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General model of Photovoltaic (PV) integration into existing public high-rise residential buildings in Singapore – Challenges and benefits

Vesna Kosorić, Siu-Kit Lau*, Abel Tablada, Stephen Siu-Yu Lau

Department of Architecture, School of Design and Environment, National University of Singapore, 4 Architecture Drive, Singapore 117566, Singapore

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ABSTRACT

Despite having the average annual solar irradiation of 1580 kWh/m^2, Singapore's current high dependency on fossil fuels (95%) cannot be sufficiently reduced through rooftop PV integrations alone, and façade integrations may present a viable solution for obtaining a higher share of renewable energy generation. The existing Housing and Development Board (HDB) buildings have great potential for both roof and façade PV integration. Since PV building integration is a complex and dynamic process requiring holistic approach and problem-solving strategies in all process stages, its major challenges are finding the proper balance between interrelated and mutually conflicting criteria related to electricity generation performance, economic, environmental, spatial/urban, functional, aesthetic and social aspects. This article defines a general model of PV integration into existing public high-rise residential buildings in Singapore, and also presents challenges and benefits pertaining to it. In order to provide a better understanding of the whole process, the model is divided into seven basic phases detailing the role of each phase and allowing model optimisation at the level of a particular phase. A systematic analysis of each phase is provided, and the problem-solving methods and/or procedures applied are discussed. Vikor method, a multi-criteria decision making (MCDM) method is recommended for a comprehensive evaluation of design variants, selection of the optimal PV integration design variant, and sensitivity analysis testing robustness of the selected design variant "optimality". The defined methodological framework is also employed to solve PV integration into an existing 12-story slab-block HDB building. The evaluation of created design variants against aesthetic criteria was supported by a customized web survey and qualitative interviews that were performed in order to provide information on opinions and perceptions of local professionals regarding different roof and façade PV integration designs. The analysis of the web survey results is presented and discussed.

1. Introduction

Burning of natural gas accounts for 95% of electricity generation in Singapore [1]. Alternatives to gas-fired power generation are very limited due to several factors:

- Nuclear power generation is not a practical solution in a densely populated environment;
- Coal-fired power generation causes high pollution levels;
- Singapore has no hydro power generation potentials;
- Wind power generation is too dispersed and requires a lot of space on land which Singapore does not have.

Singapore however has the annual irradiance level of 1580 kWh/m^2 [2]; hence, solar power generation is the only practical alternative to gas-fired power generation. Although the grid-connected installed capacity of the PV systems has almost quadrupled from 33.1 MWp in 2014–129.8 MWp at the end of the first quarter of 2017 [1], this is insufficient for reduction of dependency on fossil fuels. There are no state subsidies for PV power generation; hence the profitability of PV power generation is much lower than the profitability of natural gas power generation. This disproportion on the return of investment between PV and fossil fuels generation discourages investments in PV installations as the only alternative source of power generation. Electric power companies are not inclined to invest in PV power generation

Abbreviations: PV, Photovoltaic; HDB, Housing & Development Board; MCDM, Multi-Criteria Decision-Making; USEP, Uniform Singapore Energy Price; RES, Renewable energy source; SCBB, Solar Capability Building Programme; DM, Decision Maker; BIPV, Building integrated Photovoltaics; BIA, Building Integrated Agriculture; BAPV, Building applied/attached Photovoltaics; SCDF, Singapore Civil Defence Force; PE, Professional Engineer; CityGML, City Geography Markup Language; BoS, Balance of System; mono c-Si, Monocrystalline silicon; poly c-Si, Polycrystalline silicon; a-Si, Amorphous silicon; CIS/CIGS, Copper Indium Selenide; OPV, Organic Photovoltaic; IDP, Integrated design process; BCA, Building and Construction Authority; URA, Urban and Redevelopment Authority; EMA, Energy Market Authority; EMC, Energy Market Company; SI, System Integrator; LEW, licensed electrical worker; NUS, National University of Singapore; IRB, Institutional Review Board; LCC, Life cycle cost; LCA, Life cycle assessment

* Corresponding author.
E-mail address: slau@nus.edu.sg (S.-K. Lau).
URL: https://www.acousticsresearch.com (S.-K. Lau).

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since this would reduce the market price of electricity and hinder their main source of income from gas-fired power generation.

Reliance on rooftop PV installations alone, however, is not sufficient to noticeably reduce the dependency on natural gas. Large façade areas of high-rise residential buildings may significantly contribute to PV integration potential in the cityscape [3,4] despite the fact that the solar potential of façades is more affected by the compactness than is the case with roofs [5,6]. Although the solar irradiation on vertical surfaces is much lower than on horizontal surfaces (approximately −48.5% (east) up to −64.3% (south orientation)) [7], the use of rooftop installations is limited [8] and façade installations should be exploited as a means of electricity generation from renewable energy sources (RES) [9]. Exploring the potentials of an extensive PV installations application on building façades and public spaces in Singapore is therefore of paramount importance in reducing the dependency on natural gas for power generation as well as CO_2 emissions.

The existing HDB buildings in Singapore house 82% of its population in more than 1 million flats organized in 23 towns and 3 estates across the island [10]. HDB buildings have great potential for both roof and façade PV integration and may play a key role in driving sustainable development by helping harvest solar energy. In an effort to promote sustainable development, in 2009 HDB's Solar Capability Building Programme (SCBB) for public housing initiated differently scaled PV test-bedding in existing buildings. The programme has recently expended to new towns as well [11]. Both main block types, slab and point blocks, offer good design possibilities for PV building integration [12] since the building orientation, standardized pre-fabricated building envelope elements that enable costs reduction [13], and building envelope design, all work in favour of PV integration. PV integration plays an important role in building retrofitting since well-thought-out solutions can increase a building's value, both aesthetically and energy wise [14]. By joining together electricity production and environmental benefits with urban and architectural qualities, successful PV building integration can play a crucial role in promoting sustainability. Such factors are the driving force behind further PV integrations and encourage architects and authorities to use PVs in their designs. PV integration design touches the human dimension – not only does it stand for a strong brand of green energy, but it also motivates and empowers individuals and households to engage in sustainable behaviour [15] by developing a sense of responsible energy consumption and environmental consciousness.

PV building integration process, starting from the preliminary definition of project objectives to operation /monitoring of the installed PV system, is a dynamic and complex process. The said process involves a number of players and decision makers (DM) [16] and considers a variety of other factors such as energy performance, economic, environmental, spatial/urban, functional, aesthetic and social aspects and hence requires a comprehensive approach employing holistic problem-solving strategies. General models serve as a helpful tool for problem-analysis and problem-solving in the solar systems building integration process [17]. This article defines one such general model that focuses on PV integration into existing public high-rise residential buildings in Singapore and analyses the challenges and benefits of PV integration. The model envisages an iterative process methodically divided into seven basic phases that provide better insight into the process as a whole as well as the role and importance of each phase within the process, ultimately enabling optimisation at the level of each particular phase. All relevant factors pertaining to a particular phase are systematically analysed, graphically presented and adequate methods and/or procedure leading towards solutions are proposed. The general framework established in this article can be directly applied as a helpful tool to define general models for PV building integration in retrofitting of offices and other building types, and also in new buildings in Singapore. Its systematically derived guidelines may serve as a support platform to solve the active solar systems integration problem in other countries as well.

Vikor method [18,19], a multi-criteria Decision-Making (MCDM) method, is often applied to resolve practical considerations concerning sustainability and renewable energy since these fields are complex and involve incommensurate and conflicting criteria [20–22]. The method helps determine the appropriate compromise solution allowing DMs to arrive at a final decision. The application of the Vikor method in the proposed model helps achieve the following: (1) it addresses practical issues regarding the building integration of both solar thermal systems [17,23] and PVs [24–26], (2) it enables holistic evaluation of design variants and, optimisation of the PV building integration design variant and (3) it helps perform sensitivity analysis through which the robustness of the selected design variant “optimality” is tested. The defined general model is also used to tackle PV integration into an actual 12-story slab-block HDB building, representative of 1970s’ HDB New Town Model. In order to help evaluate created design variants against aesthetic criteria, a web survey entitled “Architectural quality of PV integration into an existing HDB block in Singapore” as well as a number of qualitative interviews were created and performed in July and August 2017. The aim was to obtain opinions and perceptions of local professionals regarding different roof and façade PV integration designs. This paper presents and analyses the results of 191 received completed surveys and discusses different preferences of architects/designers (73% of all respondents) and other professionals including engineers, contractors, and researchers in the PV systems (remaining 27% of respondents), as well as the different preferences of those with and without PV experience.

2. Potentials of the existing high-rise public housing in Singapore for PV system building integration

2.1. Potentials of the climate – direct time correlation between solar radiation/PV electricity generation and electricity consumption

A large portion of electricity consumption in Singapore goes towards air conditioning, specifically on cooling during the solar heat load at daytime. Power generation from PVs directly offsets the load of electricity consumption during the on-peak period relieving and balancing energy demand on power plants in an efficient way. Fig. 1 shows the average monthly household consumption of electricity for a typical slab-block HDB building in Clementi town in Singapore, where the building analysed in the present study is located, and it shows a favourable correlation between sun irradiation and electricity consumption.

Whereas in Europe the electricity for cooling purposes is consumed only over a three-month period, from June until August, in Singapore the consumption occurs consistently throughout the year. Other than

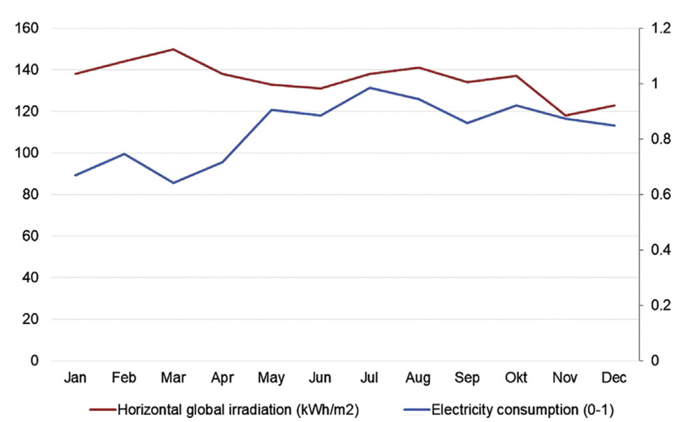

Fig. 1. Comparison of the average monthly household electricity consumption of HDB block in Clementi town in Singapore in 2015 (data source: EMA (Energy Market Authority) [27,28]) and horizontal global irradiation in Singapore (data source: Meteonorm ’97, PVSYST 4_37).