# Energy, Comfort and Cost Optimization of a Net-Zero Energy Building in Berlin

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## ABSTRACT

The planning and construction of highly energy-efficient buildings is one of the most ambitious challenges of the building industry worldwide. Especially in Europe the topic of Nearly Zero-Energy-Buildings is very present because of the legal requirements of the European Parliament on buildings. All relevant stakeholders, scientists as well as practitioners, are looking for successful strategies to achieve that goal.

In 2010 the planning phase for the first Net-Zero-Energy-Building of the German Federal Government started. The building should cover its total final-energy demand by the use of renewable energies solely. At the same time the building should have the highest standard of sustainability regarding to the assessment system used for buildings of the Federal Government (BNB). The building went in operation in 2013 and since than the building operation has been monitored.

First experiences and results of the monitoring of the energy performance, the thermal comfort and assorted aspects of the sustainability will be presented and general recommendations for improvements of details and processes are given. Furthermore a strategy for the optimization of the performance, energy and comfort as well as costs, will be introduced. Therefore a building model was created and calibrated on basis of the measured data. By varying different parameters like energetic quality and changes in the sizes of different building parts or the inclusion of new devices in the energy supply concept the influences on the total building costs but also on the energy and comfort balance were investigated in dynamic simulations.

***Keywords:*** *high-performance building, building energy simulation, energy measurement and verification*

## 1. INTRODUCTION

In the framework of the last European Directives concerning the energy performance of buildings, all EU Member States enacted legislations in matter of a low-carbon future of the building sector with increasingly stringent prescriptions for the next years. Following the 2010/31/EC Directive, public administrations and Institutions have to play a leading role in the field of energy efficiency in the building sector. The Directive concern both new and existing buildings. One of the most relevant aspects is the target of “nearly zero-energy buildings”. Member States in particular are requested to guarantee high quality buildings with a minimized energy demand and mainly using renewable energies according to the following time schedule (Article 9 of the 2010/31/EC Directive):

- For new buildings owned and or occupied by public administration and authorities, the nearly zero-energy standard is requested from January 2019;
- Starting from January 2021, all new buildings shall fulfill the nearly zero-energy standard.

In 2010 the planning phase for the first Net-Zero-Energy-Building of the German Federal Government started. The building is located in Berlin and used as office building for approximately 30 persons. Destined for the German Federal Environment Agency (UBA) and aspiring the fulfillment of the EU-requirements of 2019 the building is called UBA 2019. The building concept was oriented toward the Gold-standard of the Assessment System for Sustainable Building (BNB; www.nachhaltigesbauen.de), the rating tool for sustainable buildings of the German Federal Government (Federal Buildings).

The difference between “nearly” and “net” zero energy buildings (nearly ZEB and net ZEB) is the share of renewable energies which is used to cover the energy demand of the building. While in a nearly ZEB the energy demand is covered predominantly by renewable energies that share is 100 % in a net ZEB during a certain time period (mostly one year).

## 2. PRESENTING THE BUILDING CASE STUDY

The building UBA 2019 has a compact square shape (Figure 1). The gross dimensions - width and length - are 25 m, even if the east-west façade has a longer aspect, due to the anterior porch on the south and north exposure. Most offices are for single persons. The building has three meeting rooms; two of them can be connected. Other spaces are used for services (as kitchen and toilettes), technical rooms and common areas. In Figure 2 ground and first floor are shown.

*Figure 1: UBA 2019; view from south (left), view from west (right)*

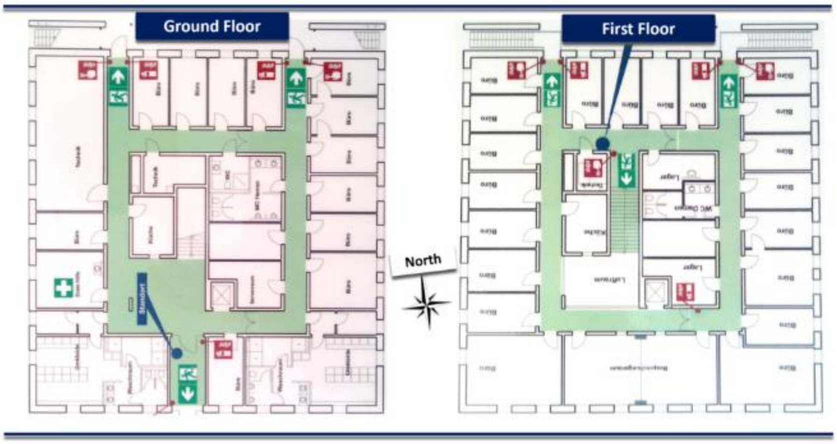


*Figure 2: Schemes of ground floor (left) and first floor (right)*

In order to reduce the energy need for heating (e.g., cooling demand can be covered almost without energy costs by using groundwater and natural ventilation), the envelope structures were strongly thermally insulated by thick layers of cellulose fiber. The structure of the thermal envelope is the following:

- External wall: The overall thickness is 0.46 m (inclusive of 36 cm of cellulose insulation). On the inner side, there is an OSB plane with a coating of drywall. Externally an air permeable wooden fiberboard is installed. The thermal transmittance (U-value) is 0.12 W/m$^2$K.
- Flat roof: The overall thickness is 0.96 m, with 53 cm of cellulose fiber insulation. The structural elements are wooden box beams, with a thickness of 28 cm. On the outer side, there are 10 cm of mixed sand, gravel, chippings, covered with extensive sedum vegetation. Other intermediate layers are two OSB boards, a vapor barrier on the inner side, a waterproofing layer on the external side. The thermal transmittance is around 0.05 W/m$^2$K.
- Floor on the ground: Wooden box beams are insulated with 16 cm of poly-urethane and 12 cm of foam glass. On the inner side, a light concrete layer of 6 cm is covered with the parquet floor. The thermal transmittance is 0.09 W/m$^2$K, with a total thickness of 0.71 m.
- Windows and skylights: Are triple-glazed systems, with certified overall U-values respectively equal to 0.70 and 0.86 W/m$^2$K. The windows are equipped with shading systems (horizontal slats). The shadings are

located externally to the third glass. A fourth pane is installed in the frame as protection of the shading device. This pane can be opened separately.

Already after finishing the air-tight sealing a first blower door test was performed in order to guarantee a certain quality of the construction. After completion the building air-tightness was measured by a second test. The testing involved a series of under-pressure and over-pressure measurements. The measured rates of air change per hour (ACH), at a differential pressure of 50 Pa (i.e., n50), ranged between 0.30 h-1 and 0.35 h-1. The calculated average value is 0.33 h-1.

For heating and cooling the offices built in capillary tube systems and handled ventilation air are installed. For heating, the capillary tubes are embedded in the inside of the external walls. The water for the wall integrated heating system as well as for the heating coil of the ventilation system is heated by a water-to-water geothermal heat pump. Conversely, the capillary tubes for cooling are embedded in the partition walls. No chiller is required. Only for pumping the ground water electric energy is needed. The temperature of the ground water is directly used for cooling the building by passing a water-to-water heat exchanger. In each office a dew point sensor prevents condensation by stopping the cooling system. The cool ground water also is used for cooling in the air supply system.

The mechanical ventilation system - designed for achieving the comfort Category II according to the Standard EN 15251 in each room - is equipped with a sensible flat plate heat recovery system.

Beyond the use of ground water for cooling and heating the building is equipped with a solar thermal energy system, with an overall solar collector area of 11 $m^2$ and two 970 l thermal heat storage tanks. The inclination angle of the solar thermal collectors is 37°, with a slight deviation, around 8°, from the south exposure. Furthermore a large photovoltaic system is installed on the building roof. In order to reduce the system visibility a tilt angle lower than 10° was chosen. The total installed capacity is approx. 66 kWp. The designed specific yield is 790 $kWh_{ELECTRIC}$/(kWp*a). Compared to the calculated annual demand of electricity for all processes in the building in the amount of approx. 46,000 kWh/a it means a surplus in generation of electricity of approx. 10 %.

The building cost around 4.2 million Euro (net), including all building categories identified by the German standards DIN 276 and DIN 277 . The specific price per gross floor area is about 3,325 €/$m^2$.

Looking solely on the costs of architectural works and indoor technical equipment, the specific price is about 2,350 €/$m^2$. An average value for Germany, with reference to highly equipped office buildings, is around 1,730 €/$m^2$. Compared to that, the costs of UBA 2019 are 36 % higher. Regarding that point it should be noted that the building meets extraordinary requirements in matter of energy, accessibility, and sustainability.

## 3. RESULTS OF THE MONITORING

UBA 2019 is equipped with a full monitoring apparatus, thus continuous metering of all energy flows is possible. In detail, there are 83 electric meters, 26 heat counters, 4 meters for cold and hot water installed. Moreover, an outdoor weather station measures the outside air temperature and relative humidity, wind direction, wind speed, global solar radiation, $CO_2$ concentration, illuminance. To get information about the indoor climate a fixed and a mobile measurement system are used. In particular, the indoor air temperature is measured in each room and, for four representative spaces, further 18-27 sensors are installed for measurements concerning the thermal comfort, the indoor air quality ($CO_2$ concentration), peoples presence, illuminance and lighting level, status of use (e.g., window contacts, use of shading devices). The mobile system - that can be installed for some days in any place in the building - measures the thermal comfort by means of 8 sensors as well as the presence of persons.

Figure 3 is showing a comparison between expected data from the planning phase and the monitored data in the first 3 years of operation of UBA 2019. In all years of operation the electricity generation by PV-system is higher than the consumption of electricity. That means that the aim of a net ZEB is achieved. The installed PV-system is more efficient than planned and the solar irradiation was higher compared to a standard year. In detail one can see that the energy demand for each single process is different from the expected one. The reasons for that are mainly the reduced occupancy of the building and the existing potential for optimizations. The decrease in generation in the 2nd year of operation was caused by an accidental shutdown of the PV-system.

The monitoring of the indoor microclimate showed that the building achieved the highest categories in terms of operative temperature and air velocity regarding Standard DIN EN ISO 7730:2006 . For relative humidity the results differ. In summertime the highest category is met but in wintertime the air is too dry. Interviews with users confirm these results. Furthermore the answers gave indications for further optimization. As example malfunctions of the heating and cooling devices in some offices could be detected.

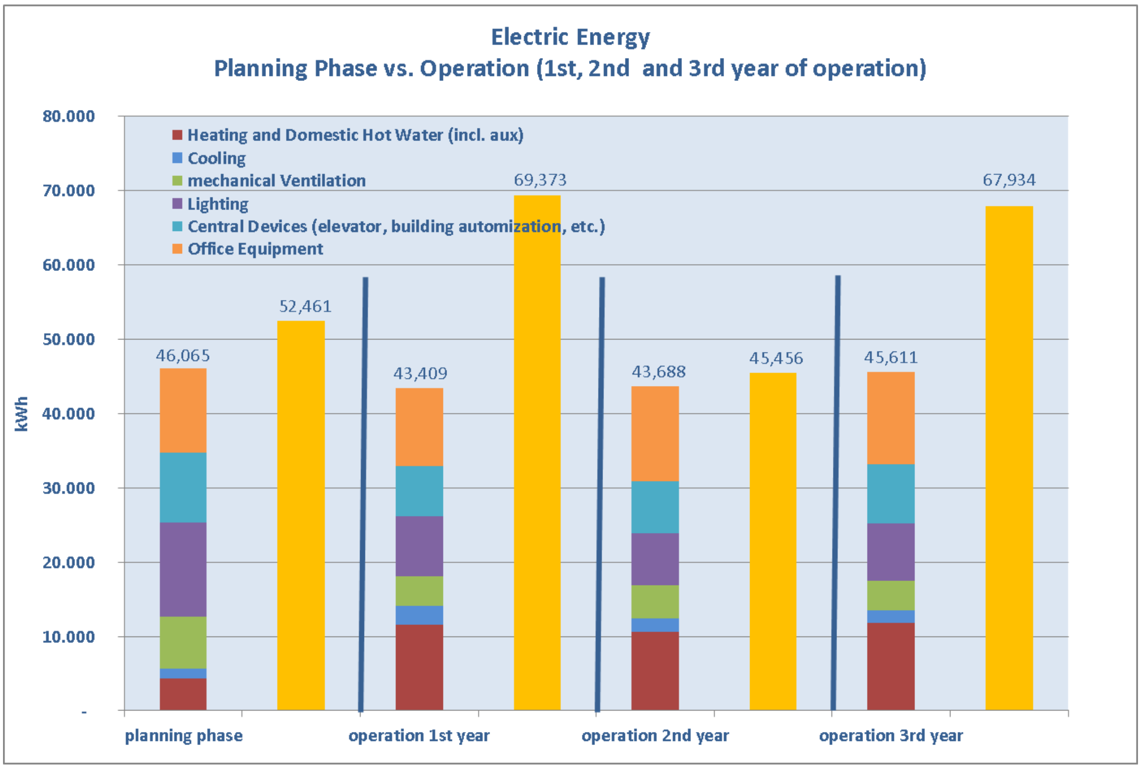


*Figure 3: Results of the monitoring UBA 2019 – Planning phase vs. operation*

## 4. EVALUATION OF THE BUILDING MODEL

Transient energy simulation, when validated based on proper calibration with monitored data is a powerful tool to understand gaps between design and operation, inefficiencies of building systems as well as to test potential energy efficiency measures aimed at improving building performance. Methods and protocols for calibrating energy models were developed by FEMP and ASHRAE [6,7 and 8] and these are applied in the investigations.

The building geometry and the general boundary conditions of the several functions of the building were implemented with DesignBuilder 3.2.0 [9]. EnergyPlus 7.2.0 [10] was used for numerical calculation and here also the materials and constructions for reproducing the real thermal-physical properties of the building envelope, such as provided by the design documentation (i.e., layers orders, materials' thermal conductivity, density, specific heat, etc.) have been defined. In the Appendix some key parameters affecting the energy simulation as the climate boundary conditions and other relevant data are reported there (Tables 1 and 2).

The relative differences between designed and simulated annual energy performance for each process based on hourly energy balances show a span between -1.2 % and 1.9 % (see Table 3).

Nevertheless, the differences between monitored energy usage and expected values from the planning phase suggested the definition of a new building model, calibrated on the present building operating conditions and patterns of use, in order to verify reasons and causes of differences in energy performance.

In order to verify a suitable calibration of the model, statistical indexes, as proposed by the M&V Guidelines "Measurement and Verification for Federal Energy Projects" [7] of the U.S. Department of Energy have been calculated. In our study the option D, suitable for the comparison of measurements of energy meters and output of numerical simulations, has been used. To understand deeply the reliability of our investigation, the indexes have been calculated not merely for the whole facility, but also with reference to every system (heating, cooling, ventilation, auxiliaries, lighting).

In particular, the followings indexes have been calculated:

- Mean bias error (MBE): It allows to estimate the fit between the simulation and the measured data. Positive values testify an overestimation of the numerical model. Conversely, negative values reveal an underestimation.
- Coefficient of variation of the root mean square error (CV(RMSE)): The overall uncertainty of the prediction, and this refers to the whole energy usage of a building. The value of CV(RMSE) is always positive.

According to [6] and [7] the following values for MBE and CV(RMSE) are acceptable, when a month is the reference calculation period over the whole time horizon investigated:

- $MBE_{month}$ (%) ≤ ± 5%,
- $CV(RMSE_{month})$ (%) ≤ + 15%.

The $MBE_{month}$ for the single processes in the building is in a span between -1.16 % and 1.95 %. The $CV(RMSE_{month})$ for the overall energy use is equal to 7.96 %. Thereby the calibration of the building model is completely satisfactory.

## 5. BATTERY STUDY

The building has an overproduction and at the same time a mismatch between electrical energy demand and generation The economically most appropriate use of on-site produced electricity is on-site consumption. Therefore, a further investigation looked at the optimization of an electric storage system under both technical and economic points of view. Presently, the on-site energy yield is about 69,000 $kWh_{ELECTRIC}$ a year, and thus the target of net zero energy building (i.e., the energy balances consider the energy flux on the basis of one year of observation period) is achieved. At the moment the grid on the property is used for supplying into the grid the surplus electricity and for getting electricity if demand is higher than production. Presently, the building uses only 27 % of the on-site generated electricity while the bigger part of the total electricity need is covered by the grid.

The energy demand for the microclimatic control in summer - the peak time of energy generation - is very low (only auxiliary devices are needed no use of chillers, low use of lighting because of the diurnal high radiation). Based on these considerations, an Electrical Energy Storage (EES) has been designed by optimizing energy capacity, discharge rate, and the costs (taking into account the feed-in tariff, the price of purchased energy, investment - 1.000 €/kW and 1.500 €/kWh - and maintenance of the battery system). The aim was to find the lowest costs of the stored kWh of electric energy while maximizing the on-site use of the PV-generated electricity.

With costs of the stored kWh similar to the price of the one bought from the supplier a battery system with a capacity of 10 kWh and a discharge power of 39 kW can rise the on-site-use up to 42 %. The costs per stored kWh can be decreased to 0.21 €/kWh if the maximum discharge power is limited to 16 kW. In this case the on-site-use is slightly reduced to 38 %. This system is characterized by the optimal performance in terms of technical and economic constraints.

## 6. COST STUDY

The present surplus of electricity and the very high insulation of the building indicates that there are alternative configurations with reduced investment costs and/ or reduced lifecycle costs. Therefore a further study was carried out on alternative solutions for the building energy concept. The aim of that study was to find ways for a reduction of the building costs (investment cost as well as lifecycle costs) while the existing qualities in terms of energy performance, sustainability (BNB Gold level) and indoor comfort are maintained. Only the level of natural lighting could be increased because the windows of the building only take approx. 16% of the surface of the external walls. Also in this case, the calibrated building energy model has been used.

Several assorted measures and packages of these measures have been taken into account. They consist of widening of window areas from 16 % to 24 % of the external wall surface, reducing the thickness of insulation of external walls, roof and bottom slab. Moreover, two different types of thermal glazing for windows (double and triple glazed) and a change in the control of the shading system have been investigated. The feasibility study has been performed according to the cost optimal methodology. For each package the global costs of the re-designed building were calculated and compared with the base case to find the package that represents the optimal level between costs, consumption and generation.

From all of the investigated measures and packages in the study the optimal one consists of changes in the size of the windows, change of insulation (i.e. 20 cm of mineral wool for both roof and external wall insulation, double glazed windows and reduced thickness of polyurethane for the bottom slab) and a different shading control system. In the simulation the measures are leading to a negligible lower annual primary energy consumption of 1.4 %. At the same time the global costs in the lifecycle for the certain measures decreased by approx. 46,000 €. In relation to the base case it means a reduction of the global costs of approx. 11 %. Regarding the total costs of the project (investment costs), the investigated improvements would led to a reduction of less than 2 %.

## 7. CONCLUSIONS

After a 4-year-phase of planning and construction the first Net-Zero-Energy-Building of the German Federal Government went in operation in 2013. The sustainability of the building was certified regarding to the Assessment System for Sustainable Building for Federal Buildings (BNB). It achieved the highest degree of performance and therefore it obtained a certificate in gold.

The monitoring of energy usage, sustainability, indoor air quality and thermal comfort shows that the ambitious aims of the project were achieved almost totally. In order to access the left potential of optimization, a building model was developed and evaluated besides onsite measurements and user surveys. The model is used for investigations of different operation strategies or the installation of additional equipment. Furthermore it is an instrument for investigations regarding the cost-optimality of the building and thereby a tool for the development of general conclusions to that topic. First investigations in possible improvements of the building envelope were already carried out. A second study identified optimal design values for electric battery storage to improve the share of self-used electricity generated by the PV-system. The next step will be the implementation and monitoring of this device.

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## APPENDIX

| MAIN BUILDINGS DIMENSIONS | | | |
|---|---|---|---|
| Gross Length (N-S direction) | 25.12 m | Gross Floor Area | 1178 $m^2$ |
| Gross Length (N-S direction) | 25.12 m | Gross Volume | 3862 $m^3$ |
| Gross Length + Porch + Stairs | 30.40 m | Roof Area | 599 $m^2$ |
| Gross Height | 7.2 m (2 floors) | Surface to Volume Ratio | 0.48 $m^{-1}$ |

| BUILDING GEOMETERY | | | | | |
|---|---|---|---|---|---|
| | TOTAL | North (315 to 45 deg) | East (45 to 135 deg) | South (135 to 225 deg) | West (225 to 315 deg) |
| Gross Wall Area [$m^2$] | 656.1 | 162.0 | 164.9 | 164.2 | 164.9 |
| Window Area [$m^2$] | 106.4 | 18.8 | 31.8 | 29.1 | 26.6 |
| Window Wall Ratio [%] | 16.2 | 11.5 | 19.3 | 17.8 | 16.1 |

| INFORMATION ABOUT SITES, CLIMATES, INDOOR USES AND ENDOGENOUS GAINS | | | |
|---|---|---|---|
| Weather data | ASHRAE Berlin IWEC → EPW | Number of zones | 58 Thermal zones |
| Set point during the heating time:<br>Offices<br>Common spaces<br>Technical rooms | <br>22 °C (Off between 19.00 - 08.00)<br>22 °C (Off between 19.00 - 08.00)<br>15 °C (Off between 19.00 - 08.00) | The set point of temperature for cooling is variable according to the trend of ambient temperature, ranging from 22 °C during the cold season, to 26 °C during the full summer. In the hottest summer days, it is 6 K lower than the outdoor temperature. | |

| BUILDING ENVELOPE | | | |
|---|---|---|---|
| $U_{WALL}$ (weighted average method) | 0.12 W $m^{-2}K^{-1}$ | $U_{WINDOWS}$ | 0.70 W $m^{-2}K^{-1}$ |
| $U_{ROOF}$ and $U_{FLOOR\ ON\ THE\ GROUND}$ | 0.05 W $m^{-2}K^{-1}$ 0.09 W $m^{-2}K^{-1}$ | $U_{SKYLIGHTS}$ | 0.86 W $m^{-2}K^{-1}$ |
| $U_{PARTION\ (OFFICE-OFFICE)}$ | 0.66 W $m^{-2}K^{-1}$ | $U_{PARTION\ (OFFICE-WET\ ROOMS)}$ | 0.26 W $m^{-2}K^{-1}$ |
| Shading systems | External venetian Blinds | Infiltration plus natural ventilation (Design) | 0.3 ACH |

| HVAC SYSTEM | | | |
|---|---|---|---|
| In room heating and cooling terminals | Separated capillary radiant systems embedded in the external envelope (heating) and in the partitions (cooling). | Ventilation | Mechanical ventilation with heating/cooling control and heat recovery from the exhaust air. Demand controlled ventilation for the meeting rooms. |
| Ventilation air flow | Design Value: 3600 $m^3$/h. | Heat Exchanger | Flat Plate, Air-to-Air, Sensible Heat |
| Fans Head | 1002 Pa (supply), 523 Pa (Return) | $\eta_{sensible}$ = 75% | |
| Geothermal Heat Pump<br>- Nominal Capacity<br>- COP and SCOP | Water-to-water Heat Pump<br>27 $kW_{THERMAL}$<br>5.0 $W_{TH}/W_E$ and 3.9 $W_{TH}/W_E$ | Cooling Generation | Passive, by means of heat exchange with the ground water (i.e., no active cooling by means of electric chillers) |

| PHOTOVOLTAIC SYSTEM (AS DESIGNED) | | | |
|---|---|---|---|
| PV Panels (66.3 kWp) | Crystalline Silicon, | Generator Efficiency | 14.5% |
| PV Panels efficiency | ≈ 17.5% | Design specific generation | 790 $kWh_{ELEC}$/kWp |
| 12 Arrays Gross Area | 391 $m^2$ | Total Designed electric generation | 52,461 $kWh_{ELEC}$ |
| Azimuth and Tilt angles | 8° and 10° | System Global Efficiency | 13.4% |

| THERMAL SOLAR SYSTEM | | | |
|---|---|---|---|
| Gross area of Solar Collectors (Glazed, Flat Plate) | 11 $m^2$ | Thermal Storages | Sequential storage, each one |
| Azimuth and Tilt angles | 8° and 37° | | with a volume of 970 liters |

| ENERGY COST, CONVERSION FACTORS AND EMISSIONS | | | |
|---|---|---|---|
| Electricity cost | 0.292 €/kWh | Electricity GHG emission factor [45] | 0.706 t $CO_2$ / MWh |

*Table 1: Building characteristics, HVAC system descriptions, renewable systems, boundary conditions and energy related parameters*

| Weather Data (i.e., Reference Year) | |
|---|---|
| Weather Data | ASHRAE Berlin IWEC {GMT +1.0 Hours} |
| Heating Degrees-Day | 3284 Kd annual (standard) (18.3°C baseline)<br>(Official German Value for Berlin Tempelhof, G20/15: 3134) |
| Cooling Degrees-Day | 147 Kd annual (standard) (18.3°C baseline) |
| Latitude and Longitude | {52° 28' North} { 13° 23' East} |
| **Simulation Parameter** | |
| Surface Convection Algorithm Inside | TARP – Variable Natural Convection Based on Temperature Difference |
| Surface Convection Algorithm Outside | DOE-2 – Correlation from measurements for rough surfaces |
| Heat Balance Algorithm | Conduction Transfer Function, 4 time-steps/hour |
| Minimum System Timestep: 1 | Maximum HVAC iterations: 20 |
| Winter Design Day | Outdoor Maximum Dry Bulb Temperature = -13.9 °C (Wet Bulb = - 13.9 °C), No solar radiation, Sky Clearness = 0, Barometric Pressure 100776.7 Pa, Wind Speed 14.1 m/s, Daily Dry-bulb Temp Range = 0°C |
| Summer Day in Winter | Outdoor Dry Bulb Temperature = 34.0 °C (Wet Bulb = 29.1 °C), Solar radiation from weather file, Sky Clearness = 0.98, Barometric Pressure 100776.7 Pa, Wind Speed 0 m/s, Daily Dry-bulb Temp Range = 13.4°C |

*Table 2: Climate boundary conditions*

| | Designed Building | Simulated Building | % GAP |
|---|---|---|---|
| Electric Energy for the space Heating (kWh/m²a) | 2.31 | 2.28 | - 1.2 |
| Electric Energy for Fans (kWh/m²a) | 5.93 | 6.04 | 1.9 |
| Electric Energy for Pumps (kWh/m²a) | 9.14 | 9.03 | - 1.2 |
| Electric Energy for Artificial Lighting (kWh/m²a) | 10.75 | 10.83 | 0.7 |
| Electric Energy for Office equipment (kWh/m²a) | 9.57 | 9.47 | -1.0 |
| Specific Electric Energy for the building use (no DHW) (kWh/m²a) | 37.7 | 37.65 | - 0.1 |
| Total Electric Energy for the building use (no DHW) (kWh) | 44’411 | 44’352 | - 0.1 |

*Table 3: Comparison between the energy demands of the designed building and simulated performance by means of EnergyPlus 7.2.0*