735: BIPV Design for Singapore Zero-Energy Building

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Abstract
This paper presents the design for Building Integrated Photovoltaic at Singapore's first Zero-Energy Building (ZEB). It introduces the general recommendations of the international integrated design workshop and the solar opportunities derived from a site analysis leading to BIPV design concept. An assessment method supported with interviews and performance simulation in preparation for the PV tender award is also presented.

Keywords: Building Integrated Photovoltaic, Integrated Design, Zero-Energy Building

1. Background

Singapore's first Zero Energy Building or ZEB in short, is a retrofit of a 3-storey office block of approximately 3,000m^2 gross floor area located at the Building Construction Authority (BCA) Academy. Three research teams from National University of Singapore (NUS) with their respective international collaborators support the design, construction and evaluation in terms of Daylighting and Building Integrated Photovoltaic (Associate Professor Wittkopf), Natural Ventilation and Vertical Greening (Associate Professor Wong) and Energy Efficiency (Associate Professor Lee) respectively. The ZEB is expected to top the rank of energy efficient buildings in Singapore, with the highest score for Green Mark, Singapore's building performance assessment. An early design was presented during PLEA 2007 in Singapore (Figure 1).

Figure 1: Presentation of the ZEB model during PLEA 2007

2. Integrated Design Workshop

Generally, an integrated design process is a collaborative approach to whole-building design, in which a multi-disciplinary team comprising all project stakeholders comes together in the early stages of the design process to discuss and develop design solutions.

In June 2007, the author conducted the first 2.5 days of integrated design workshop to kick-start the design development of the Zero-Energy-Building (ZEB) with a focus on BIPV. According to the International Energy Agency, an integrated design approach to a sustainable building like the ZEB requires a wide range of issues to be addressed [i], including the optimized use of solar and renewable technologies coordinated with optimized sizing of technical systems to achieve maximum performance. All project stakeholders including international experts were invited. The PV related objectives were documented in a ZEB Project PV Scope Report, concluding with the following recommendations:

- Position as a **Net-Zero-Energy Building**
- Quantify the **Energy Target**
- Promote **multifunctional PV benefits** through building integration
- Facilitate **experimental research**

2.1 Introductory presentations

The Workshop started with a presentation by the Principal Investigator (PI) for BIPV and daylight addressing specific strategies for the design, construction and evaluation of the ZEB in terms of BIPV. International collaborators to the PI presented frameworks, concepts and applications pertaining to BIPV and daylighting in their respective countries as listed in Table 1.

Topic	Speaker
High-performance facades in the tropics	Assoc Prof Eckhart Hertzsch, University of Melbourne, Australia
BIPV in Australia	Prof Deo Prasad, University of New South Wales, Australia
PV-Demo site and daylight redirection systems in Europe	Prof Jean-Louis Scartezzini, Swiss Federal Institute of Technology Lausanne, Switzerland
BIPV and daylight mirror duct systems in Japan	Prof Toshiharu Ikaga, Keio University, Japan
Daylighting and Green Buildings in Hong Kong	Assoc Prof Stephen Lau, University of Hong Kong,

Table 1: Titles and speaker of invited presentations

BCA as the lead organization introduced the overall project deliverables, funding and organization chart. They informed that the ZEB ownership model is of the Owner-Occupant mode, by which BCA as the owner accepts higher initial building construction costs due to the green building technologies, provided significant savings be made in the long run.

2.2 Definitions of Zero-Energy Building

According to Wikipedia [ii], zero energy buildings are gaining considerable interest as a means to cut greenhouse gas emissions and conserve energy' … 'are promoted as a potential to a range of issues, including reducing emissions and reducing dependence on fossil fuel'.

ASHRAE speaks of net-zero energy buildings in their recent 2008 Winter meeting and defines it as a 'building which, on an annual basis, uses no more than the energy that is produced by on-site renewable energy sources' [iii]. Similarly the National Renewable Energy Laboratory in the United States states: 'A net zero-energy building (ZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies'[iv].

Considering the above guidelines, we have arrived at our definition: A retrofit into a net-zero energy building in which substantial energy savings of at least 50% are achieved through innovative energy efficient technologies and adaptive user control. In addition, the remaining energy is supplied through electricity from Photovoltaic (PV) modules integrated in the building envelope.

Unique to our ZEB is the exclusive use of PV due to two reasons. Singapore receives superior solar radiation Located just one degree north of the equator, incident global solar radiation on optimally tilted surfaces accumulate to 1.68 MWh/m^2 as can be seen in Figure 2. This is for a typical meteorological year [v] Singapore has, since it acceded to the Kyoto Protocol in 2007, launched funding programmes [vi] dedicated to Test bedding of PV technologies, which we intend to utilise.

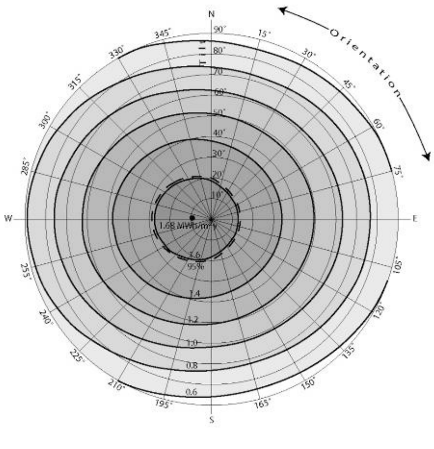


Figure 2: Global Solar Radiation Map Singapore

2.3 Maximum PV electricity supply

According to Figure 2, near horizontal surfaces receive the highest solar radiation in Singapore. On the main ZEB roofs, an area of up to 1200 m^2 is available for PV deployment. A full coverage of PV modules (14% efficiency or normalized nominal power of 140 Wp/m^2) will result in an array with a nominal power of 168 kWp equivalent to a real energy yield of 184 MWh/year assuming an annual yield factor of 1,100 Wh/Wp/year using the following equation.

$E_{real} = P_{PV} \times FY$, where $P_{PV} = A_{PV} \times P_{PVA}$

Parameter	Symbol	Unit
Real energy yield of PV array	E_{real}	Wh/year
Nominal power of the array	P_{PV}	Wp
Area of installed PV array	A_{PV}	m^2
Normalised nominal power of PV	P_{PVA}	Wp/m^2
Annual Yield factor	FY	Wh/Wp/ year

Table 2: Parameter for yield forecast

The above calculation hinges on the annual yield factor. This factor reflects the solar radiation as well as all typical performance losses through cables, power electronics and PV temperature coefficient. Particularly for mono- and poly-silicon PV-technologies, losses through high module temperature can be quite significant. Operating module temperature on site may well be 40deg above STC, resulting in an efficiency drop of 0.4 x 40 = 16%. This and other performance losses of PV systems are quantified with the so-called performance ratio PR. The above annual yield factor is simulated using PVSYST and confirmed through observations from large roof top PV installations in Malaysia [vii], a country with very similar climate.

Given the limited roof area and annual yield factor, one can only increase the energy production with PV module efficiency. Efficiencies of up to 20% are available; however, the choice would become too small and would disadvantage the many SI that do not have contracts with suppliers of such modules. Owing to this market situation, we agreed to cap the requirements for energy production to 185 MWh/year.

2.4 Estimation of the energy consumption

An initial consumption target of 70kWh/m^2/year was considered, two third below the national standard for office buildings in Singapore. As such, the typical yearly energy consumption for the 3,000m^2 ZEB would be around 210 MWh, a value that was further reduced to 185 MWh due to the fact that some area will be naturally ventilated and hence would not require energy for air-conditioning. A detailed calculation including schedules and loads is the subject of another paper.

2.5 Multifunctional PV

PV modules are usually seen as generators of electricity only. However, with new and emerging technologies, PV modules can turn into design elements with no limitations on colours, shapes, transparencies, texture, rigidity etc. In addition, they can serve as shading elements and daylight modulators, reducing energy consumption in buildings in the first place.

This shift from an M&E device into a multifunctional component with architectural qualities is an important aspect to develop BIPV for widespread adoption. Hence, the ZEB will be a Demo-Site for PV-Shadings, PV Windows, PV-Facades and PV-Railings.

2.6. Experimental research

Besides relying on proven technologies, R&D into new technologies is necessary to further develop Green Building Technologies in Singapore. Such research could test for example how Solar Cooling which works well in temperate climate, actually performs in hot and humid climate. Do certain PV technologies perform relatively better in hot and humid climate with mainly diffuse solar radiation? What is the optical, thermal and electrical performance of semitransparent PV? In addition, how can PV module rating schemes be developed to address the multifunctional aspect? Feasible systems must be identified for future promotion and inclusion into building performance assessment schemes.

In addition to creating novel or combine established technologies, development of planning tools to predict their performance becomes important. Building and testing 1:1 models of often complicated systems can become quite expensive and can be a huge risk if the concept fails. In such cases, use of reliable simulations software would be a cheaper and practical alternative. However, many tools are unable to model for example, the complex interrelations between airflow and solar radiation.

The ZEB will provide a platform for testing of new technologies through small scale testing and evaluation of computational simulation tools.

3. Design Concept

3.1 3D CAD based planning

Owing to the different background of the team members using different standards for building design representations, we used CAD Modelling and Real-Time walkthrough techniques to visualize the design context and proposals in three-dimensional (3D), a representation that all team members understand equally well.

3.2 Site analysis – Solar opportunities

The BCA Academy comprises of seven building blocks, with separating protruding staircases to form a u-shaped courtyard. The outer facades receive strong morning and afternoon sun, while the inner facades are shaded by an open corridor providing horizontal access to the 2-3 storeys high blocks. Main access is from the square admin building located southwest, leading to the inner circulation to access the office and workshop blocks. The central courtyard is undergoing major renovations to become a central activity zone. The block north of the admin block will retrofitted to become the ZEB. Figure 3 shows the site with superimposed sun path diagram to identify solar opportunities and challenges.

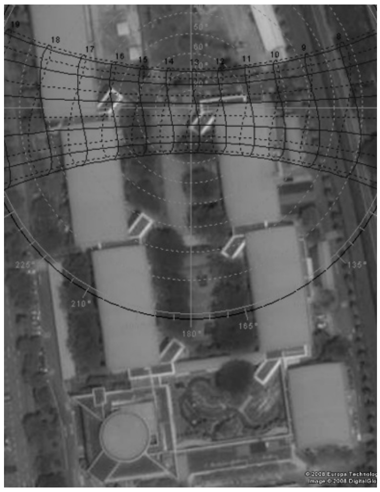


Figure 3: Site plan with superimposed sun path

The site and building context offer many opportunities for BIPV. The roofs are fully exposed to sunlight and are clear of any M&E components. The gentle slope of the barrel-shaped roof provides an almost ideal surface for maximum PV energy generation.

Second, the high solar gain through the west facing façade, would suggest shading devices to reduce the air-con load. PV integrated shading devices would be ideal here, promoting the multifunctional benefit of BIPV. Third, the central position of the protruding staircase in between the admin and ZEB block provides an ideal gathering point for public display of the many 'looks' of PV-modules and technologies. There are several other areas where BIPV could be integrated while benefiting from public visibility and exposure to sunlight. This includes the car park shelter in front of the west façade, the roof over the open walkway to the opposite block and the railings along open corridors facing the activity areas in the courtyards.

3.3 BIPV Design Concept

The BIPV design concept is the design response to the solar opportunities of the site and building while considering the recommendations from the integrated design workshop (Energy target, BIPV, experimental research).

All main roofs will be covered with high-efficiency PV-modules. This includes the main roof (1.a) as well as the walkway shelter (1.b) as seen in Figure 4 and 5. Maximum energy production and shading of the metal roof are the main objective. For maximum energy production, we specified PV modules with an efficiency of at least 13%. They have to be elevated off the main roof to provide sufficient ventilation reducing the losses through high cell temperature. The material and surface of the car park shelter provides an ideal substrate to laminate thin-film (1.c). Here, demonstrating easy addition of PV into existing building surfaces was considered. Generally, thin-film PV is also less sensitive to partial shading, which we expect from surrounding trees.

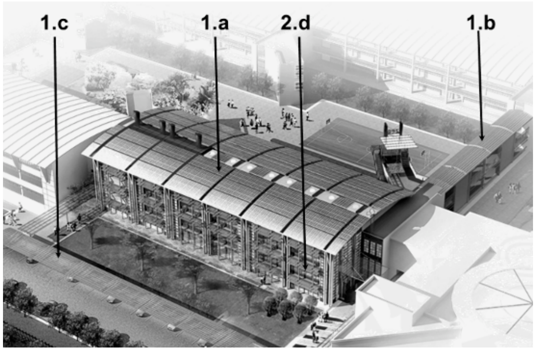


Figure 4: BIPV roofs, shading and facade

The central staircase will receive two treatments. A viewing platform will be added to allow for a 360-degree view over the whole precinct, including the central activity areas, the massive PV roof and other façade integrated green building technologies.
Secondly, the concrete front wall will be converted into glazed PV curtain wall bringing light into the formerly gloomy staircase (2f). Here, semitransparent and opaque PV modules will be integrated in staggered horizontal bands to further demonstrate their light modulating qualities in reducing glare, colouring and redirecting daylight.

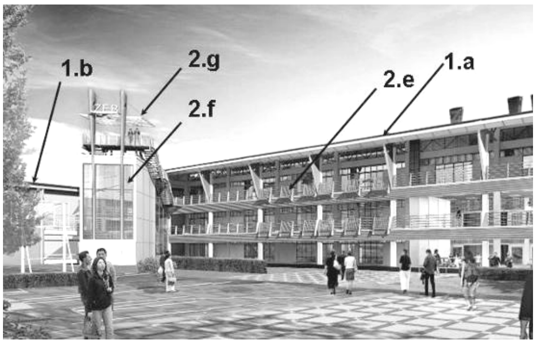


Figure 5: BIPV design of PV staircase glazing, viewing platform, PV roofs, PV railing

First generation PV technologies such as wafer based mono- or polycrystalline are located on the ground floor; 2nd generation thin-film PV follows on the second floor, topped by novel 3rd generation PV technologies the highest level, the viewing platform. Bi-facial organic cells will be integrated into the glazed railing and canopy (2.g). All curtain wall PV modules are within close range allowing a 'look and feel' experience. The specific vertical layout becomes the 'PV-Technologies Evolution Gallery', marking a unique aspect of our educational and architectural mission of the ZEB.

4. Tendering

Ideally, one would be looking for a façade and roof contractor that also takes care of PV modules and their integration into the building envelope. However, the current regional market is split into PV system integrators (SI) and main contractors. Given the complex and non-standard PV specifications, we concluded that only SI can meet the BIPV requirements.

4.1 Call for PV tender

The call for tender was made public through the common channels such as regional newspapers and online tender system. In addition, it was sent to the various PV Power Systems tasks of the International Energy Agency (IEA) to attract international SI. Interested parties, who collected the detailed tender specifications, were invited to attend a presentation with Q&A session and a site inspection. The presentation stressed the following key challenges:

- The tender calls for performance in terms of meeting an energy production target, rather than installed capacity. SIs were to present comprehensive energy predictions and warrant the performances. The overall energy target as well as the PV technologies for the various integrations was a non-negotiable criteria. However, in terms of PV module efficiency and used space we offered some flexibility as long as the overall energy target is met (figure 6).
- A variety of PV technologies must be displayed to compare performance and looks. Rather than dealing with one supplier or one PV module type, system integrators had to source for additional supplier of other types outside their usual range.
- PV modules were to be multifunctional integrated into shading, glazing and railing besides the usual roof-top installation. Innovative proposals were required to integrate various sizes architecturally and mechanically
- Detailed monitoring of cell temperature, power and incident solar radiation must be provided, All data must be fed into a central Building Management System.

		AC Energy Generation (MWh/yr)*	PV Techn.	*Min Installed kWp DC*	*Min PV Module efficiency (%)*	*Min Area (m2)*
1.	Rooftop					
	a. Main curved roof	**155**	**1G**	*> 140*	*> 13*	*>940*
	b. Walkway shelter roof	**21**	**1G**	*> 19*	*> 13*	*>128*
	c. Car park shelter roof	**9**	**2G (TFSI)**	*> 8*	*> 6*	*>136*
2.	Facade					
	d. Sun shade West	**0.64**	**2G**	*> 1.4*	*> 6*	*> 24*
	e. Railing East	*> 0.09*	**2G**	*> 0.4*	*> 2*	*> 7*
	f. Staircase	*> 1.27*	**1G/2G/***3G*	*> 2.8*	*> 5 / 2 / TBC* *> 11 / 4 / TBC*	*> 43*
	g. Optional canopy over staircase platform	*TBC*	*3G*	*TBC*	*TBC*	*> 30*

Italic fonts denote negotiable values, bold fonts denote non-negotiable targets
*) Assuming 1100Wh/Wp/yr or 3Wh/Wp/day for energy generation
1G: Wafer-based crystalline silicon
2G: Thin film silicon, Copper-indium/gallium-diselenide/disulphide and relate CIGSS, Cadmium telluride
3G: Emerging PV-technologies such as inorganic thin-film spheral CIS, organic cells

Figure 6: BIPV specifications

Notably, around 55 representatives from companies operating locally and internationally attended and were interested to take on the challenge to grow with this project.

4.3 PV-Tender submissions

After a tendering period of four weeks, seven SI eventually submitted. Only four provided energy calculations indicating that the energy target was met. The others just submitted data on capacity without any energy calculations or performance guarantee. All offered the required comprehensive drawings and string plans for the roof PV arrays, three submitted architectural drawings presenting the intended integration of various PV modules into the staircase façade. Only one SI offered a customized framing system capable of holding PV panels of various thickness and size. Four offered the full range of PV technologies. Initially, one SI was able to offer 3G PV technology Three more SIs followed suit after the interview. The overall costs deviated around 10%, lesser on the PV module cost, but around 50% for integration costs. The costs for additional maintenance over a 5 years period differ almost 10 fold, particularly for those who offered for low overall costs.

4.4 Quality Assessment

The team had earlier on agreed on an assessment following the Price-Quality Method (PQM), where price-related criteria account for 70% and quality-related criteria account for 30% respectively. The PQM criteria included Quality Performance, Safety Performance, Financial Performance, Track Records, Module Efficiency, System Efficiency, Resource Planning and Method Statement, Awards Obtained and Tangible and Intangible Benefits. Table 3 lists the criteria assessed by the author.

Assessment Criteria	Max Score
Track records	20
Module/System Efficiency	30
Resource Planning, Method Statement	10
Tangible and Intangible Benefits	20

Table 3: Assessment criteria

The following list present some of the criteria assessed to compute the scores:

- Energy target
- Reliable energy predictions
- Range of PV technologies offered
- Integration with façade/roof contractor
- Qualification of the team
- Comprehensive schedule and strategy
- Provision of test certificates for PV modules
- Layout and string plan
- Performance warranty
- Monitoring
- Maintenance

4.5 Post-Tender Interview assessment

Following an initial PQM, the shortlisted three SI were invited for interview. They had to prepare proposals on selected topics, including:

A. Energy Target

- Present details and method of the energy output calculation. Highlight what energy output you can warrant over which period. What will your warranty include?
- We are exploring an option to leave the horizontal ducts over the main roof leading to the solar chimneys uncovered by PV modules, which means that the available area will be reduced by 50 m^2, which would result in a reduction of the energy output of roughly 5%. Present alternatives to maintain the energy target by either covering alternative roof areas or offering higher module/system efficiency to make up for that loss.

B. BIPV Demo-site

- Present the proposed PV layout including info on PV-technologies and efficiency for the main roof and staircase facade.
- Visualize the look of the staircase façade with the different PV-technologies of the PV panels and their architectural integration
- Present mounting/integration details and how you would collaborate with roof and facade contractors to ensure a presentable and fully functioning integration of the PV modules in the roof, facade, shading, staircase, railing, canopy etc., demonstrating leadership in BIPV. Clearly identify responsibilities and warranties.

C. Research

- Present the string plans for all roofs and staircase façade with location of the inverters and type and location of the various sensors. Consider partial shading and different inclinations of the PV modules.
- Present the data that can be monitored by the inverters and clarify how one can access the data via Internet even outside the BMS.

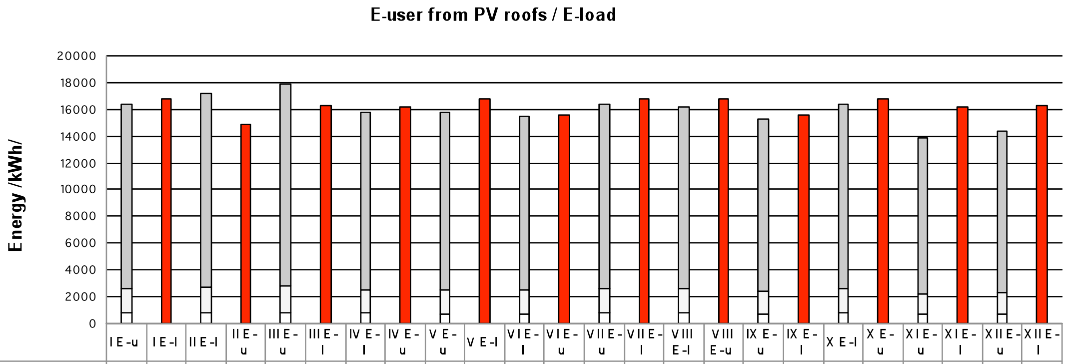
4.6 Independent energy checking

The PV energy calculations of all shortlisted submissions were subjected to an independent and detailed check using the validated simulation software PVSYST V4.3. The simulation parameters included the following:

- Singapore weather data
- PV module collector plane tilt and azimuth
- Horizon and near shading modelled in 3D
- Heat loss factor
- PV-module product, number
- PV array layout, current and voltage
- Inverter product PV

Each array-inverter-tilt/azimuth combinations resulted in on simulation run and the results include:

- Produced annual Real Energy, Yield Factor and Performance Ratio defined in chapter 2.3



	I E-u	I E-l	II E-l	II E-u	III E-u	III E-l	IV E-l	IV E-u	V E-u	V E-l	VI E-l	VI E-u	VII E-u	VII E-l	VIII E-l	VIII E-u	IX E-u	IX E-l	X E-l	X E-u	XI E-u	XI E-l	XII E-u	XII E-l
E load		16819		14854		16238		16164		16819		15583		16819		16819		15583		16819		16164		16238
E-user - Main roof	13771		14445		15048		13204		13242		12968		13797		13577		12821		13819		11663		12082	
E-user - Walkway	1834		1921		1983		1770		1766		1737		1835		1807		1710		1844		1566		1625	
E-user - Carpark	766		803		843		776		750		744		782		798		750		767		657		683	

Figure 7: Normalised Production across all months

- Normalised production across all months as in Figure 7.
- Monthly breakdown of global and incident solar radiation, ambient temperature and energy before and after the inverter.
- Detailed loss diagram over the whole year.

The total annual energy was then calculated by adding all arrays for the main roof, car park and walkway shelter. These values were then compared to those calculated by the SI.

Overall, all three SI met the required overall energy targets, however with designs slightly different from the specifications. As introduced earlier on, we allowed for that flexibility, but used the deviations to rank these shortlisted SI.

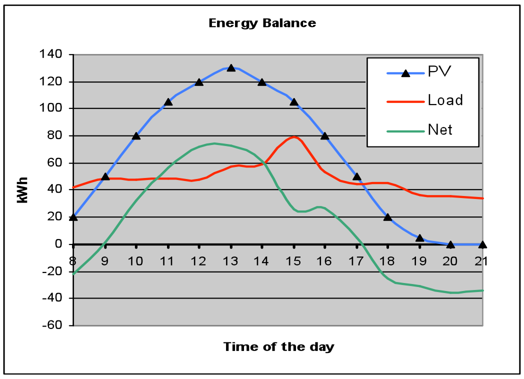


Figure 8: Daily energy balance

4.7 Tender award

The detailed tender specifications lead to comprehensive submissions. Following their assessment using the Price-Quality Method (PQM) including the clarifications during the interview, a suitable SI was identified. Tender award is scheduled for July 2008 together with the award for the main tender for façade and roof of the ZEB.

5. Conclusion

The presented work introduced the BIPV design development, final designs specifications and tender assessments. Commissioning is scheduled for fall 2008 followed by a one-year evaluation and fine-tuning period. The presented rendering and performance calculations will serve as a reference for the actual performance once built. An initial simulation of the energy balance comparing the monthly (Figure 7) and daily (Figure 8) energy load and the supply from PV indicates that we on the right track in achieving the net-zero-energy target.

6. Acknowledgements

ZEB at BCA Academy is BCA's flagship R&D project with funding support from Singapore's Ministry of National Development and Economic Development Board. The presented work is a result of the entire project team, comprising the Principal Investigators (A/Prof Lee Siew Eang and A/Prof Wong Nyuk Hien) of the respective research teams, the Architect (DP Architects), the Project Manager, M&E/C&S Consultants (Beca Carter Hollings & Ferners) and the Quantity Surveyor (Davis Langdon & Seah). NUS Visiting Scholar Vesna Kosoric was instrumental in the assessment of the PV energy simulations submitted by the PV system integrators.

7. References

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ii Internet: en.wikipedia.org/wiki/Zero_energy_building

iii ASHRAE '08 Winter Meeting New York: Guidance for Net-Zero Energy Design Highlighted in technical Program, Internet: http://www.ashrae.org/pressroom/detail/16503

iv Definition of ZEB under Commercial Building Design and Performance. Internet: http://www.nrel.gov/buildings/comm_building_design.html

v Around 10% deviation depending on the sources, the value used here is an average of data from Meteonorm, Building Simulation Weather data, and measurements in Singapore

vi Clean Energy Research and Test-bedding (CERT), launched by Singapore Clean Energy Programme Office (CEPO)

vii ZEO and LEO Building, http://www.ptm.org.my/PTM_Building/