TOWARDS RESILIENT BUILDINGS FOR THE URBANISED TROPICS

Runa Tabea HELLWIG [1*]
Cluster Director Solar and Energy Efficient Buildings Cluster (SEEB), Solar Energy Research Institute of Singapore (SERIS), National University of Singapore (NUS)[1*]

*Corresponding author: runa.hellwig@nus.edu.sg

ABSTRACT

The objective of the keynote is to provide a definition for resilient buildings in the urbanised Tropics and to discuss how the current built environment could be converted into a more resilient environment. A resilient built environment or building in the tropics whether air-conditioned or not does incorporate the low-energy tropicality elements typical for this region. These are low window to wall ratio, use of sufficient shading, suitable low solar heat gain coefficient and a proper selection of materials depending on whether the material is exposed to the sun or not. Energy generating measures to be integrated into facades do provide synergies towards passive design. Applying these measures will strengthen the resilience of tropical buildings and at the same time be conducive to climate change mitigation. Additionally, it may also contribute to a new tropical architecture.

Keywords: buildings, tropics, resilience, climate change, facade

1. INTRODUCTION

About 600 million people live in Southeast Asia and 42% of them live in urban areas [1]. It is projected that this proportion will rise. People living in highly urbanised tropical cities are affected by the effect of urban heat island which can lead to an increase of the temperature of about 4°C compared to rural areas. In order to provide liveable resilient cities and comfortable indoor environ¬ments there is a need to design buildings which are suitable for the tropical climate in urbanised areas.

In this paper, information and data mainly from Singapore will serve as an example but may also be applicable to other highly urbanised cities in the warm and humid equatorial climate belt in Southeast Asia. Between 1980-2009, the mean daily temperature in Singapore was 27.4ºC. The mean maximum daily temperature in the same period was 31.8ºC. The number of warm days between February and May with temperatures above 34.1 ºC was 25 days [2]. Mean relative humidity is about 85%. Following the two Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5, mentioned in [2] the projections for the end-century period (2070-2099) are:

- Mean daily temperature of 28.8.-30.1ºC and 30.3-32.0ºC respectively
- Mean maximum daily temperature of 33.3-34.6 and 34.9-36.7ºC respectively

- Number of warm days (>34.1ºC) 74-108 and 105-all respectively
- Mean sea level rise of 0.25-0.6 m and 0.35-0.76 m respectively

The annual global horizontal solar radiation in Singapore as a long-term value is 1632 kWh/(m2.yr) and the annual diffuse global horizontal radiation is 934 kWh/(m2.yr) [3].

While we have been trying to escape the outdoors we are boosting the effect of the urban heat island effect by extracting more heat from larger air-conditioned spaces.

The objective of this keynote is to discuss what it could mean to design resilient buildings for a highly urbanised tropical city like Singapore. A definition of resilient buildings will be given, barriers identified and strategies towards mitigation proposed.

2. RESILIENT BUILDINGS

Larsen et al. [4] provide a summary of terms related to climate change:
Mitigation strategies comprise actions that aim to reduce the CO_2-emissions by increasing the efficiency of energy usage and by increasing the share of renewable energy.

Adaptation describes the adjustment of our built environment in order to respond to changing or extreme weather events expected to take place and to reduce their effects. While mitigation measures aim to reduce the dimension of climate change adaptation aims to diminish the effect of extreme weather events.

Vulnerability describes the degree to which a system, i.e. a building, is capable to cope with the climate change, i.e. extreme weather conditions or electrical power outages due to extreme weather events whereas a resilient system is not sensitive to climate variability and allows for adaptation. A resilient built environment or building has the capacity:

- To absorb external stresses, some of these stresses we may not know until they will occur
- To maintain its function when facing climate change caused by external stresses
- To adapt and develop into more sustainable solutions in order to be better prepared for future climate change impacts

So, how can we convert our built environment towards more resilience? Will a resilient building also be conducive to the climate change mitigation process?

3. ENERGY

3.1 Energy Usage

In many countries different sources of energy are available, i.e. different fossil fuels, electricity from the grid based on fossil fuels, biomass, wind, solar thermal energy or solar PV electricity. These different forms of energy have been used in buildings. In order to provide a fair comparison of the environmental impact of different buildings, procedures in many countries make use of CO_2-emissions or primary energy as an indicator.

In Singapore, while the carbon intensity (CO_2 emissions per US$ GDP) declined annually by 3.7% on average, absolute carbon emissions increased annually by 1.6% (2002-2012) [5].

Primary energy accounts for the energy content of the fuel as well as the energy for the processes due to extraction and transport of resources as well as conversion to energy. For electricity generated in power plants, it therefore takes into account the efficiency of the power plant and the distribution losses of the grid. In Singapore, the efficiency of the power plants is 44%. Figure 1 shows that the electricity (48 TWh) generated in Singapore in 2013 used a total of 109 TWh of primary energy from fossil fuels. The final energy in form of electricity used in Singapore is then 45 TWh [6]. The factor to calculate the primary energy used to generate a certain amount of electricity (final energy) was 2.4 in 2013.

In order to characterise the use of non-renewable energy sources many countries make use of so called primary energy factors which describe the relation between the final energy and the primary energy [7]. For instance, a primary energy factor of 3.0 for the electricity generated in Germany was used for many years [8]. With the steadily growing share of renewables in the generation of electricity, the primary energy factor has been decreasing from 3.0 over 2.7, 2.6 to 2.4 and will be 1.8 from 2016 onwards [8]. Solar electricity and solar thermal energy have a primary energy factor of 0.0.

In Singapore, it has not yet been common to report on the primary energy use of a building since for many buildings, especially commercial and residential buildings, electricity from the grid has been the only energy source used for building operation.

3.2 Commercial buildings

For Singapore, the yearly BCA Energy Benchmarking Report [9] provides benchmarks for the final energy usage of office buildings, hotels, retail buildings and mixed developments, characterised by the energy utilisation index (Figure 2). The median energy utilisation index (EUI) for commercial buildings is 316 kWh/(m2.yr).

The mean final EUI of green marked office buildings (228 kWh/(m2.yr)) was 16 percent points lower than the EUI for non-green marked office buildings (271 kWh/(m2.yr)) (Figure 3).

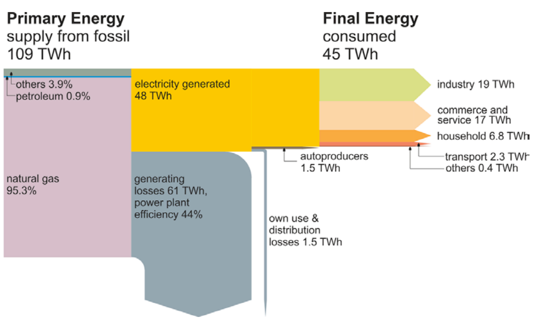

Figure 1: Primary energy usage for electricity in Singapore 2013, (own graphic, data from [6])

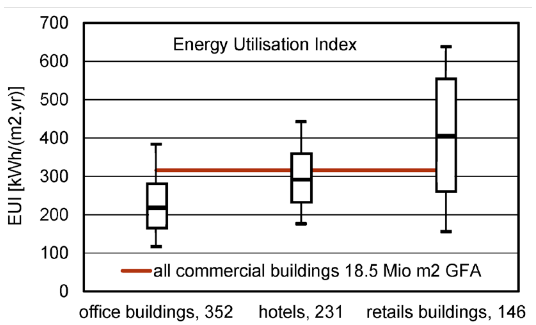

Figure 2: Energy Utilisation Index (EUI) of commercial buildings: office buildings, hotels, retail buildings in Singapore, Box-whisker-plots show 10th, 25th, 50th, 75th and 90th percentile (own graphic, data: [9])

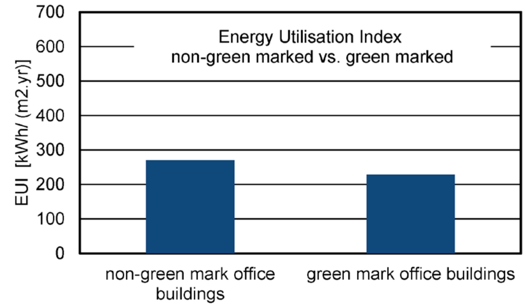

Figure 3: Energy Utilisation Index (EUI) of non-green marked office buildings (N=84) versus green marked office buildings (N=51) (own graphic, data: [9])

3.3 Residential Buildings

For a residential apartment's overall electricity consumption (final energy) the annual Singapore Energy Statistics [6] provide useful benchmarks. A mean public housing unit in Singapore has an annual electricity usage of 4460 kWh/yr whereas a mean private housing unit (condominiums and landed properties) has a mean electricity usage of 9223 kWh/yr.

Figure 4 compares the annual electricity usage of a non-air-conditioned 2-bedroom apartment (GFA 90 m2, 1 person, 1020 kWh/yr, 11 kWh/(m2.yr)) with the annual electricity consumption benchmark of comparable apartments (7300 kWh/yr) provided by Singapore Power [10]. According to [6] the mean electricity usage of a residential unit is 5628 kWh/yr.

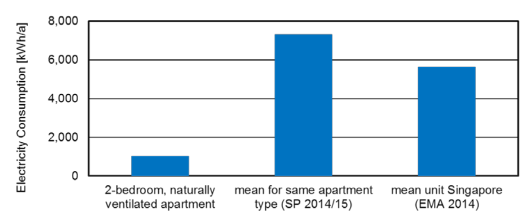

Figure 4: Annual electricity consumption of a non-air-conditioned 2-bedroom apartment, floor area 95 m², 1 person (data [10]), the mean electricity consumption for comparable apartments of the same type [10] and of a mean residential unit in Singapore [6]

There is no data available on the proportion of energy used for lighting, cooling, hot water generation and domestic appliances in Singapore. Owners of HDB flats in Singapore normally install air-conditioning units in their flat by themselves (prevalence: 99% in bedrooms, 33% in studies, 14% in living rooms) [11]. In many apartments the air-conditioning unit is used for intermitted cooling only for certain hours a day, very often in the evenings (35%) or during night (75%). Usually apartments are naturally ventilated and do not use mechanical ventilation. Fans are often used to maintain thermal comfort during daytime (afternoon 89%, evening 76%) [11].

3.4 Potential for Renewables

In Singapore, solar radiation is the most important available renewable energy source. Besides energy efficiency measures, in the future the city's electricity demand has to come from solar PV. High density cities need to keep space for greenery within the cities. Therefore ground mounted systems do not provide opportunities for energy harvesting in those cities.

The Solar Photovoltaic Roadmap for Singapore [12] identified the potential area for PV installations in Singapore. Of overall 45 km² potential installation area 4 km² are assigned to facades based on the 2011 building stock and taking into account only the top 5 stories of the buildings only. For façade integrations, Building Integrated Photovoltaic (BIPV) systems can be used. Nowadays most commercial office buildings use highly or almost fully glazed facades which contribute to an increased energy consumption of these buildings because of a higher sensible cooling load. The industry has developed several solutions for BIPV, e.g. glass in glass integrated photovoltaic which can be used for commercial building's facades. Other BIPV systems can be used as a façade cladding providing shade for the external wall behind it. Facades in Singapore receive 43% of the annual solar irradiance on a horizontal surface [12].

For a commercial and industrial thermal energy demand it may be interesting to investigate the viability of a solar thermal system. A solar thermal system converts solar radiation into thermal energy which is normally transferred to the heat application using hot water. The efficiency of a solar thermal collector varies between 60 and 80% depending on the collector type, brand and the targeted temperature increase in the collector. There is also the opportunity to integrate solar thermal collectors into facades (see section 5.5).

4. Barriers Towards Higher Resilience

The origin of the energy consumption as well as the impact of the energy usage on the urban environment and climate change is not yet well understood by the public. By using more energy for expanded air-conditioned spaces we release more heat into the urban environment intensifying the urban heat island effect and diminishing the potential of natural cooling of outdoor spaces.

Winter [13] argues for "a questioning of AC [air-conditioning] as a (pre) condition of modern urban life, rather than proposing its exclusion". He argues for the benefit from re-inserting local traditions of tropical architecture and low-energy environ¬mental technologies like sun shading, vents and fans as well as climate adapted furniture and clothing. While "the traditional uses of nature as an agent for cooling" [13] is appreciated especially in Singapore (e.g. greenery in the built environment and on buildings) many of the traditional low-energy environmental technologies are rarely applied especially to commercial buildings. Vernacular, colonial and early modern architectures in the Tropics did make use of these low-energy environmental technologies.

The outdoor environment is often associated with air and heat pollution, dust, noise, and in some cities with crime. Nowadays, highly urbanised cities offer a network of connected cooled spaces (office, public transport, car, restaurant, shopping mall) which allow residents to move from one cooled space to another with minimal exposure to the outdoors [13].

Materials and technologies identified to stand for modernity are often solutions suitable for the cold or temperate climate built environment. They may not be suitable for a tropical modernity. Furthermore, buildings are far too often regarded as being the result of the pure assembly of different technologies rather than the result of an integrated design process integrating different technologies and their interaction into a well-performing building system.

Another barrier is the space shortage in highly urbanised area which may restrict the wide application of traditional practices e.g. overhangs as fixed shading devices as they may contribute to the building's footprint.

5. STRATEGIES

The passive design of buildings impacts the energy buildings consume. The building envelope is the interface between the outdoor and the indoor conditions and is also supposed to protect against natural elements (e.g. rain, solar radiation). Facades do not consume energy directly. Facades are, however, the key element of a building to manage the indoor environmental conditions, in particular thermal comfort, daylight and indoor air quality, largely influencing the cooling load and the electricity load, and thus the energy consumption of the entire building.

For conditioned spaces the targeted indoor operative temperature is 24ºC although for the majority of air-conditioned buildings the indoor air temperature is far below 24ºC. The resulting mean daily temperature difference between inside and outside would be: 3ºC. The temperature difference between indoors and the annual mean maximum of the outdoor temperature is 8ºC. These are a rather low values compared to the mean outdoor temperature during the heating period in a temperate climate of about 15ºC.

Whereas the contribution of the temperature difference between inside and outside appears to be of minor prioprity in a tropical climate, the avoidance of heat gains from solar radiation is the main objective.

5.1 Tropicality of Architecture of South-East Asia

The analysis of the design of vernacular architecture in Southeast Asia reveals the main principles for a low-energy architecture design in the Tropics. It is obvious that neither all vernacular materials nor the vernacular building design can be used as is in modern urbanised areas. But what we can learn from this architecture is the tropical principles and transform them into suitable design approaches for a future tropical building design in Southeast Asia. The principles are:

- Shading - Avoiding heat gains to indoor spaces
- Radiation shield (low thermal inertia, low internal surface temperature)
- Air movement - Permeable to air
- Vents - Removal of warm air
- Low thermal inertia or avoiding high thermal inertia of building elements to be exposed to solar radiation

Even today when visiting examplars of these vernacular buildings they provide a rather comfortable indoor environment without using any energy. Figure 5 shows examples from vernacular and colonial architecture in the region using different types of shading. The principle is to avoid direct solar radiation on external walls and on openings (vernacular) or glazings (colonial).

Figure 6 shows different roof materials used in vernacular buildings like multiple layers of bamboo shingles, wooden shingles and very lightweight, thin clay tiles. These materials provide either certain insulation and have a low specific heat capacity (bamboo and wood) or because of their thickness and arrangement in layers limit the surface temperature. Compared to the bamboo or wooden shingles the clay tiles will have a higher internal surfaces temperature when exposed to solar radiation (see also section 5.4).

Figure 7 shows ventilation openings used to release heat from the roof. Some of the vernacular buildings did not even use a ceiling in their indoor spaces for this reason. A difference between buildings located in the lowlands (Figure 7) and in the highlands regarding the number and size of openings for enhanced air movement can be found.

Figure 5: Examples of vernacular and colonial architecture of the region using wide overhangs and shading, photos: © RT Hellwig

Figure 6: Examples of vernacular architecture of the region using different types of roof materials: multiple layers of bamboo shingles, wooden shingles, thin clay tiles, photos: © RT Hellwig

Figure 7: Examples of vernacular and colonial architecture of the region (lowlands) using vents to release heat photos: © RT Hellwig

There are of course examples of contemporary architecture following the principles of tropicality, e.g. see examples by Jimmy Lim [14]. Among others, in his buildings he has been celebrating multiple layers of roofs allowing diffuse light to illuminate the indoors, providing views to the outside, allowing for air movement and at the same time providing sufficient shading. For high rise buildings, there are few good examples available, e.g. the recent HDB development by WOHA architects Skyville@Dawson [15]. To date most HDB apartment buildings in Singapore are designed for natural ventilation of both the apartments and the common corridors and sky gardens.

5.2 Building Facade Performance

Various technologies for high performance facades are available and some have been applied for many years in cold and temperate climates. Having in mind the use of glazings in greenhouses to grow vegetables in temperate climates, the wide use of glazings and their exposure to solar radiation without using shading devices seems to be an inadequate measure in contemporary architecture in the tropics or temperate climate to cope with the climatic conditions in an energy efficient way. Highly glazed buildings in the Tropics are more vulnerable towards interruptions of electricity delivery and mainly contribute to the energy consumption for cooling in this region. In addition, there is proof that highly glazed buildings using low-e glazings contribute to boost the urban heat island effect by reflecting solar radiation downwards where it will be absorbed and converted into heat [11].

The recently launched BCA Green Mark for New Buildings (Non-Residential) for pilot application [17] has tightened the requirements towards the Envelope Thermal Transmittance Value (ETTV). The maximum permissible ETTV has been 50 W/m2 for all buildings in Singapore for many years [18]. Table 1 shows the maximum permissible ETTV for different levels of award according to the new green mark scheme for pilot application. The reported values are part of the pre-requisite requirements for all buildings.

Table 1: Maximum ETTV for different levels of award according to the BCA Green Mark for New Buildings (Non-Residential) for pilot [17].

Level of award	Maximum ETTV, W/m^2
Certified	45
Gold	45
GoldPlus	40
Platinum	38

The new green mark scheme also lists requirements towards a tropical façade performance which have to be proved by simulation or in case the window to wall ratio is equal to or below 40% on basis of a checklist. The baseline checklist values take into account the effect of the U-values of the opaque wall area and the centre of glass value (often referred to as fenestration system) and the shading coefficient of the glazing. The effect of a shading device is not part of the baseline as well as the effect of the colour (absorption) of opaque walls. The latter cannot be considered using the ETTV formula [18].

The baseline values given in this checklist have been used to investigate the sensitivity of the ETTV to changes of the façade properties. Table 2 provides information on the investigated cases comprising the base case using the checklist characteristics for the facade, the base case but with 90% glazed area and without a shading device, the combination of the best values given in the checklist (best GM), a best case, a worst case and the case of an existing building's façade. The investigated office room has a floor area of 16 m2 and a façade area of 12 m2.

Table 2: Façade characteristics for the investigation of ETTV sensitivity

property, unit	Base case	Base case, WWR 0.9, no shading	Best GM 2015	Best case	Worst case	Exis-ting
Façade area, m^2	12	12	12	12	12	12
Floor area, m^2	16	16	16	16	16	16
U_w, W/m^{2}K	1.6	1.6	0.8	0.5	2.0	2.0
WWR, -	0.4	0.9	0.3	0.3	0.9	0.4
U_f, W/m^{2}K	1.5	1.5	1.5	1.3	6.0	6.0
SHGC, -	0.35	0.35	0.22	0.25	0.87	0.75
SC, device, -	0.9/ 0.7*	1.0	0.90/ 0.7*	0.50	1.0	0.5

U_w: U-value opaque wall
U_f: U-value fenestration system (here: centre of glass U-value)
WWR: Window to wall ratio
SHGC: Solar heat gain coefficient of the glazing
SC, device: Shading coefficient of the shading device
*0.9 for North and 0.7 for East orientation.

Figure 8 shows the results of the sensitivity analysis of ETTV. With the base case, the North and East façade meet exactly the requirements of the BCA Green Mark for new non-residential buildings (pilot), platinum.

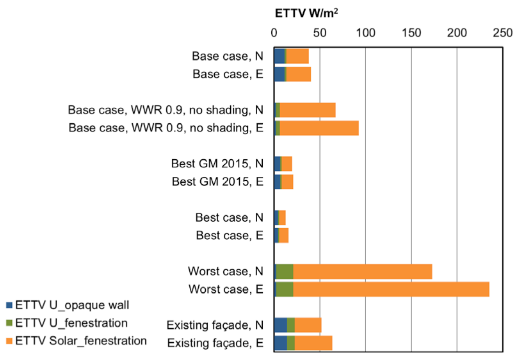

Figure 8: Sensitivity of ETTV to changes in the façade properties of a 12 m2 façade, oriented to the North or to the East, properties are given in Table 2.

The base case but with a WWR of 90% and without a shading device does not meet the minimum requirements for green mark. It performs even worse compared to an existing building with just a single glazing a WWR of 0.4 but using a sufficient fixed shading device. Those shading devices combining an overhang and side fins can be found in older buildings in the Tropics. An almost fully glazed façade without any shading device and using new building materials requires a maximum of SHGC of 0.30 in order to meet the requirements of the Green Mark Scheme. An existing building with north orientation does almost meet the minimum requirements set by the Building and Construction Authority for all buildings in the ETTV regulation [18].

In the calculations, the centre of glass U-value was used instead of the fenestration system U-value as in the ETTV calculation in everyday practice. SERIS conducted a study for a façade company on the impact of the use of thermally broken aluminium frames on the thermal performance of fenestration systems. The results of the study are summarised in [19]. The differences found in the ETTV result when considering the thermal performance of the fenestration system instead of just the centre of glass values are 2-3 W/m2. When comparing the fenestration system with a non-insulated frame to one with a thermally broken frame the overall improvement of the ETTV for fenestration system will be around 4-6 W/m2.

The sensitivity of the ETTV to changes in the solar properties of the façade (WWR, SC of the shading device and SHGC) can clearly be identified from Figure 8.

The effect of claddings on external walls was investigated [20]. It was found that a cladding can improve the ETTV by 6 W/m2. A cladding system improves the U-value of the wall but does also reduce the effect of solar absorption.

Converting the values of 38 and 40 W/m2 façade area of the base case in Figure 8 to the floor area of the office room provides us with sensible heat load values of 28 and 30 W/m2. For comparison, the sensible heat load for 1 person occupying this office would be about 5 W/m2. The sensible heat load of an energy efficient lighting system in office spaces without daylight is 8-12 W/m2.

The ETTV calculation formula uses an equivalent temperature difference of 12ºC in order to consider for the effect of solar absorption. The equivalent temperature difference varies between 8 and 18ºC for an absorptance ranging from 0.2 to 0.8 [20]. If the solar absorptance of the base case (about 0.45 as determined from to [20]) would be changed to 0.8 (e.g. dark brown colour), the ETTV of the base case would increase by 6 W/m2 from 38 to 44 W/m2 for North orientation and from 40 to 46 W/m2 for East orientation.

The effect of several improvements of the thermal performance of roofs was investigated by Tong et al. [21]. Cool roof colours were shown to significantly reduce the heat gain of roofs by 11% for both unventilated and ventilated roofs in Singapore. Comparing the positive effect of a ventilated roof with an unventilated roof shows an improvement of 42%. A minimum insulation of 2.5 cm on an unventilated roof reduces the heat gains by 68%.

While all above mentioned measures reduce the sensible cooling load of a space the same measures also positively impact the internal surface temperature. Especially for persons sitting next to a façade the perceived temperature is influenced by the air temperature and the internal surface temperature of the façade. A warm surface temperature can lead to an increase in perceived temperature (operative temperature) for the person sitting next to the window of 2ºC or more.

5.3 Air Movement

Isothermal air movement is one of the most important traditional cooling technologies in Southeast Asia's vernacular and colonial architecture did account for air movement. In today's buildings, isothermal air movement is replaced by air-conditioning, often with temperatures even below the targeted room temperature of regulations or standards. Schiavon et al. [22] investigated the effect of isothermal cooling by enhanced air movement using energy efficient direct current fans. The thermal comfort (at 60% relative humidity) was found to be better at 26°C and 29°C compared to the set point of 23°C if a personally controlled fan is provided.

5.4 Thermal Inertia

Thermal inertia of buildings has not been addressed in contemporary buildings in Singapore. Most buildings appear to have a low thermal inertia indoors. But the wall materials outdoors, especially those of residential buildings often have a medium thermal inertia because of the wall material predominately used, i.e. light-weight concrete or brick. To predict the speed of heating of materials under load or cooling of materials after being heated up the material property thermal diffusivity has been used. It relates the ability to conduct heat to the material's capability to store heat. A high thermal diffusivity means that heat moves rapidly through the material. For outer wall material, in the case of high solar radiation and absorptance the heat would be rapidly transported to the inside of the wall leading to higher internal surface temperatures affecting a person's thermal comfort. For instance the thermal diffusivity of Aluminium is 98.8·10-6 m2/s. Aluminium is used as a frame material for fenestration systems and is known to rapidly conduct heat from the outer surface to the inner surface of a frame. Compared to aluminium reinforced concrete and glass have a lower thermal diffusivity (0.98 ·10-6 m2/s and 0.5·10-6 m2/s). But wood shows an even lower thermal diffusivity of 0.12·10-6 m2/s which supports the observation that the wood used in vernacular buildings as a wall material and when exposed to solar radiation does not show high internal surface temperatures. Although the thermal diffusivity of brick is below that one of concrete it is still higher than the value for wood, which does provide proof for the observation that a clay tile roof shows a higher internal surface temperature than a roof made of plant materials.

On the other hand, building materials like concrete, when not exposed to solar radiation can act as a thermal buffer during daytime and improve the thermal comfort in outdoor spaces, e.g. open meeting places in the first level of HDB buildings. The heat stored in these elements during the day may be discharged during night.

5.5 On-Site Generation of Renewable Energy

For façade integrations building integrated photovoltaic (BIPV) systems can be used. Because of non-attractive design options and perceived high costs, BIPV has not yet been widely adopted in Singapore. Recent new technologies offer a wide range of colours. An important feature is that the recent BIPV technologies can be applied frameless – a beneficial property for architectural integration into facades. Different from standard PV modules recent technologies appear as a second skin and can be used for new buildings as well as for retrofitting of existing buildings (Figure 9).

One of the barriers to adopt BIPV is the perceived high cost. This is because the current procurement decisions for façade systems solely depend on the upfront investment cost. This upfront investment cost is rarely compared to the overall benefits a BIPV façade can provide compared to a traditional non-BIPV façade. A fairer economic analysis should therefore not only compare the upfront investment cost between a BIPV façade and a common façade but as well include an overall cost and benefit analysis of both types of facades. Levelised cost of energy (LCOE) for rooftop PV can be carried out using the LCOE calculator developed by SERIS and available at:
www.solar-repository.sg/lcoe-calculator/ [23].

Figure 9: Building integrated coloured photovoltaic used as a cladding for an external wall, colours: blue, grey, gold, green colour, Photo: Courtesy to Façade Global Master Pte Ltd/ Kromatix®; glass in glass photovoltaic used in a canopy Photo: © A Majdouli/ SERIS

For solar thermal collectors several technologies are available. Solar thermal collectors, especially evacuated tube collectors as shown in Figure 10, provide the potential for a seamless façade integration. The advantage of such collectors is that the absorber sheet can be optimally tilted also when the collector is mounted on a vertical façade. Furthermore, because of the vacuum in the collector, the surface does not get hot and the collector can add also a certain amount of shading to the façade while also providing aview to the outside.

In [24] the levelised cost of solar thermal energy was in investigated for the case of an industrial process heat application. The levelised cost of thermal energy generated by a conventional gas fuelled system was determined at 21 SGDcents per kWhth for the example case (assuming a certain thermal energy demand and profile and a certain targeted temperature increase in the collector). Instead, the levelised cost of thermal energy generated by a solar thermal system is only 11 SGDcents per kWhth. The levelised cost of solar thermal energy depends on the system's configuration and the targeted temperature level. Therefore the LCOEth may vary for other applications.

Figure 10: Evacuated solar thermal collector which can be used also on a vertical wall. The tilt of the absorber can be adjusted for optimal solar gain. Photo: © MA Wahed/ SERIS

6. CONCLUSION

After having discussed aspects of the energy usage in buildings, the nature of expected climate change for a tropical city like Singapore, and the tropicality of vernacular, colonial and contemporary architecture in the Southeast Asian region it seems to be necessary to define the character of a resilient building in the Tropics.

A resilient built environment or building in the tropics does incorporate the low-energy tropicality elements typical for this region. This does not mean to abolish air-conditioning. Even an air-conditioned building's energy usage will benefit from the implementation of low-energy tropicality elements. These are:

- A low WWR just adequate for daylight use, for office buildings typically around 40%.
- The use of a sufficient shading device providing shade for the glazing.
- The use of a suitably low SHGC allowing for a good daylight quality.
- A suitable selection of materials which do not tend to store heat when exposed to the sun or will be integrated into the building in such a way that the material is not exposed to the sun.
- The use of materials which do not boost the urban heat island effect
- The use of façade integrated solar technologies, e.g. building integrated photovoltaics (BIPV) or solar thermal collectors (if there is a thermal energy demand) as a cladding or shading element in front of opaque walls. In addition of this beneficial effect these elements will generate renewable energy at the building site.

The application of these measures will turn our built environment into a less vulnerable and hence more resilient built environment. Since there are synergies when integrating active technologies for the generation of renewable energy into facades such a resilient building will also be conducive to the climate change mitigation process.

In addition, re-calling and re-inserting elements of tropicality will lead to higher appreciation of the local architectural heritage. The blending of traditional principles and new materials will also be supportive for the development of a new Southeast Asian architectural modernity.

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