Developing the Net Zero Energy Design
for the School of Design and Environment of the National University of Singapore

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ABSTRACT: Developing a net zero energy building is not only technically challenging, it is also a challenge to the design process, i.e. how a team of client, architects and engineers approach problems in an informed manner. The paper describes the methodology and the design process we went through to guide the technical design for an university building in the tropics, highlighting key elements of the process as well as some of the design solutions that are particular to the tropics such as daylight and thermal comfort.
The development of a façade for tropical conditions - which has a high ratio of diffuse solar radiation - sought to balance out contradictions of high daylight autonomy vs. low glare probability. The question of appropriate thermal comfort was of major importance to the net zero energy story. Rather than designing conventional thermal comfort systems with low air temperature and low humidity - which drive up energy cost - the design team chose a hybrid system that combines a carefully designed supply air system with ceiling fans for elevated air speed. This system satisfies goals of high thermal comfort, good indoor air quality and a low energy budget that in turn allows the building to achieve its target of net zero.

Keywords: net zero energy building, integral design process, adaptive comfort, hybrid system, daylight, glare, tropics

INTRODUCTION

The National University of Singapore (NUS) is developing a new campus building with educational facilities for the School of Design and Environment (SDE4) at the Department of Architecture. In the client brief it reads: “The building shall be offering an optimistic and bold representation of what the SDE is teaching. The new building shall become a model of low consumption and reduced emissions. The new building shall be a net zero energy building, (NZEB)” and benchmarks and targets are given which are relevant for the energy design:

a) Energy efficiency index of building-in-use: not more the 75 kWh/m²y
b) Daylight access: at least 75% of GFA
c) Cross ventilation and/or mechanical ventilation with due provision to avert potential humidity related problems: at least 50% of the GFA
d) Green plot ratio: not less than 4
e) Optimize adoption of renewable energy potential
f) High energy efficient AC equipment with innovative air distribution

An international design competition was held in 2014 from which the entry of Serie Multiply Architects, London and Singapore was chosen for design. Design services for local architects of record, structural design, MEP and sustainability (certification) are provided by Surbana, Singapore.

The building will hold about 7600 m² (GFA) on 5 floors with total occupancy of about 890 persons. Major program areas are given in table 1, about 3500 m² are conditioned. The people density is high (about 4 m² per person) and the hours of occupancy (7:00 to 22:00) are long as it is characteristic for architectural faculties. There are few office-like spaces.

Table 1 Overview on major program areas

PROGRAM	AREA [m²]	PERSONS	VENTILATION	THERMAL ZONE comfort
studios	1630	380	tempered air	hybrid
library	300	60	tempered air	AC
laboratory	980	250	tempered air	AC
seminar	260	120	tempered air	hybrid
workshop	260	60	natural	eas
social interaction space	1020		outdoor	eas
office	110	20	tempered air	hybrid
corridor	2250		outdoor	NA
auxiliary rooms	790		natural/mechanical	NA

Basically the SDE4 is a “real world project” rather than a research project, therefore this paper describes “how we designed it” rather than studying the topic of net zero buildings in general. Some general aspect which might be universal are summarized before we describe design aspects which are related to the tropical climate in greater detail.

Design process for high comfort – low primary energy: Any approach typically can be broken down in 3 steps of action with different main stake holders, see Figure 1.

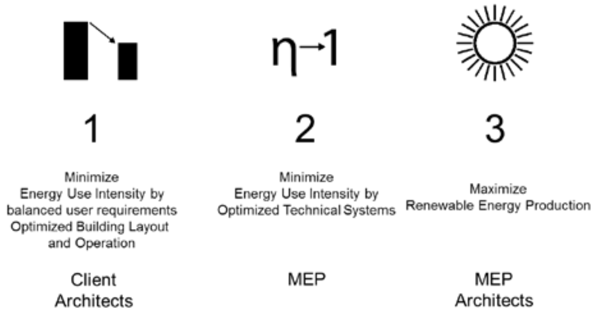


Figure 1: Process and major stake holders for low energy design

Integral design – iterative design process: The design process needs to be iterative and the design has to be evaluated against the achievement of the goals. For a ZEB this is more challenging and needs to be more detailed during the design: detailing of design brief, of operation and building use (client), detailing of façade qualities and performance specifications (architect), detailing of mechanical systems specifications (MEP). Based on this process a more-than-usual detailed technical performance specification needs to be produced for the tender to give a precise definition of qualities to the contractor.

Zero energy building and footprint: There are several definitions for zero energy buildings [1]. We choose to design for net zero source energy. One simple rule is: the building has to produce its energy on its own footprint. The principle potential of achieving a net energy building can be roughly estimated by comparing the potential renewable energy production on the roof with the Energy Use Index per unit GFA (EUI). Given a maximal potential of 500 MWh/y an electrical energy demand of about 66 kWh/m²y can be satisfied. This simplified comparison gave priority to maximize roof areas for renewable energy production in favour to having a green roof. This exercise further highlighted the demand of optimizing and reducing the EUI way beyond the typical Singaporean standard for small offices of 252 kWh/m²y according BCA [2].

Certification: The Singaporean Building and Construction Authority (BCA) is offering a green mark certification which is well accepted and widely used in Singapore (and Asia). The certification procedure and requirements have not been useful to inform the design process as they emphasize an incremental improvement over the existing best practice. Anyhow the high comfort - net zero energy design should satisfy the highest BCA standard (platinum) in these fields.

ADAPTIVE THERMAL COMFORT MODELS FOR THE TROPICS

Buildings today require massive energy inputs. The way we define ‘comfort’ plays a significant role in this, specifically the design of systems needed to cool indoor spaces to a narrow bandwidth of conditions. Adaptive comfort models, developed in field studies on tropical and subtropical climates, suggest that extended temperature and humidity ranges is acceptable, especially if combined with elevated air speed. Adaptive comfort delivers the same comfort but with lower reliance on mechanical systems and more architectural freedom to open façades and connect indoor and outdoor spaces. For the SDE4 a hybrid system was developed as an alternative to conventional air conditioning and the performance was verified by numerical simulations and with a testing. This is not however a new concept. It is really about re-thinking how to do more with less.

DESIGNING WITH ELEVATED AIR SPEED

Elevated air speed has long been used in practice as a mean to off-setting higher temperatures. Updated in 2013, the ASHRAE Standard 55 includes a procedure for evaluating the cooling effect of elevated air speed using the PMV for elevated air speed (PMVeas) [3]. PMVeas estimates the impact of six environmental and personal parameters: air temperature (Tair), mean radiant temperature (MRT), relative humidity (RH), clothing factor (clo), metabolic rate (met) and average elevated air speed (v) to evaluate thermal comfort. Compliance occures when $-0.5 < \text{PMVeas} < 0.5$ – equivalent to 90% satisfaction of occupants is achieved. This update allows the evaluation of design strategies in tropical climates where elevated air speed is combined with supply of tempered air. The procedure was implemented in TRNSYS 17 3D.

In the following 4 design concepts are compared for the example of a design studio, facing south with an occupant density of 4 m² per person. For all modelled systems typical assumptions are made for the building quality, shading, insulation, electrical lights and internal loads. Operation is from 7:00 to 22:00. In Figure 2 the comfort conditions are displayed in individual psychrometric charts with hourly dots representing pairs of temperature and humidity. The colours indicate the achieved PMVeas, achieved with the optimal air speed.

Conventional design, AC: This conventional design has sealed façades with full air conditioning. Energy efficient design includes a low infiltration rate of 0.2/h and a latent and sensible heat recovery. Fresh air supply is for good indoor air quality and low CO_2 levels: 30 cubic meters per hour and person. The room is allowed to go up to 26 °C operative temperature and 12 g/kg humidity. This is compliant with comfort according the conventional "static" PMV standard. There are no systems for elevated air speed in use.

Hybrid system design, 20/20 or 18/18: In the hybrid system the same fresh air rate is supplied to the classroom, however the supply air is tempered: cooled to 20°C (resp. 18 °C) air temperature and dew point, equal to a humidity ratio of 14.8 g/kg (12.9 g/kg). Supply air pressurizes the room and spills over to the hallways, minimizing infiltration. This allows a simplified window design as well as omitting any return air system. Ceiling fans are deployed. For evaluation of comfort with fans in operation, the air velocity is automatically elevated in three steps: 0.3 to 0.7 to 1.2 m/s if perceived comfort exceeds 0.5 PMVeas. This is in line with limits for air speed of sedentary work (0.7 m/s) and maximum air speed under occupant control (1.2 m/s) according to ASHRAE Standard 55. For 20/20 the fresh air supply is constant (simple air volume control), the 18/18 design is with variable fresh air volume.

Natural ventilated system, Nat Vent: A design with natural ventilation and ceiling fans is modelled for reference. The air change rate, driven by thermal boundary conditions, ranges from min. 4.8/h to about 10/h and will always satisfy indoor air quality.

Comfort: Both the conventional and hybrid options provide high comfortable conditions but the interaction of environmental parameters is different. With the conventional system, air temperatures in the room offset radiant temperature of the enclosure. The operative temperature is about 26 °C. The humidity level at 11 g/kg is low; high comfortable conditions are achieved without any air movement. In the hybrid designs the operative temperature is between 26 °C and 29 °C; the humidity level is about 15 to 20 g/kg. The impact of higher temperature and humidity is compensated by elevated air speed. For estimating conservatively on the effect of achieved comfort air speed has only been elevated to 0.7 m/s in the given examples of comfort, Figure 2 and energy, Figure 3.

Both systems will provide comfortable conditions with PMVeas values < 0.5.

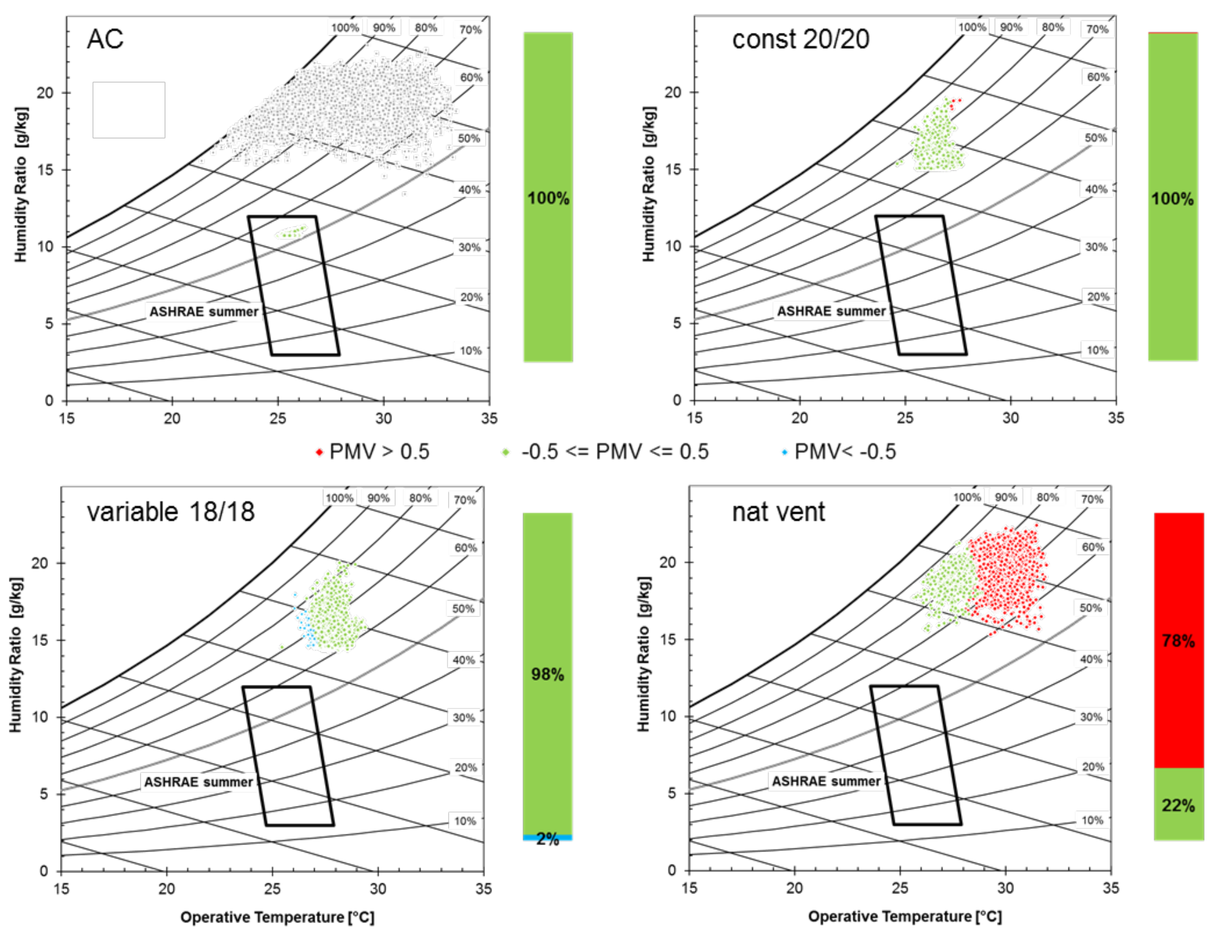


Figure 2: Comfort conditions for 4 options. The colors indicate the PMV with elevated air speed of max 0.7 m/s. Hybrid systems design create comfortable conditions with PMVeas < 0.5. Upper left: the grey conditions represent Singapore climate for reference. The black envelope indicates comfortable indoor conditions for fully air conditioned spaces according ASHRAE in summer. The bars charts to each individual psychrometric chart indicate the percentage of time the PMVeas is within the given ranges.

Energy: Figure 3 shows the electrical energy demand for cooling of the compared options. This includes the energy demand for cooling and dehumidification of the fresh air, for cooling of the space (option: conventional AC) and electrical energy for the fans and air handling. The cooling energy has been converted with a COP of 5.5 to electrical energy.

Compared to a conventional system the energy savings for the hybrid systems ranges between -36% to -56% without compromising comfort. For the natural ventilated design studio the energy demand for fans is very low but comfort is not acceptable. The energy demand to cool and dehumidify air to 18 °C rather than 20 °C is overcompensated by a variable air flow. Systems design is for 18/18 to have a booster mode but typical operation should be at 20/20.

VERIFICATION WITH TESTING

Typical room conditions with higher air temperatures and humidity have been mimicked in testing in an occupied classroom at the United World College, UWC in Singapore.

For this testing the set point conditions of the AC system have been adjusted for a couple of days to allow the classroom to adjust. Environmental parameters and the PMVeas have been measured and the effect of elevated air speed on thermal comfort was observed and perceived together with the client. This gave further evidence that an adaptive comfort design with hybrid systems and elevated air speed will satisfy the high thermal comfort requirements of SDE4.

Figure 4 shows the classroom used for testing. In the foreground the instruments are placed for measuring the environmental parameters: air temperature, humidity, air speed and globe temperature. From the parameters recorded online on a 30 second base the comfort parameter PMVeas and trend lines for MRT, air temperature and relative humidity have been calculated.

Figure 4: Testing of thermal comfort with elevated air speed at occupied class room in UWC, front: comfort sensors

FAÇADE FOR TROPICAL CONDITIONS DAYLIGHT AUTONOMY VERSUS GLARE

In the tropics and in particular in South East Asian regions people tend to protect against the sun and are much more sensitive to glare due to the permanently bright sky. So façades designed for tropical conditions need to balance between effective solar gain control, high daylight autonomy and low glare probability. A comprehensive matrix was developed to support the architects in developing the façade design, see Figure 5.

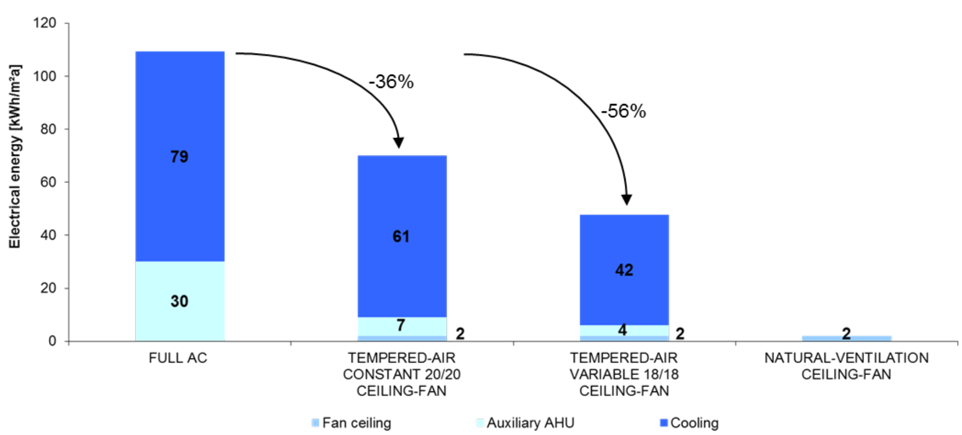


Figure 3: Electrical energy demand for cooling of compared options. Hybrid system design will reduce electrical energy demand by up to 50% without compromising thermal comfort. COP of chiller = 5.5

Thermal comfort was evaluated with detailed room by room dynamical thermal simulation with TRNSYS 17 3D. Many options for overhang design, external and internal shading (fixed and operable) have been studied in combination with different high selective glazing. The hybrid system is designed to supply a given amount of fresh air with specified conditions (e.g. 20/20) to the room. So cooling load for conditioning is fixed and the thermal comfort will vary for each option. Thus the resulting effect for solar gain reduction was evaluated as percentage of operation hours when operative temperature is exceeding 29 °C.

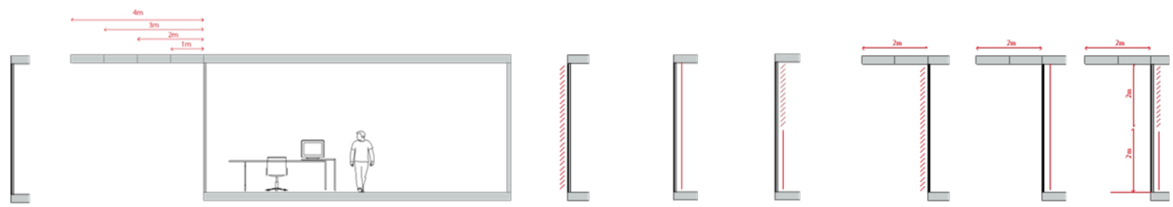
With the design brief, the client was asking for a high daylight access of 75 % of GFA. This requirement was translated into an objective to achieve a high **spatial Daylight Autonomy** (sDA). The sDA is defined as percentage of floor area which receives a specified illuminance level for 50% of occupied hours. For the SDA4 building sDA300lx/50% describes the percentage of floor area that receives at least 300 Lux for at least 50% of the annual occupied hours during daytime (8:00 to 18:00). This metric was evaluated with RADIANCE for all floor plates and the same façade options.

As a consequence of high spatial daylight autonomy in the depth of the floor plates, perimeter zones at the façade receive high daylight levels which often go beyond 2000 lx thus increasing glare probability.

The required glare protection devices reduce daylight availability in the depth of the room. To identify glare issues for the different façade options the vertical illuminance was evaluated at a distance of 3 meters from the façade, eye level 120 cm, view 5° downwards and 45° to façade. Hours with **Glare potential** were predicted when vertical illuminance was exceeding 1000 lux. This method was chosen recognizing existing limitations of the numerical sky models representing tropical skies [4].

Figure 5 shows the comprehensive results as used to inform client and design decisions for a space facing South (East and West façades are protected by external structures). Green colours indicate better performance. Contradictions can be identified. E.g. for 2 m overhang and external shading: if the operation of shading is due to solar loads on the façade, thermal comfort is good, sDA is high (78%) but glare potential is also high (65%). For 2 m overhang and internal screen operated for glare protection, thermal comfort is reduced (9% of operation hours exceeding 29 °C), glare potential is low (good) but sDA is also low.

A façade with overhang and fixed internal lamellas at the upper part and operable screen at the lower part have been chosen for design.



overhang	no	1m	2m	3m	4m	no	no	no	2m	2m	2m
shading	no	no	no	no	no	ext. shading operable	int. screen operable	int. screen low operable	ext. shading operable	int. screen operable	int. screen low operable
50/25	51%	34%	18%	7%	3%	0%	24%	37%	0%	9%	6%
% of operation hours **operative temperature** exceeding 29 °C (hybrid system)											
50/25	100%	100%	100%	99%	92%	81%	3%	57%	78%	0%	76%
spatial Daylight Autonomy ($sDA_{300lx/50\%}$)											
50/25	85%	84%	83%	83%	82%	67%	1%	0%	65%	0%	4%
glare potential (over 1000 lx; @3m); hours of exceeding in relation to operation hours											

Figure 5: Evaluation of façade options to optimize solar gain control, high daylight autonomy and low glare potential.

DESIGN TABLE

Compared to conventional building design the design brief of a net zero building needs to be challenged even more carefully. Client's briefs are often written as wish lists. So the initial important step in developing the concept is to consolidate the clients brief and create a so called design table which documents the user requirements including the intended and required qualities for thermal comfort, daylight comfort, fresh air demand etc. as well as utilization and operation. There are many ways to document that.

We found it practical to initiate a table which was shared among the planning team and filled in step by step and verified until it forms part of the agreed client brief and of the tender documents and specifications for the contractor. The table also allows simple calculations such as specific loads and ventilation rates. The design table documents the relevant client requirements as well as additional specifications for façades and systems, some of them based on simulation results. These are among others:

program areas and geometry: floor by floor and room by room (or zone by zone)

thermal comfort requirements: envelopes of relevant thermal comfort index: operative temperatures and humidity, PMVeas

visual comfort requirements: target illuminance level for electrical lighting, for daylighting, target daylight autonomy, maximal glare potential

occupancy: persons, density and occupancy schedules working days, weekend, holidays

internal electrical loads: electric lighting, personal computers and appliances, plug loads, other electric appliances, machines and schedules thereof

ventilation requirements: natural ventilation, mechanical fresh air requirements to satisfy good IAQ and low CO_2 levels

THE NET ENERGY STORY

Based on the consolidated detailed design table the operation of the building was modelled with simulation tools and the complex interaction of façade design and utilization is studied to inform design decisions, architectural as well as technical. The working method in general initiates an iterative design process in order to find the best design solution but also to engage the user in re-visiting and re-defining his objectives and requirements. The energy demand for the building was estimated in several iterative steps. With each step the level of detailing as well as new design ideas have been introduced and tested.

This methodology created the framework for the design development. Major steps have been (see also Figure 6):

1. Benchmarking against a reference building
2. optimizing the building envelope: selective glazing, sun protection, overhang, optimized shading, thermal mass and materials
3. Optimizing technical systems: high efficient supply and return air system with sensible and latent heat recovery
4. Paradigm shift to adaptive comfort with elevated air speed and hybrid system for optimized fresh air design
5. Detailed modelling of 31 thermal zones, optimized daylight and artificial light design, coordinated design table
6. Optimized operation concepts, increased operation with natural ventilation, VAV 18/18, reduced plug loads, invest in high efficient chiller with total system COP > 5.5

For each step the required Photo Voltaic (PV) areas at roof and façades have been evaluated to identify the gap on the path to net zero energy.

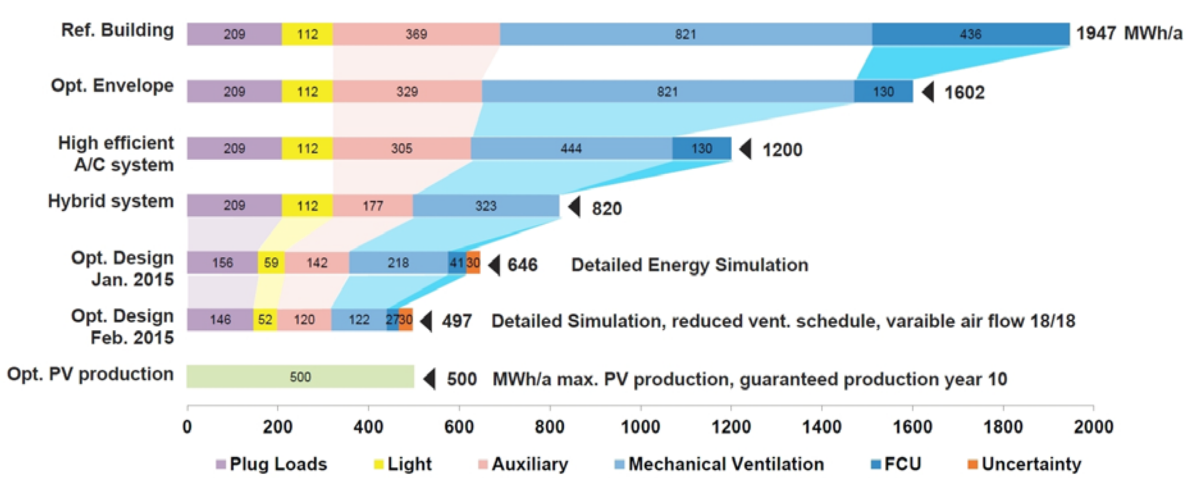


Figure 6: The energy story shows the step by step strategies and improvements towards a net zero energy design.

YEAR 10 PRODUCTION WITH PV

The horizontal solar radiation in Singapore is about 1650 kWh/m²y. The usable roof area was increased by a horizontal cantilever to maximize production with PV. Further to that, options with highest efficient modules have been explored.

PV-production decreases because of aging of the modules. So for the net zero energy balance the year 10 performance of the PV-modules was anticipated. This basically means that installed PV-system need to be about 10% bigger in year 1 so that produced energy and demand will match in year 10. For the following 10 years it was anticipated that performance increase in efficiency e.g. for laptops and lighting will compensate.

Figure 7 shows how the production of a PV system will decline with the time of exposure of the module to the sun. In data sheets often a maximal production (110%) is indicated (see orange bar), which differs from norm production (100%) and from the guaranteed production in year 1 (95%). After 25 years production is reduced to 80%.

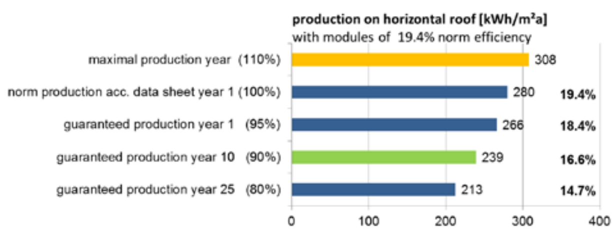


Figure 7: Guaranteed production with PV modules will decline with time, example of a typical module. Percentages in bold indicate the resulting module efficiency.

CONCLUSION

This paper showed some aspects of the net zero energy design for a faculty building in the tropics. Of major importance is the paradigm shift to design for adaptive comfort with elevated air speed and the development of the hybrid system design.

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