

## AN OPTIMIZATION PROCEDURE BASED ON THERMAL DISCOMFORT MINIMIZATION TO SUPPORT THE DESIGN OF COMFORTABLE NET ZERO ENERGY BUILDINGS

Salvatore Carlucci<sup>1</sup>, and Lorenzo Pagliano<sup>1</sup>

<sup>1</sup> end-use Efficiency Research Group, Energy Department, Politecnico di Milano, Milan, Italy

### ABSTRACT

The European standard EN 15251 specifies design criteria for dimensioning of building systems. In detail, it proposes that the adaptive comfort model is used, at first, for dimensioning passive means; but, if indoor operative temperature does not meet the chosen long-term adaptive comfort criterion in the “cooling season”, the design would include a mechanical cooling system. In this case, the reference design criteria are provided accordingly the Fanger comfort model. However, there is a discontinuity by switching from the adaptive to the Fanger model, since the best building variant, according to the former, may not coincide with the optimal according to the latter.

In this paper, an optimization procedure to support the design of a comfort-optimized net zero energy building is proposed. It uses an optimization engine (GenOpt) for driving a dynamic simulation engine (EnergyPlus) towards those building variants that minimize, at first, two seasonal long-term discomfort indices based on an adaptive model; and if indoor conditions do not meet the adaptive comfort limits or analyst’s expectations, it minimizes two seasonal long-term discomfort indices based on the Fanger model. The calculation of such indices has been introduced in EnergyPlus *via* the Energy Management System module, by writing computer codes in the EnergyPlus Reference Language.

The used long-term discomfort indices proved to provide similar ranking capabilities of building variants, even if they are based on different comfort models, and the proposed procedure meets the two-step procedure suggested by EN 15251 without generating significant discontinuities.

### INTRODUCTION

One of the recognized strategies towards green buildings is the reduction of energy required during their operational life. In current buildings (both residential and commercial), space conditioning constitutes a predominant portion of their primary energy demand, both in EU and USA (Carlucci et al., 2013a; Perez-Lombard et al., 2008). In May 2010, European Union recast the Directive 2010/31/EU on the energy performance of buildings, which states that the new buildings occupied and owned by public

authorities and all new buildings shall be nearly zero energy buildings respectively after 31/12/2018 and after 31/12/2020 (European Parliament and Council, 2010). One rational and promising path toward net zero energy buildings (NZEB), starts with optimizing the building envelope and passive technologies in free-floating mode with respect to an adaptive comfort model. In parallel, efficient lighting and electrical appliances have to be selected. In case the adaptive thermal comfort requirements cannot be met, efficient HVAC systems are introduced in the energy concept of the building and thermal comfort conditions have to be verified against the Fanger model. Finally, the overall energy required by the building (delivered or primary energy according to a specified NZEB definition) has to be covered by on-site energy production from renewable energy sources, over a chosen time period for the balance (often one year, but other choices are possible, and performing the balance with a time step of a day, an hour or less, ensures the possibility to check how much energy is taken from the grid due to non-coincidence between generation and load, which implies in reality the use of conventional sources) (Carlucci et al., 2013c). This path is also suggested by the European standard EN 15251 (CEN, 2007).

The idea at the base of the integrated energy design procedure presented in this paper is to focus on the problem space consisting of a large number of available building variants concerning the building envelope and the passive strategies, and to search for the one(s) which minimize(s) two objective functions (or a combination of them) representing winter and summer thermal discomfort. This procedure can be executed both in case the building is in free-floating mode or it is mechanically conditioned.

A number of researchers have optimized buildings using several discomfort metrics, and most of them referred exclusively to the Fanger comfort model (Fanger, 1970) that introduced two indices: the *Predicted mean vote (PMV)* and the *Predicted Percentage of dissatisfied (PPD)*. Wang and Jin (Wang and Jin, 2000) use a sum weighted method to scalarize a multi-objective optimization problem where one of the terms chosen is thermal discomfort defined as the square of the hourly-simulated *PMV*. Kolokotsa et al. (Kolokotsa et al., 2002) and Mossoly et al. (Mossoly et al., 2009) instead use the

square of the difference between a reference *PMV*-value chosen by the user and the hourly simulated *PMV*. Nassif et al. (Nassif et al., 2004), Nassif et al. (Nassif et al., 2005) and Kummert and André (Kummert and André, 2005) minimize hourly simulated *PPD* to optimize an HVAC control strategy. Magnier and Haghighat (Magnier and Haghighat, 2010) build a utility function by multiplying the average *PMV* over the whole year and over all occupied zones for a function proportional to the number of hours when the absolute value of *PMV* is higher than 0.5. Corbin et al. (Corbin et al., 2012) use as objective function the deviation of actual *PMV* with respect to neutrality ( $PMV = 0$ ), weighted with the floor area of every zone of the building. Hoes et al. (Hoes et al., 2009) minimize summer overheating and winter underheating hours in order to ensure a minimal thermal comfort level defined as a constraint on the maximum number of discomfort hours fixed at 200 hours. Angelotti et al. (Angelotti et al., 2004) use a long-term index based on *PMV* to optimize the design of ground exchangers and night ventilation strategies. More recently, the standards make available to the designer also the adaptive comfort model for use in naturally ventilated buildings (ANSI/ASHRAE, 2004; CEN, 2007). Stephan et al. (Stephan et al., 2011) used *Percentage outside range* and *Degree-hour criterion* to optimize openings for night natural ventilation to activate the thermal mass and so reduce thermal discomfort. Carlucci and Pagliano (Carlucci and Pagliano, 2012) present a detailed review of a number of long-term discomfort indices proposed in the scientific literature and standards.

## METHODOLOGY

In physical terms, the aforementioned procedure towards NZEBs consists in designing the building envelope for achieving thermal comfort by using primarily passive strategies, so that, if a next step including mechanical cooling is required, efficient HVAC systems shall only deliver a limited amount of energy to provide the required thermal comfort conditions. At the same time, efficient lighting and electrical appliances have to be selected to reduce the electricity demand of the building. Then, the overall energy required by the building has to be covered by renewable energy preferably produced on-site.

To set up this procedure, a reliable method for the assessment of thermal discomfort in a building has to be established. It shall be available for both the adaptive models (de Dear and Brager, 1998; Nicol and Humphreys, 2002) and the Fanger model (Fanger, 1970), and it should allow a similar ranking of building variants according to such three comfort models. To this aim, the *Long-term Percentage of Dissatisfied* is used; it is a long-term discomfort index specifically designed in three versions to cope with such three comfort models (Carlucci, 2013). The

proposed two-step procedure optimizes the building, first, in free-floating mode against the requirements of a chosen adaptive model (it is called *Free-floating scenario*), then (and if required) in mechanically conditioned mode against the requirements of the Fanger model (it is called *Conditioned scenario*) (Carlucci et al., 2013b).

In practice, the proposed optimization procedure couples an optimization engine (GenOpt) and a dynamic simulation engine (EnergyPlus). A comprehensive review about optimization techniques and tools coupled to building performance software tools is presented in (Attia et al., 2013).

## Thermal comfort assessment in buildings

A number of authors used disparate indices or metrics to estimate thermal discomfort. Such methods, often, calculate the percentage of hours when uncomfortable conditions are recorded, or cumulate the number of degree of exceedance of a given thermal comfort temperature (Carlucci and Pagliano, 2012). Thus, they do not accurately reflect the predicted thermal response of a typical individual based on a subjacent comfort theory, rather they are *ad hoc* analytical constructions that give a very rough account of how far from comfort the situation is. In order to overcome this limit, the proposed optimization procedure uses the *Long-term Percentage of Dissatisfied (LPD)* (Carlucci, 2013), which quantifies predicted long-term thermal discomfort by a weighted average of discomfort over the thermal zones of a given building and over time of a given calculation period

$$LPD(LD) \equiv \frac{\sum_{t=1}^T \sum_{z=1}^Z (p_{z,t} \cdot LD_{z,t} \cdot h_t)}{\sum_{t=1}^T \sum_{z=1}^Z (p_{z,t} \cdot h_t)} \quad (1)$$

where  $t$  is the counter for the time step of the calculation period,  $T$  is the last progressive time step of the calculation period,  $z$  is the counter for the zones of a building,  $Z$  is the total number of the zones,  $p_{z,t}$  is the zone occupation rate at a certain time step,  $LD_{z,t}$  is the *Likelihood of Dissatisfied* inside a certain zone at a certain time step and  $h_t$  is the duration of a calculation time step (e.g., one hour).

The *Likelihood of Dissatisfied*,  $LD$ , is an analytical function that estimates “*the severity of the deviations from a theoretical thermal comfort objective, given certain outdoor and indoor conditions at specified time and space location*” (Carlucci, 2013). Since the theoretical thermal comfort objective depends on the reference comfort model, the equation used in combination with the EN adaptive model is the so-called *Overheating Risk* (Nicol et al., 2009)

$$LD_{Adaptive}^{EN} = \frac{e^{0.4734 \cdot \Delta\theta_{op} - 2.607}}{1 + e^{0.4734 \cdot \Delta\theta_{op} - 2.607}} \quad (2)$$

where  $\Delta\theta_{op}$  is the absolute value of the difference between the indoor operative temperature and the

optimal comfort temperature calculated accordingly to the European adaptive model.

The equation used in combination with the ASHRAE adaptive model is the so-called *ASHRAE Likelihood of Dissatisfied (ALD)* (Carlucci, 2013)

$$LD_{Adaptive}^{ASHRAE} = ALD = \frac{e^{0.008 \cdot \Delta\theta_{op}^2 + 0.406 \cdot \Delta\theta_{op} - 3.050}}{1 + e^{0.008 \cdot \Delta\theta_{op}^2 + 0.406 \cdot \Delta\theta_{op} - 3.050}} \quad (3)$$

where  $\Delta\theta_{op}$  is the absolute value of the difference between the indoor operative temperature and the optimal comfort temperature calculated accordingly to the ASHRAE adaptive model. It is a continuous function obtained by the authors *via* the statistical analysis of the comfort surveys in the ASHRAE RP-884 database (de Dear, 1998), and it overcomes the main problems arising when using the simplified and rough functions cited above.

On the other hand, the analytical model used for the Fanger model is *PPD*, which is directly computable from *PMV*, using the equation (Fanger, 1970)

$$LD_{Fanger} = PPD = 100 - 95^{-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2} \quad (4)$$

The *LPD* is calculated for both summer and winter, and it is used for optimizing the building in free-floating mode and in mechanically conditioned mode. According to (Carlucci, 2013) the *LPD* in the ASHRAE adaptive version and in the Fanger version have a similar ranking capability of indoor thermal discomfort. Therefore, such two versions of the *LPD* are used to construct the objective functions needed for the proposed two-step optimization procedure.

### Approach for solving multi-objective optimization

Usually, in multi-objective optimization problems, a single solution is not able to simultaneously minimize all objective functions; and a goal of a multi-objective optimization problem may consist in finding those variants that are better than others with regards to, at least, one objective function and, at the same time, not worse concerning all remaining objective functions. Such variants are called *non-dominated variants* and belong to the so-called *Pareto front*. The goal of this paper is not to identify the set of the non-dominated variants (the Pareto-front) for the presented case study, but rather to set an optimization procedure and test it on the case study to support the designer to identify at least one reliable comfortable NZEB (among others available). Thus, the bi-objective optimization problem is solved recurring to a *scalarization* technique that provides only one optimal solution for every optimization run. Scalarization implies to combine all objective functions according to a given *utility function*; the single objective functions can be also weighed through weighting factors. To scalarize the two objective functions, it is assumed to prefer those building variants that minimize their distance from

the *utopia point* (where the two functions to be minimized take both the value zero), therefore the adopted utility function,  $f_U$ , is the *weighted exponential sum method* (Marler and Arora, 2004)

$$f_U = \sum_{i=1}^n w_i [F_i(\mathbf{k})]^p : F_i(\mathbf{k}) > 0 \quad \forall i \quad (5)$$

where  $w_i$  are the weighting factors of each objective function, such that each  $w_i > 0$ ,  $\mathbf{k}$  is the vector of the values of the design parameters, and  $F_i(\mathbf{k})$  are the values assumed by the objective functions. For this optimization problem, there is not an apparent reason to weigh differently the two objective functions, thus the weighting factors have been set equal to 1. The exponent  $p$  is set equal to 2; hence, the utility function measures the square of the (Euclidean) distance between a certain solution point and the utopia point, so that the shorter the distance, the better the building variant. This optimization approach does not provide a set of optimal solutions belonging to the Pareto frontier, but only one optimal solution. This simplifies the activity of the final user, but the use of the scalar utility function *a priori* forces the result of optimization.

The optimization engine GenOpt (Wetter, 2001), release 3.1.0, is used for minimizing the chosen combination of the two specified seasonal thermal discomfort objectives.

### STATEMENT OF THE OPTIMIZATION PROBLEM

The energy design of a building is a multivariable problem, which can accept different sets of solutions, and the number of design alternatives could be very large and not all them can be simulated in a time span compatible with the design phase of a building.

To explore a very large number of building variants in a relatively short time, the adopted methodology consists (i) in identifying the design parameters to be optimized, (ii) in identifying the options or the range of variation for every design parameter, (iii) in running the dynamic energy simulations of the building in free-floating mode *via* EnergyPlus, (iv) in driving the selection of the design parameters *via* an optimization engine.

### Design variables and options

Since the first optimization step of the two-step procedure deals with the building in free-floating, the design variables are selected among those that only influence the passive means and the passive strategies (Table 1).

Given the number of the design parameters and their alternative options, the total number of the available building variants obtainable by combining the number of alternative options for each design parameter is 17 006 112.

Table 1

Design parameters and options used in optimization

DESIGN PARAMETERS	PHYSICAL QUANTITIES	ALTERNATIVE OPTIONS
External-wall construction	U-value ( $W\ m^{-2}K^{-1}$ )   Phase shift (h)	0.149   14.0 0.147   9.9 0.152   4.6 0.261   12.9 0.254   9.2 0.246   2.9 0.387   12.6 0.387   8.9 0.410   2.2
Roof construction	U-value ( $W\ m^{-2}K^{-1}$ )   Phase shift (h)	0.154   12.3 0.148   8.2 0.147   4.9 0.252   13.1 0.251   9.4 0.248   5.0 0.398   12.3 0.404   9.3 0.381   5.8
Floor construction	U-value ( $W\ m^{-2}K^{-1}$ )   Time shift (h)	0.143   12.8 0.150   9.6 0.152   5.7 0.250   13.1 0.240   9.0 0.246   5.4 0.397   12.9 0.401   9.3 0.401   4.8
Constructions of glazing units on southeast	U-value ( $W\ m^{-2}K^{-1}$ )   g-value (%)	0.586   36 0.582   49 1.099   38 1.065   53 2.667   34 2.667   75
Construction of glazing units on southwest	U-value ( $W\ m^{-2}K^{-1}$ )   g-value (%)	0.586   36 0.582   49 1.099   38 1.065   53 2.667   34 2.667   75
Construction of glazing units on northeast/northwest	U-value ( $W\ m^{-2}K^{-1}$ )   g-value (%)	0.586   36 0.582   49 1.099   38 1.065   53 2.667   34 2.667   75
Construction of glazing units on the central court	U-value ( $W\ m^{-2}K^{-1}$ )   g-value (%)	0.586   36 0.582   49 1.099   38 1.065   53 2.667   34 2.667   75
Control strategies for shading	Set-point quantity and threshold	$T_{air,int} > 25\ ^\circ C$ $T_{air,out} > 25\ ^\circ C$ $I_{g,w} > 100\ W/m^2$
Opening pivoted windows	Percentage of the window area opened (%)	0 100
Opening double-leaf windows	Percentage of the window area opened (%)	0 50 100

## The objective functions

The proposed two-step procedure consists in optimizing the building, first, in free-floating mode against the requirements of an adaptive model (*Free-floating scenario*), then (and if required) in mechanically conditioned mode against the requirements of the Fanger model (*Conditioned scenario*).

Since two comfort models are available for analyzing a building in free-floating mode, two distinct optimization runs have been executed, using the winter and summer *LPD* in the EN and ASHRAE adaptive versions. A third optimization was run using the *LPD* in the Fanger version.

The optimization run that used the *LPD* in the ASHRAE adaptive version identified an optimal variant very similar to that identified after the third optimization using the *LPD* based on the Fanger model. This is in line with what shown in (Carlucci, 2013). Therefore, the *LPD* in the ASHRAE adaptive version is used in the Free-floating scenario.

## Optimization algorithm

The Particle swarm optimization (*PSO*) algorithm was selected due to its robustness and efficiency to converge towards the global minimum (Hopfe, 2009). The setting parameters used in the optimization runs are: the type of algorithm is the *PSO* with inertia weight, the neighborhood topology is von Neumann, the neighborhood size is set to 5, the number of particles is set to 20, the number of generations is set to 30, the cognitive acceleration to 2.8, social acceleration to 1.3, the initial inertia weight is set to 1.2 and the final inertia weight is set to zero. The total number of optimization runs is 600.

## THE BUILDING MODEL

The proposed methodology is tested on the design of a detached single-family house, located in Mascalucia (CT) in Southern Italy. In the intention of the owner, this house (Figure 1) should be designed in order to minimize its overall effect on the environment and, thus, to be a green building.



Figure 1 Three-dimensional model of the house

The single-family home is composed by one occupied story and one unoccupied basement used as technical space. Its net floor area is 148 m<sup>2</sup> and its net conditioned volume is 445 m<sup>3</sup>. The family is composed of four people, and one room of the house is devoted to be used as an office.

Mascalucia is in the zone 'Csa' (Köppen, 1930), characterized by a temperate climate with dry summer, also called Mediterranean climate. In order to consider in the simulations the most likely local weather conditions, a typical weather year has been constructed by using the measured hourly weather data recorded in Pedara (CT), located at 1 km distance from the construction site, from 2003 to 2009. The daily typical occupancy schedule and the daily typical lighting and electrical appliances usage rates have been defined according to owner information about intended use and a database of measurements on electric loads by the eERG (eERG, 2004). In order to provide a comfortable indoor air quality, a minimum air change rate of 0.6 h<sup>-1</sup> was estimated according to EN 15251 and a mechanical ventilation system, equipped with a high efficiency heat recovery unit, was included in the design.

The energy simulations of the building were run with EnergyPlus (Crawley et al., 2001) release 6.0.0.23 and the physical models and algorithms for calculating heat exchanges were selected with a trade-off between precision and computation time: (i) the update frequency for calculating sun paths was set to 20 days, (ii) the heat conduction through the opaque envelope was calculated via the conduction transfer function method with four time steps per hour and (iii) the natural convection heat exchange near external and internal surfaces was calculated via the adaptive convection algorithm (US-DoE, 2010).

## DISCUSSION OF THE RESULTS

According to the proposed procedure, the first step consists in optimizing the building in free-floating mode by minimizing the chosen combination of the summer and winter *LPDs* in the ASHRAE adaptive version (*Free-floating scenario*). In case the identified optimal building variant satisfies the thermal comfort requirements, the design procedure can be stopped, and the building does not require energy for thermal control; on the contrary, if the indoor conditions even for the optimal variant do not satisfy designer's expectations, it is possible to continue to the next step. This consists in optimizing the building in mechanically-conditioned mode by minimizing the chosen combination of the summer and winter *LPDs* in the Fanger version (*Conditioned scenario*).

### Free-floating scenario

The optimization procedure identified an optimal solution that provides both winter and summer aforementioned *LPD* lower than 10% when the building is in free-running mode during the whole

year (Figure 2). We remind here that, even at the ideal comfort conditions, *LD* (both in the ASHRAE and Fanger versions) cannot be lower than 5% by definition.

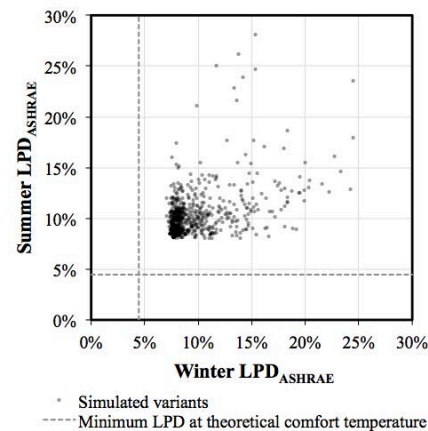


Figure 2 Optimization procedure: position of the simulated variants in the space of the two objective functions in the free-floating scenario

The main features of such optimal building variant are: (i) external walls and the roof with very low steady-state transmittance,  $U = 0.15 \text{ W}/(\text{m}^2 \text{ K})$ , which limits heat exchange with outdoor in both the seasons; (ii) the floor with relatively high steady-state transmittance,  $U = 0.40 \text{ W}/(\text{m}^2 \text{ K})$ , implies that the basement constitutes a heat sink during summer without compromising excessively winter performance; (iii) the roof and the floor with high time shift ( $S > 12 \text{ h}$ ) and external walls with a lower time shift ( $8 \text{ h} < S < 10 \text{ h}$ ); (iv) to every orientation, optimal glazing units have very low values of transmittance,  $U_g = 0.59 \text{ W}/(\text{m}^2 \text{ K})$ , and solar factor,  $g = 0.36$ , which reduces uncontrolled heat exchange through glazing; (v) only on the southeast orientation (such orientation is characterized by large glazed surfaces in this building) glazing units have a slightly higher solar factor,  $g = 0.49$ , which works in favour of enhancing solar gain during winter; (vi) the opening of windows (only in the living rooms) is set to the maximum value during summer nights which provides maximum night natural ventilation cooling; (vi) the control parameter of solar shading (e.g., beam solar radiation incident on a window) is not fundamental if it is reliably set, and can be selected considering the tradeoff with other non-thermal performance such as daylighting and glare risk for occupants. The optimal building variant, in free-floating mode, offers indoor operative temperatures compatible with the 80% acceptability class of the Standard ASHRAE 55 (ANSI/ASHRAE, 2010); only few deviations occur outside the Adaptive comfort zone defined in such standard (Figure 3).

Regarding the energy performance, the energy breakdown in energy uses of delivered energy is: (i) 3.1 kWh<sub>e</sub>/(m<sup>2</sup> a) for ventilation; (ii) 6.5 kWh<sub>e</sub>/(m<sup>2</sup> a) for lighting; (iii) 15.3 kWh<sub>e</sub>/(m<sup>2</sup> a) for electric

equipment; (iv)  $2.6 \text{ kWh}_{el}/(\text{m}^2 \text{ a})$  for the production of domestic hot water (DHW). The annual required electricity is  $4\,087 \text{ kWh}_{el}$ . Consumption due to electric equipment is relatively high since the house is also used as a small office for 5 days per week and 8 hours per day.

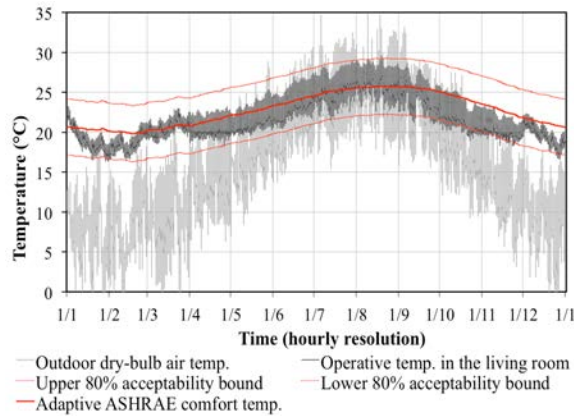


Figure 3 Operative temperatures inside the living room in free-floating mode compared with the 80% acceptability range of the ASHRAE adaptive model

Since the slope of the roof is  $22^\circ$  and assuming to install southwest facing mono-crystalline cells with a covered roof area of  $21.2 \text{ m}^2$  13 PV panels (with a nominal efficiency of 18.4% and a peak power of 300 W per panel), with an overall DC to AC derate factor of 0.77) offer a nominal peak power of  $3.9 \text{ kW}_p$  and it is estimated to generate  $4\,911 \text{ kWh}_{el}$  per year. Thus, considering the balance over a year, the expected on-site electricity generation should be slightly higher than the whole electrical demand, including lighting and appliances (Figure 4).

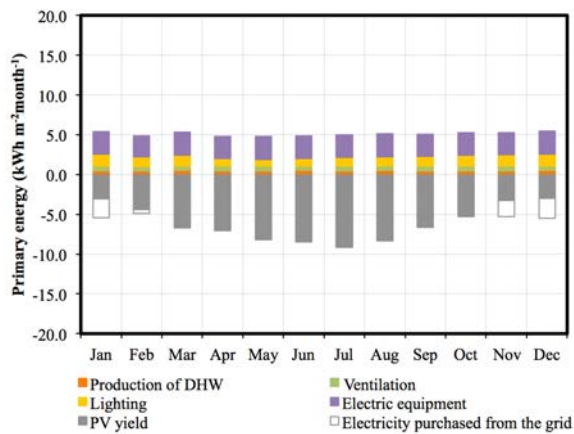


Figure 4 Electric energy balance of the house including PV yield in the Free-floating scenario

On the other hand, on monthly, daily and hourly basis there would be a mismatch between generation and self-consumption.

### Conditioned scenario

When a mechanical heating and cooling system (e.g., a reversible heat pump) is added to the previously calculated optimal free-floating variant, indoor thermal comfort requirements shall be referred to the Fanger comfort model.

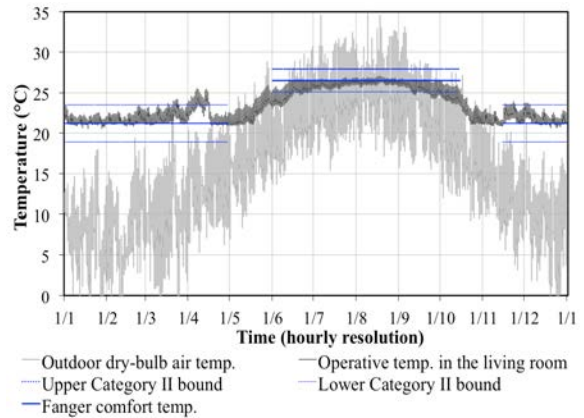


Figure 5 Operative temperatures inside the living room in conditioned mode compared with the Category II range of the Fanger model

The seasonal optimal comfort temperatures were calculated assuming a metabolic activity of 1.2 met, a fixed summer clothing resistance of 0.5 clo, a fixed winter clothing resistance of 1.0 clo, an air velocity of 0.1 m/s, a relative humidity of 50% and an external work set at zero met. They were used as set-points ( $\theta_{conf.Fanger}$ ) the departure from which determines the value of the LD. The boundary temperatures of the comfort range were calculated in compliance with the Category II of EN 15251 suitable for new buildings (Figure 5).

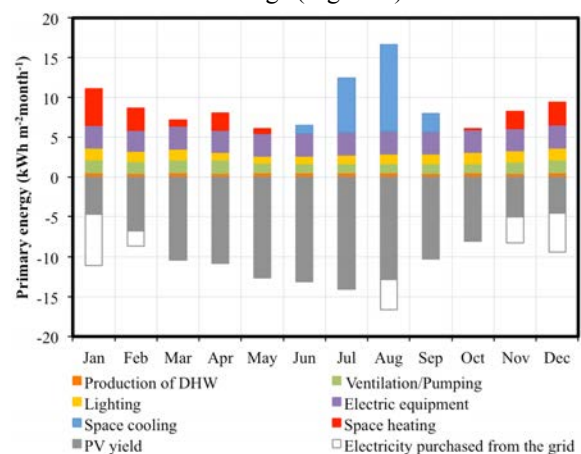


Figure 6 Electric energy balance of the house including PV yield in the Conditioned scenario

According to this scenario, the building is all-electric and delivered energy can be used equally well as primary energy to express the breakdown of energy uses (Figure 6). Annual delivered electric energy for space heating amounts to  $7.3 \text{ kWh}/(\text{m}^2 \text{ a})$  and annual delivered electric energy for space cooling (sensible

plus latent) is 9.5 kWh/(m<sup>2</sup>a). The overall electricity demand is 7 253 kWh per year, i.e., 48.8 kWh/(m<sup>2</sup>a).

Therefore, according to the previous assumptions about the PV field, 20 PV panels are sufficient to balance (over one year) the whole electricity demand of this scenario. The PV field is characterized by a nominal peak power of 6.0 kW<sub>p</sub> and a covered area of 32.6 m<sup>2</sup>. The expected annual PV yield is 7 580 kWh per year, hence, the building, also in this scenario, is expected to produce more electricity than it requires.

## CONCLUSIONS

A novel optimization procedure aiming at the minimization of two seasonal long-term discomfort indices in a free-floating building is presented. It was used to support the design of a real building and select an optimal building variant, which, in free-floating mode, offers indoor operative temperatures compatible with the 80% acceptability class of the Standard ASHRAE 55 with only few deviations outside such comfort zone (Free-floating scenario). When such optimal building variant is equipped with a heating and cooling system, its delivered (or primary) energy requirement for space conditioning is much lower than primary energy for lighting, electrical appliances, DHW production and ventilation. Finally, since annual primary energy required by the house, in the Conditioned scenario, amounts to 108 kWh/(m<sup>2</sup>a), the optimized building fulfills also the *Passivhaus* certification criterion for residential buildings of having a total primary energy requirement lower than 120 kWh/(m<sup>2</sup>a) (PHI, 2012). It should be noted, however, that the modeling and the optimization approach outlined in this paper can be applied to any residential or commercial building prototype.

## ACKNOWLEDGEMENTS

The authors would like to thank all participants of Subtask B of the joint IEA SHC Task40/ECBCS Annex52 project titled *Towards Net Zero Energy Solar Buildings* for the useful discussions.

The study was partially developed within the framework of the MaTriD Project focussing on integrated design and supported by the *Intelligent Energy for Europe* Programme.

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