and the equipment simulation were brought together in one model. Thereby the building model was complemented by components of the heating, ventilation and air conditioning (HVAC) technology. In addition controller blocks for the modelling of complex systems and various elements for different load or user profiles were integrated into the simulation.

2.3 Photovoltaic – renewable electricity production and cooling load reduction

The dynamic simulation of the grid-connected photovoltaic system belonging to the Passivhaus-Villa was also realized with the Toolbox Carnot. The functional scope of the used simulation model also includes the calculation of the direct and diffuse solar irradiation in the inclined pane of the photovoltaic-modules in which the diffuse irradiation model according to Perez is implemented. The modelling of the photovoltaic modules is based on the one-diode model equation for solar cells of crystalline silicon, with the possibility of manufacturer-independent model adjustment through the input of specific parameters from module data sheets. Furthermore the temperature dependence of the module efficiency is considered. In addition the used photovoltaic system model allows the simulation of installations with an arbitrary number of modules and variable performance. The power of the photovoltaic inverter is freely parameterisable, whereby the calculation of the characteristic efficiency curve considers different losses (no-load losses, semiconductor losses, ohmic losses).

The photovoltaic installation of the Passivhaus-Villa consists of 136 modules with an installed power of 36 kWp. As the photovoltaic modules almost completely cover the roof of the Passivhaus-Villa they do not only generate electric energy, but they also serve as shading elements for the building. The influence of the PV modules is strongly noticeable in a reduction of the cooling load of the Passivhaus-Villa from 25.6 MWh/a to 21.8 MWh/a (Figure 2-3), which corresponds to a saving of 15 % with respect to the variant without a PV installation. The simulation of the cooling load within the framework of the dynamic building and equipment simulation occurred without the consideration of internal heat sources (persons, electrical devices, artificial, lighting). For simplicity it was assumed furthermore, that through the shading by the PV installation only diffuse and no direct solar irradiation is striking onto the surface of the roof.

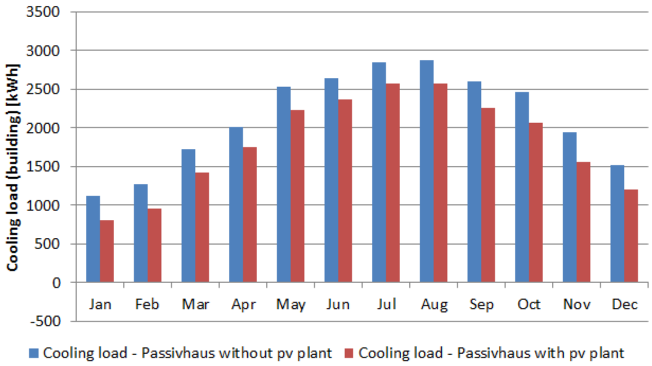

Figure 2-3: Cooling load of Passivhaus-Villa without (blue) und with PV installation (red)

The level of the global horizontal irradiance at the location of the Passivhaus-Villa with an annual potential of approx. 1870 kWh/(m²a) varies in the seasonal trend with a maximum in the summer months. On the other hand the global solar irradiation in the inclined plane of the PV modules is with a yearly total of approx. 1970 kWh/(m²a) at a corresponding level but with a clearly smaller seasonal variation. This is also proven with the simulation of the annual PV electric power generation of approx. 60,000 kWh/a with a total system efficiency of about 13 % (Figure 2-4), in the case of a module inclination of 35 ° and face orientation of the PV modules of 155 °.

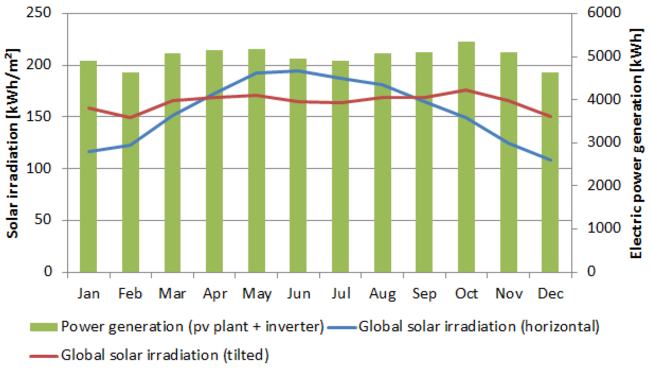

Figure 2-4: Monthly electric power production of the photovoltaic system on the roof of the Passivhaus-Villa (green) and monthly sums of the global solar irradiation into the horizontal (blue) and the module-pane (red) (module inclination: 35°, module orientation: 155°).

3 Comparing the energy efficiency of standard house and Passivhaus

In comparative consideration of the construction standard of Passivhaus-Villa and the reference building with a far higher thermal insulation standard or the approx. 60 % smaller u-value and therefore a lower transmission heat flow into the Passivhaus it is to be expected, that also the cooling energy demand is substantially smaller. In addition the solar heat input into the Passivhaus-Villa is clearly lower because of the shading by the PV-installation. For the simplified approach it was assumed that no internal loads are existent. Accordingly the simulation of the standard reference building indicated a cooling energy demand of about 58 MWh/a, which corresponds to a specific cooling load of 257.5 kWh/(m²a) (Figure 3-1). The simulated cooling energy demand of the Passivhaus-Villa of approx. 21.8 MWh/a or a specific value of 96.8 kWh/(m²/a) undercut the result for the reference building about 62 % (Figure 3-2). The reduced cooling energy demand of the Passivhaus is also reflected in the simulated consumption of electric energy by the air-conditioning system, which contains both the power consumption through the compression refrigerating machine as well as the operation of the cooler. Thus the air-conditioning of the reference building requires an annual electrical energy expenditure at the level of 18.5 MWh_{el}/a (82.3 $kWh_{el}/(m^2a)$). In comparison the air-conditioning of the Passivhaus consumes approx. 5 MWh_{el}/a (22.2 $kWh_{el}/(m^2a)$) per year, which corresponds to an effective energy saving of 73 %.

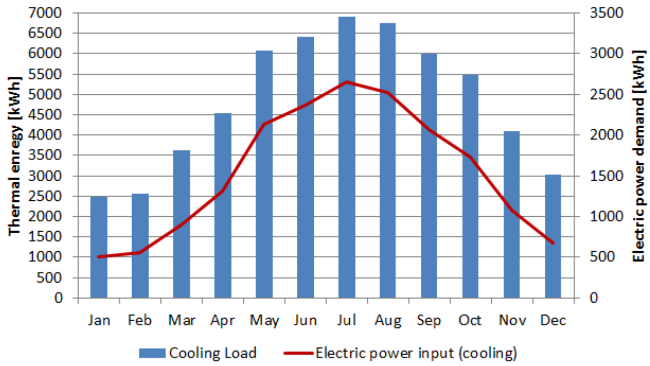

Figure 3-1: Cooling load of the reference building and electricity consumption of the air-conditioning as monthly sums

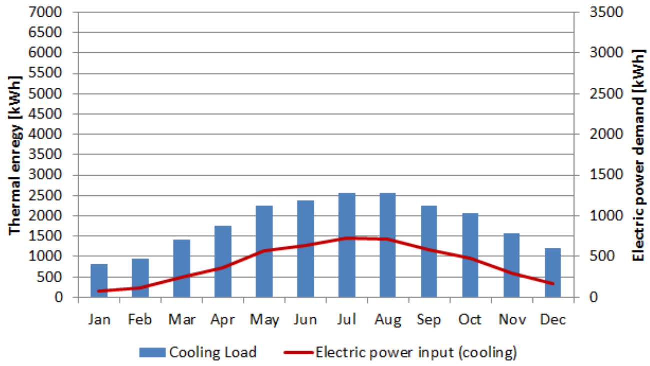

Figure 3-2: Cooling load of Passivhaus-Villa and electricity consumption of the air-conditioning as monthly sums

4 Energy saving through performance optimization of the ventilating system

According to the high efficiency behind the Passivhaus concept the ventilating system of the Passivhaus-Villa has an energy recovery system in the form of a cross-counterflow heat exchanger (Figure 4-1). The built-in heat exchanger has an additional bypass-channel or bypass-function. That makes it possible for the ventilation system to ventilate the building with fresh outside air during the night hours provided that the ambient air temperature is below the room air temperature. This opens additional energy saving potentials. The Passivhaus can be cooled at a still comfortable temperature during the night by means of the cool outside air. Over the day the thermal mass of the building contributes to the passive cooling of the interior and thus reduces the final energy demand for the air-conditioning of the building.

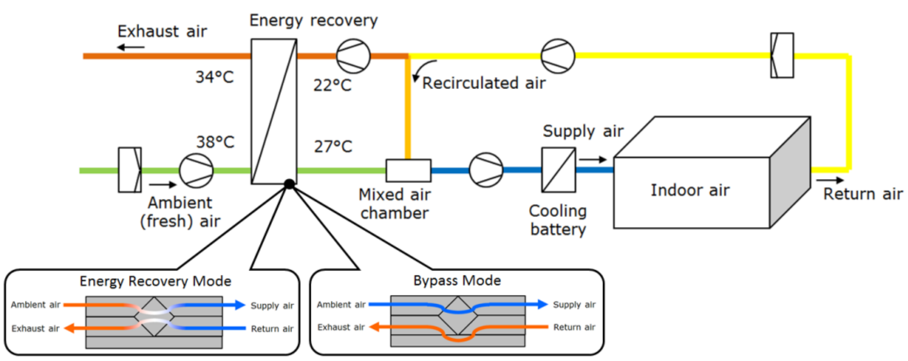

Figure 4-1: Simplified scheme of the ventilating system of the Passivhaus-Villa

At the moment of the examination by the Solar-Institut Jülich the bypass function integrated into the energy recovery system was not activated, so that the height of the energy saving-effects was to be evaluated furthermore. For this purpose the operating parameters of the building ventilation system in the dynamic building and equipment simulation were adjusted, so that the bypass function kept on being activated for night ventilation or cooling of the Passivhaus-Villa in the simulation, as long as the ambient air temperature is below the calculated air temperature in the interior. As a result of the simulation an energy saving of 2 % could be determined for the case of an activated bypass-mode with a constant fresh air volume flow of 100 l/s. The specific energy demand of the supply air conditioning of 100.3 kWh/(m²a) is reduced to 98.5 kWh/(m²a). The mentioned results are also confirmed by the equipment simulation and calculation of the electric energy consumption of the refrigerator and cooler (Figure 4-3). At this the specific electric energy consumption of the air conditioning with 22.5 kWh_{el}/(m²a) is reduced to 22.2 kWh_{el}/(m²a).

In further simulations the energy saving effect by the use of the bypass function could be increased to approx. 4 %, provided that the Passivhaus is ventilated with a maximum fresh air volume flow of approx. 640 l/s and without recirculated air at correspondingly favorable weather conditions (Figure 4-2). In this way the energy demand of the supply air cooling of 100.3 kWh/(m²a) is reduced to 94.8 kWh/(m²a) whereby the electric power consumption of the cold production technology decreases from 22.5 kWh_{el}/(m²a) to 21.4 kWh_{el}/(m²a). Furthermore the evaluation shows that the energy saving effects by the use of the bypass function as a part the energy recovery system are limited to a period of middle November until the end of March. In the remaining period the ambient air temperatures lies constantly above the internal room air temperature so that a use of the bypass mode of the ventilation is not reasonable.

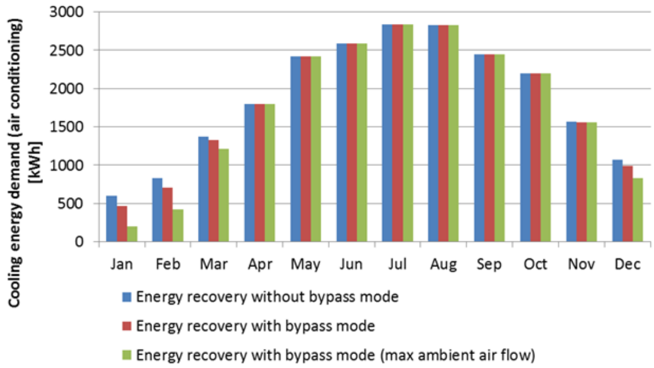

Figure 4-2: Energy demand of the ventilating system for the conditioning of the supply air for operating states without and with activated bypass function of the energy recovery system

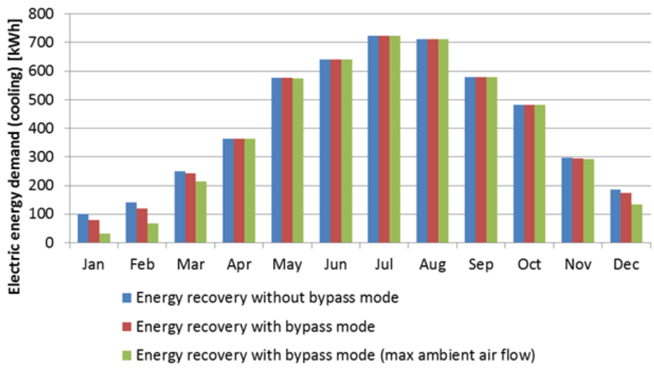

Figure 4-3: Electric energy demand of the ventilating system for operating states without and with activated bypass function of the energy recovery system

An evaluation of the simulated temperatures in the Passivhaus-Villa (Figure 4-4) demonstrated a significant cooling of the operative room temperature due to the ventilation of the building with outside air in the case of an active bypass function. The comparison of the different operating states showed, that the room temperature can be reduced by around 2 K during the night. This will also cool the external and inner walls, which absorb heat during the day and thus contribute to the passive cooling of the building. For short time periods the cooling of the supply air can be stopped completely in combination with the energy recovery system. However, attention is to be paid, that in hot-humid regions the room air humidity does not exceed the comfort levels (see also the following chapter).

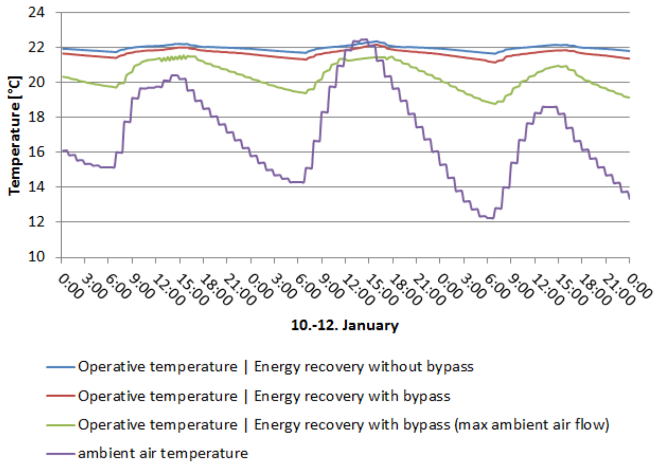

Figure 4-4: Trend of operative interior temperature for ventilation without bypass (blue), ventilation with bypass (red) and ventilation with bypass (max. outside air flow) as well as the ambient air temperature (purple) for three characteristic days in January

5 Evaluation of the user comfort in the Passivhaus-Villa

For the evaluation of the user comfort in buildings at first it is necessary to define suitable standards or limiting values. During the assessment of the interior temperatures with regard to the thermal comfort the European norm EN 15251 was used, where general criteria are defined and peak values of the operative room temperatures for machine cooled residential buildings or interior ventilation systems sorted to categories for the activity degree of persons are recommended. The dynamic building and equipment simulation for the Passivhaus-Villa with a cool temperature limit of 22.5 °C showed, that the building can be chilled sufficiently with the installed ventilation system and the pre-set refrigeration capacity. This demonstrated by means of Figure 5-1 and the represented operative room temperatures in dependence of the moving average of the enclosing surfaces. These lie in the simulated period of a whole year clearly below the maximum temperature of 25.5 °C for the activity degree of the category 1 of 4 (yellow line in Figure 5-1).

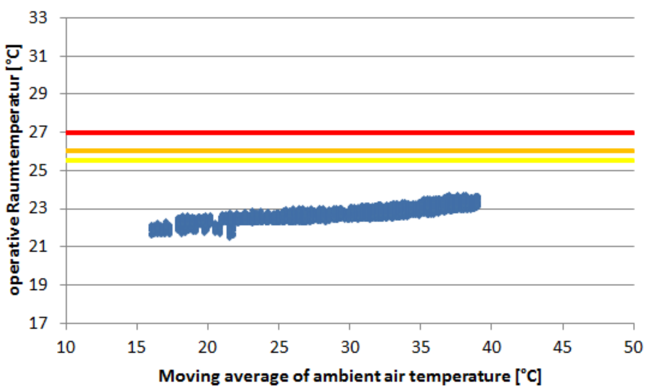

Figure 5-1: Image of the operative room temperature (Simulation) in dependence of the moving average of the ambient air temperature for the period of a year

The well-being and the performance of human beings are influenced by its heat balance in a substantially way. At that the already as characteristic value used operative room temperature represents a valuation standard. This is formed as an arithmetic average from the room air temperature and the average radiation temperature of the room-marking internal surfaces (Walls, floor, ceiling). The air temperature and the average temperature of the enclosing surfaces can be separately used for the evaluation of the thermal comfort. To that a comfort field is defined under definition of a lower and upper limiting value for the operative room temperature. In this case a lower boundary of 20 °C and upper temperature limit of 24 °C were set for the operative room temperature. The use of the mentioned context for the calculation of the operative room temperature results in the comfort field of the interior air temperature and temperature of the enclosing surfaces of the building as shown in Figure 5-2. The results of the dynamic building and equipment simulation of the Passivhaus was evaluated for the period of a year with regard to the room air temperature and average radiation temperature. The resulting temperature data were plotted into a corresponding diagram, shown in Figure 5-2. The representation of the average temperature of the enclosing surfaces in dependence of the room air temperature shows that the interior climate is well within the comfort zone.

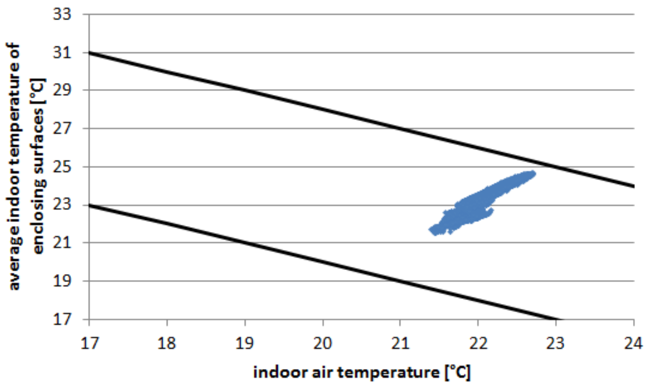

Figure 5-2: Average temperature of enclosing surfaces (simulation) in dependence of the room air temperature for the period of a year

A further clue for the evaluation of the thermal comfort in interiors is the relative air humidity. The generally recommended field lies between a minimum of approx. 20 % and a maximum value of 85 % in dependence of the room air temperature. If the values of the relative air humidity in the room lie above the comfort field shown in Figure 5-3, the interior climate is felt as too moist and sultry by persons. Below the lower limits of the comfort field the room climate is too dry. The related evaluation of the user comfort of the Passivhaus-Villa by means of the air humidity / air temperature data from the dynamic building and equipment simulation for the period of a year showed that the comfort field is crossed only on few days per year.
Concerning the relative interior air humidity during the hours with active bypass-function, the dynamic simulation of the Passivhaus-Villa with an operation of the ventilating system adapted to the night ventilation and to cool the building with cool outside air suggests that outside air humidity has only a small influence on the comfort level of the interior climate. The reason for this is the absolute humidity of the outside air in the affecting season, which is not reaching any critical values. However, a standard weather data record was used and possible weather extremes with high outside air humidity are not to be excluded. In general, a drying of the supply air should be planned in the operational concept of the ventilating system. Furthermore the limiting conditions of the simulation model do not yet consider the moisture absorption and loss of humidity by walls as an adjusting element in the humidity balance of the interior climate.

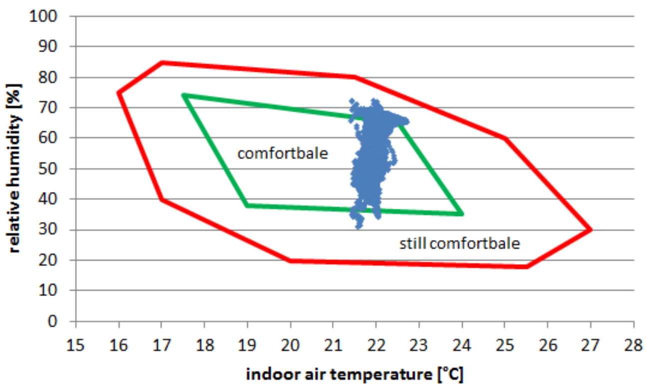

Figure 5-3: Relative air humidity in the interior (Simulation) in dependence of the room air temperature

6 Coverage of cooling energy demand by photovoltaic power generation

The dynamic simulations of the Passivhaus-Villa and the reference building as well as the PV-installation has shown that the coverage of the cooling energy demand of both buildings is possible through the photovoltaic electric power generation, also the including internal heat sources (persons, electrical devices, artificial lighting). Looking at the annual need of electric energy for the cooling and/or cold generation system of the Passivhaus with 5,000 kWh_{el}/a and the reference building with 18,500 kWh_{el}/a without consideration of internal heat sources and comparing it with the annual electric power generation of the photovoltaic installation with 60,000 kWh_{el}/a reveals a surplus of 36,500 kWh_{el}/a in the yearly energy balance, but without further consideration of the general power consumption. The representation of the monthly sums of the electric power need for the building cooling as well as the PV electric power production in Figure 6-1 illustrates the advantage of the Passivhaus with the possibility of the synchronization of the energy demand for the cold production with the electric power generation from the PV installation. This would also lead to a reduction of peak loads in the electricity grid.

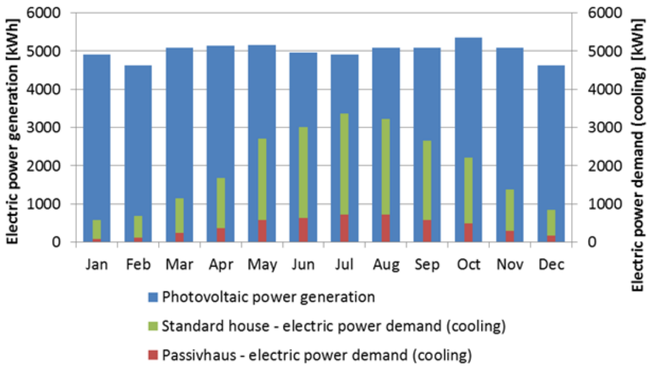

Figure 6-1: Monthly sums of the electric power requirement for the building cooling system as well as the photovoltaic electric power generation

7 Summary

Building up on the presented results the summarizing assessment can be made that the Passivhaus concept has a high energy saving potential for the use in the hot and humid climate of the Arabian Peninsula. Compared to the conventional standard construction the building cooling energy demand can be reduced significantly. This does not only create a high user comfort for the building due to the favorable interior temperatures, but also reduces the use of fossil energies considerably.

For the existing Passivhaus-Villa of the Qatar Green Building Council a further small energy saving potential through performance optimization of the ventilation system (air-conditioning) and without the necessity of additional investments could be proven by the use of the dynamic building and equipment simulation. However, it is to be recommended, to examine the building energetically in an inhabited state during the following utilization period.