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Integrability Evaluation Methodology for Building Integrated Photovoltaics' (BIPV): Case Studies

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Abstract

Integrability is an evaluation methodology developed for Building Integrated Photovoltaic (BIPV) systems. The need for such a framework had stemmed from the complexity of evaluating the entire system (BIPV + building) and not only one of its components (PV). This means that designing BIPV systems based on solely the electricity generation goal may not always result in optimal design. The current paper deals with the application of Integrability through two different case studies. The first one discusses the utility of Integrability in assessing a BIPV system while the second one utilizes Integrability as a decision support tool to locate the ideal PV placement on the building. Integrability as a decision-making tool has been the highlight of this paper.

Keywords: *Buildings, Integrability; Building Integrated Photovoltaic.*

1. Introduction

The performance evaluation of a BIPV system has been looked at as separately through electrical, thermal, economic and environmental observations. However, in a BIPV, as soon as PV is integrated into a building as an envelope material, it has to satisfy the functions of an envelope and thereby satisfy building climate-responsiveness. How can performance evaluation of PV in a solar power plant differ from that as a building envelope? Is it justified, if BIPV systems are appraised only on their electricity generation aspects? The current evaluation does not provide any distinction and is more oriented towards a part (PV) rather than the entire system (BIPV). The function of the part (here PV) is to produce electricity and the aim of evaluation is limited to evaluating energy generation in order to maximize the output. Although the technology of energy conversion still remains the same, the application of PV technology into the building gives it a multi-functional bearing as a part of the building. None of the present performance appraisal methods consider this into account and make the evaluation mostly electricity centric. It is to be realized that the usage of PV as a renewable and decentralized energy option comes at a price as its low energy densities demands extensive shade free space. It is only counter intuitive to go renewable with respect to the power generated but consume the same on the conditioning of the building. A truly effective alternative would passively integrate PV into the building by appropriate climate-responsive design. A residential BIPV system is a home first and then only a mini solar plant. Emphasis on the electrical performance has to be thus considered in conjunction with the indoor thermal comfort. The impact of BIPV as a building material on the living conditions fulfilling the basic functionalities of a shelter is yet to be comprehended and only such an understanding should be truly considered as the "overall performance" of any given BIPV system. Currently, the focus of most of the researchers has been in parts understanding the ways in which efficiency of the solar panels gets affected [1-5] or in determining the heating and cooling loads of the building [6-7]. There is a need of a holistic evaluation methodology that looks at an integrated approach to

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efficiency of the panels, the electricity requirements of the building and the indoor thermal comfort of the occupants which comprise the three pillars of a BIPV system i.e. building, people and PV. Integrability is the study that tries to fill this research gap, focusing on the

'functionality' of the building system. The functionalities, in this case, provide a blend of building, PV and people (including but scoped to in this work to provision of thermally comfortable indoors and economical generation of maximum electricity from the PV system).

2. Integrability Methodology

Integrability is an aid which helps us to evaluate, rate and compare BIPV systems. An attempt has been made to look at the three fundamental spheres of a BIPV system (Building, PV and occupants) and identification of corresponding quantifiable parameters to deliver a better performance evaluation scheme. In the Integrability approach, the BIPV system is divided into its three interactive majors viz. building, photovoltaic and people/occupant, to understand quantification of parameters for evaluation of a BIPV system. The functionality of a residential building includes provision of a safe shelter, comfortable stay compared to the ambient and sound aesthetics. For this study, BIPV has been considered to be a multifunctional system in that it generates electricity, replaces traditional envelope by forming the building envelope and catering to the buildings energy requirements. "*The functionality of a BIPV system (scoped in this paper) is to provide thermally comfortable indoors, generation of maximum electricity from the system by catering to the energy demands in a climate responsive building environment and ensuring an economically viable system".* Depending on the aim of the evaluation (whether to compare or rate or simply evaluate a single system) these perspectives may change and thus Integrability is a generic methodology that can cater to a variety of users.

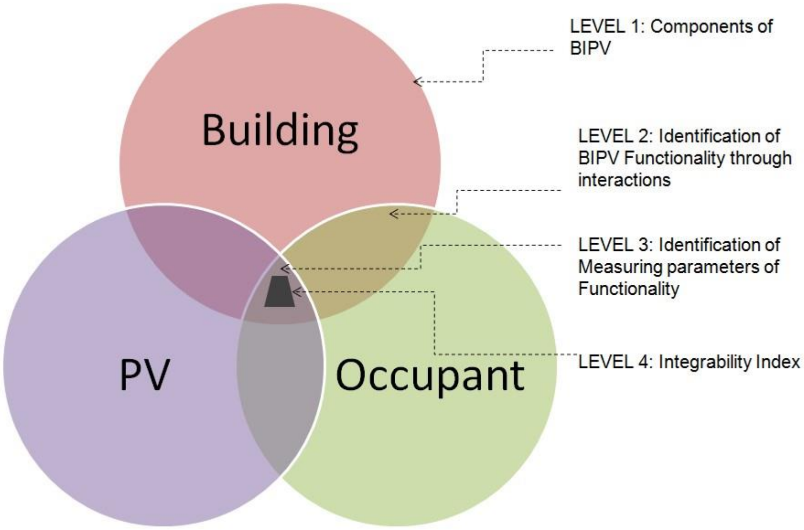

Figure 1. Schematic of the Integrability Methodology

2.1. Integrability Index

It is important to mathematically quantify Integrability based on the functionalities. Each functionality may have a measuring parameter that may not be consistent (in the units) with other parameters. Integrability index has been defined as the geometric mean of the various functionalities appropriately normalized would give the evaluation parameter known as the

Integrability Index with the general formulation as below [8]. The aptness of the geometric mean in the formulation of the Integrability Index and the associated terminologies has been explained in [8]. The aim is always to maximize performance of each of the functionalities in order to maximize the Integrability Index (which is a number between 0 and 1). The schematic of Integrability methodology can be illustrated superimposed on the pillars of BIPV as shown in Figure 1.

$$\text{INTEGRABILITY INDEX (II)} = \sqrt[n]{(\boldsymbol{f1} * \boldsymbol{f2} * \boldsymbol{f3} \dots\dots * \boldsymbol{fn}} \tag{1}$$

2.2. Integrability Parameters

The Integrability framework has identified the necessary parameters to compute Integrability. As has been mentioned, functionalities of the system (in the paper), has been classified as electricity generation and provision of thermal comfort through climate-responsiveness and energy management for efficient consumption and economic feasibility which correspond to the five quantifiable parameters. The electricity generation from PV (denoted as PV energy, PVE) while the energy required for thermal comfort (denoted as thermal comfort energy, TCE). The building actual energy demand has been represented as TEC (total energy consumed) and the total costs and benefits as C and B respectively. Apart from B and C, all other values can be either calculated theoretically or measured real-time. The choice of these parameters has been explained well in the paper [8-9]. Their formulations which will yield quantitative values (which is the interest in this paper) have been listed out through equations 2 – 5. Utilizing these equations and the formulation of the Integrability Index certain case studies have been worked out in order to document the utility of the index as a decision-making tool. The following sections shed light on the same.

$$PVE(normalized) = \frac{Actual\ PVE\ (per\ unit\ area) - Minimum\ PVE(per\ unit\ area)}{Maximum\ PVE\ (per\ unit\ area) - Minimum\ PVE(per\ unit\ area)} \tag{2}$$

$$TCE(normalized) = \frac{Maximum\ TCE - Actual\ TCE}{Maximum\ TCE - Minimum\ TCE} \tag{3}$$

$$PV\ Loading\ Ratio(normalized) = \frac{\left\{\frac{PVE-TECe}{PVE+TECe}+1\right\}}{2} \tag{4}$$

$$CBR\ (normalized) = \frac{\left\{\frac{C-B}{C+B}+1\right\}}{2} \tag{5}$$

3. Case Study – Single Room

32 % of the urban residential households (~ 330 million households surveyed) have been found to be single-room residences as per Census of India survey of 2011 (Government of India 2011). As a representative of the Indian urban conditions thus, a one room naturally ventilated concrete building (geometrically a cube of 5.9 m X 5.4 m X 2.7 m) has been modelled and simulated in Design-Builder software to understand the impact of PV placement on TCE for BIPV (Figure 2). A very simple cubic structure has been considered and it has been assumed that the PV can be placed as either the roof or the walls. Considering there is a possibility that a building may not always exist in isolation and there might be other surrounding buildings that might cast a shade, the various possibilities to place PV (as a complete façade) exist on one side, two sides, three sides, four sides (roof and walls, eliminating the floor). Thus, cube with a total of 5 surfaces, the total available combinations for PV placement has been found to be 31 (one-sided: 5, two-sided: 10, three-sided: 10, four-sided: 5 and all-sided: 1). Also considering the possibility that a building may not always exist in isolation and there might be other surrounding buildings that might cast a shade. The TCE values have been computed for 31configurations. To shed light on the suitability of TCE

as a measurement parameter, a comparison of 5 cases with PV on five different walls (each one a BIPV system) has been shown (see Figure 3).

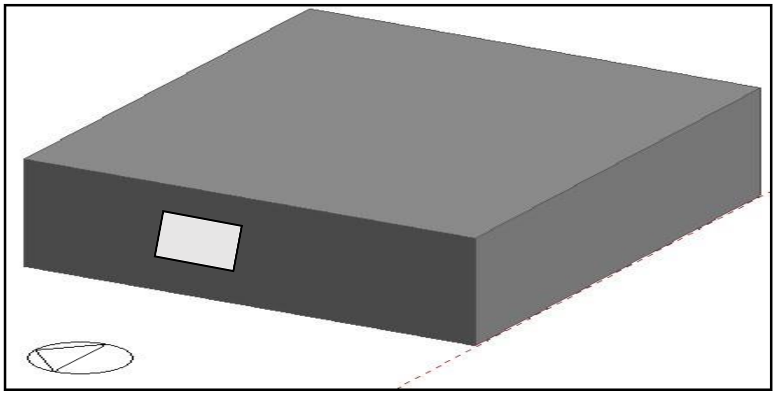

Figure 2. Single-room Design Builder model.

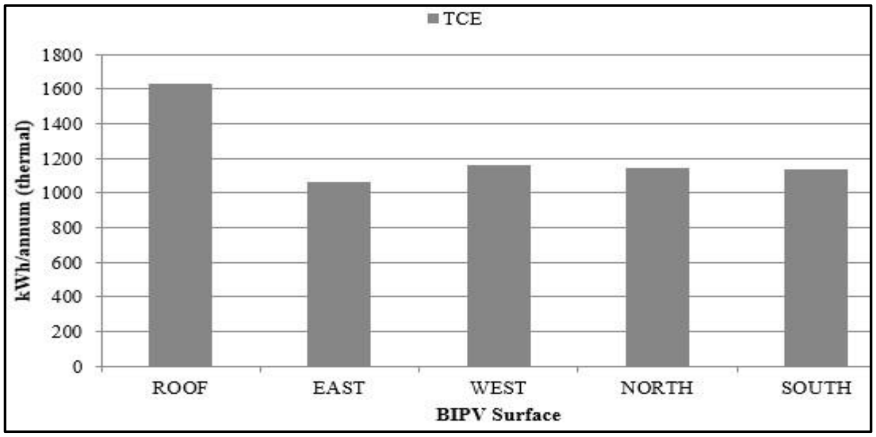

Figure 3. Simulated comparison of TCE and DDH for different surface BIPV system Roof

Integrated BIPV one room naturally ventilated system has the highest value of TCE while the east wall integrated BIPV one room naturally ventilated system has the lowest values (the values have been arranged in the ascending order of TCE). A complete variation of TCE for all the 31 cases has been shown in Figure 4. It can be seen that the value of TCE is the lowest for the east façade. Similarly, for the two, three and four wall systems it has been NE, SNE and NEWS respectively. On the higher side, the TCE varies as roof (single façade), RS (two façade), RWS (three façade) and REWS (four façade) with the highest value of TCE for the five-façade system (RNEWS). The value of TCE for the roof system has been higher and thus roof system (although ideal for high PVE in tropics) can deteriorate climate- responsiveness. For the same 31

cases, a normalized comparison of DDH and TCE has been made in the Figure 5.

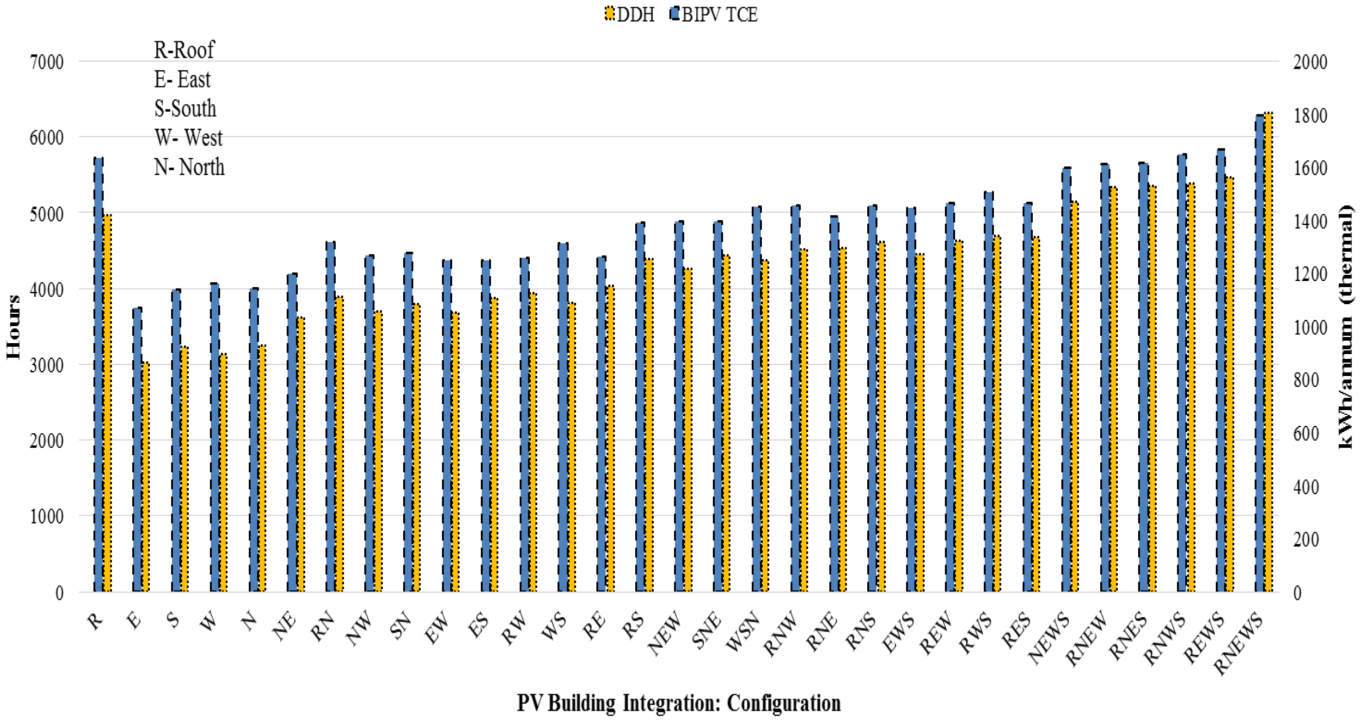

Figure 4. TCE and DDH computed for various roof and facades (31) configurations
(The graph indicates the TCE and DDH computed for corresponding PV installations on each and a combination of the four cardinal building facades and the roof).

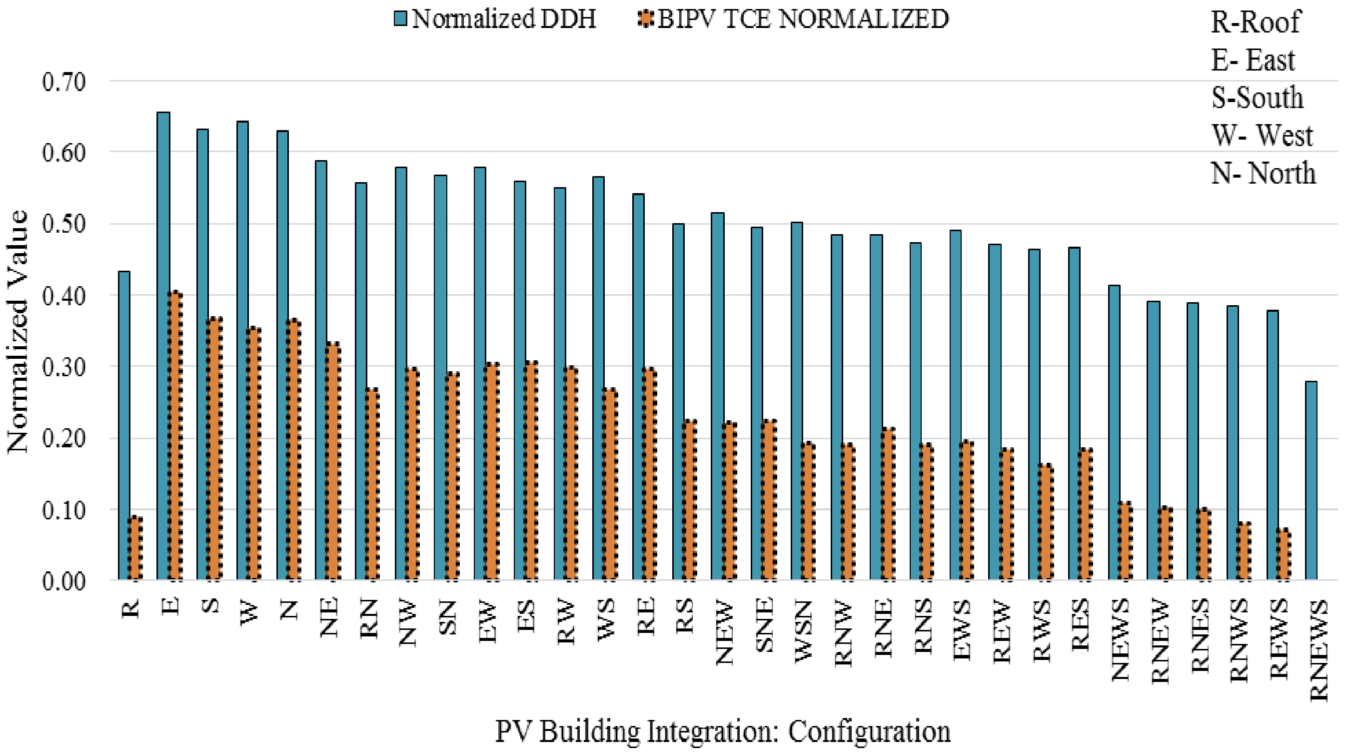

Figure 5. Normalized TCE and DDH computed for various roof and facades (31) configurations.

The PVE and TCE values for the highest PVE producing surface in the respective one surface, two-surface, three-surface, four and five-surface systems has been plotted in Figure 6. As expected from the earlier discussions, with an increase in the PV area, the TCE also increases almost linearly. The TCE value of the roof system is comparable to the four and five façade systems. A comparison of TCE and PVE for all the 31 BIPV cases has been illustrated in Figure 7. It is to be noted that the TCE values between each other are not related, it is just to show the trend. They have to be treated as individual points and not as a continuous function.

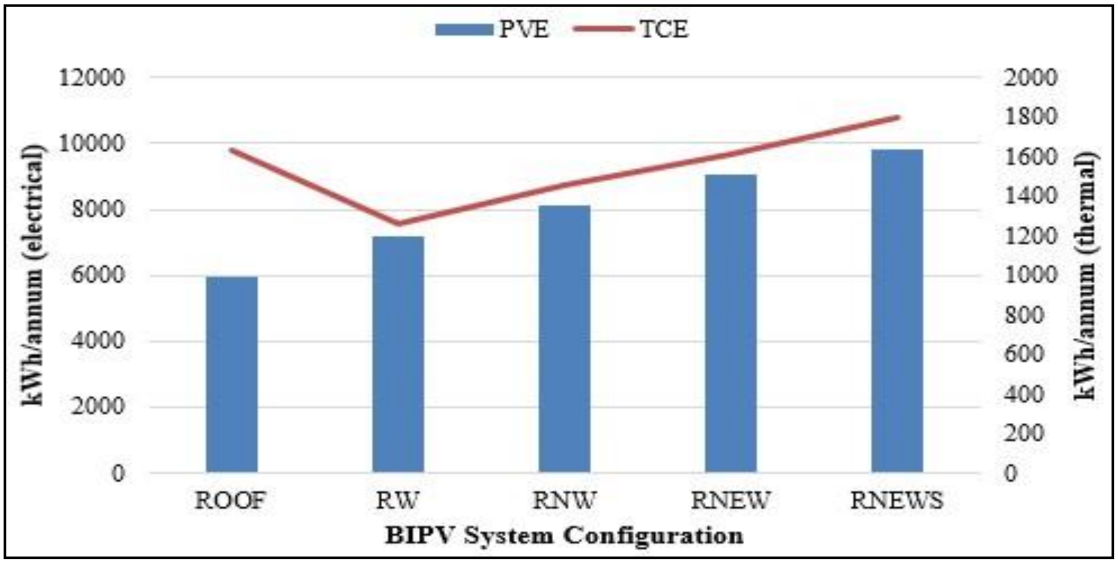

Figure 6. Simulated comparison of PVE and TCE values for the best electricity producing façade systems (category-wise).

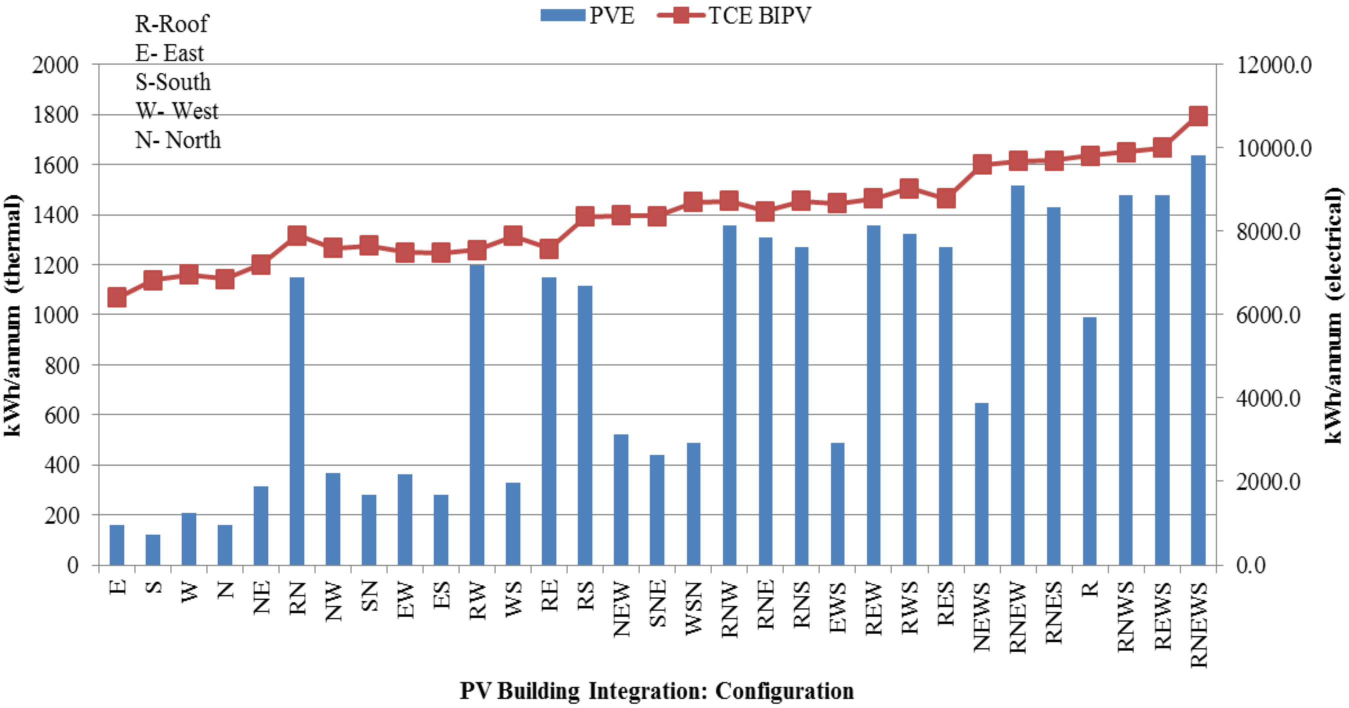

Figure 7. Simulated comparison of TCE with PVE.

3.2. Ideal PV Placement: Applying Zone-Wise TCE

One of the most important viewpoints that has evolved as a result of Integrability has been the ideal placement of PV panels on a building and understanding if there are any preferences for the same. Conventionally, only the shade free available area has been looked at to place PV at the required tilt and orientation. However, it is now known that PV as a building material causes thermal discomfort to the indoor occupants. Thus, it is important to design the system in a manner that can minimize this impact of PV and at the same time meet the energy requirements (or a considerable fraction) of the building. In this analysis the case discusses the 2 BHK BIPV system (Figure 8) with PV to be installed as a combination of roof and west wall (Bangalore climate). The purpose is to first evaluate the Integrability Index for the system and then utilize this tool as a decision support tool by finding the apt location of PV placement on the building.

Integrability has been defined at a BIPV building level and so for a sub-building level, decision making has to be carried out using individual functionalities alone. Another constraint is that while computing TCE for the entire building, it has been assumed that all the rooms (sub-building level zones) would be occupied. Occupancy becomes an important criterion for analysis at the zonal levels. Zones are building spaces that are isothermal based on materials, orientation, ambient temperature, and solar radiation and are connected to each other and with the elements like walls, windows, doors and vents. This translates to a building design problem of meeting the building energy requirement with minimal TCE. Keeping all other functionalities apart, only TCE and PVLR have been considered here for identifying alternatives at the zonal level. Table 1 describes the zonewise case with the type of room and its orientation, the exposed roof area and wall area and the time spent daily in a particular zone. TCE has been computed zone-wise for the entire year by considering the entire building covered with PV panels on all surfaces. Tables 2 and 3 discuss about the order of preference of PV placement considering TCE and PVLR as factors for alternatives. In the case of finding preferences based on maximizing thermal comfort in a climate-responsive manner, severity factor has been considered to include the effect of occupancy patterns in the zones. Severity factor has been defined as the ratio of the total number of hours spent in the zone in a year to the total number of hours in a year. This severity factor is applied to the TCE value of the particular zone to provide the necessary impact. It can be readily seen that TCE (electrical value) after considering the severity effect, the toilet zone is the ideal location for PV placement. The ratio PVE/TCE_e sheds light on this and suitable preferences have been provided for the six zones. The toilet area is low compared to other zones and thus it will not suffice to generate the energy requirement of the building (5876 kWh). In order to satisfy this criterion, preferences 1, 2, 3 and 4 would have to be utilized. In a similar fashion, using PVLR, preferences have been made and here it indicates that the ideal location to place PV is the living room. Again here, this zone alone would not suffice for the energy consumption of the building and to meet the energy demand a minimum of preference 1 and 2 would be needed. Thus, only two choices are left, PV placement on the toilets, kitchen and the children room or on the living room and master bedroom. This issue can be resolved by computing the Integrability index for both the solutions. Table 4 sheds light on the index computation. For both these choices, with the new PV placement, simulation is carried out and TCE is computed (see Table 4). Integrability Index turns out to be higher for the alternative considered with thermal comfort as preference. This case displays the utility of the Index as a decision support system tool. Integrability turned out higher for alternatives that place PV on zones with low occupancy. This case study reveals a new way in which residential BIPV systems can be designed with the aid of Integrability.

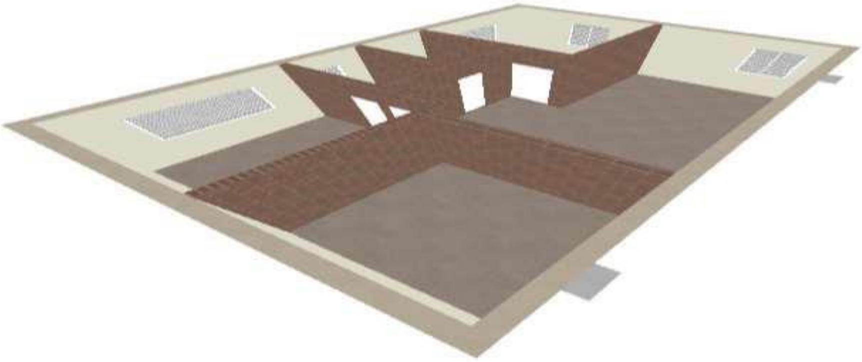

Figure 8. Case- Study of 2 BHK residence.

Table 1. Zone-wise description of the 2 BHK case.

Zones	**Room**	**Orientation**	**Room/Roof Area (m^2)**	**Exposed Wall Area (m^2)**	**TCE (kWh/ annum**	**Time Spent Daily (Hours)**
z 1	Toilet -1	West	3.00	4.16	102.7	2
z 2	Kitchen	South East	9.90	17.47	373.2	10
z 3	Master Bedroom	South West	11.25	18.53	432.3	12
z 4	Toilet -2	West	3.12	4.32	107.0	2
z 5	Children Bedroom	North West	10.17	17.67	376.6	10
z 6	Living	North East	25.48	27.31	906.7	12

Table 2. PV placement preference order with thermal comfort as criteria.

Zones	**PVE**	**TCE**	**Severity Factor**	**Modified TCE_e**	**PVE/TCE_e**	**Order of Preference**
Toilet 1	694.1	102.7	0.08	2.6	267.6	2
Toilet 2	796.3	107.0	0.08	2.7	294.6	1
Kitchen	2785	373.2	0.42	47.1	59.1	3
Master Bedroom	3225.2	432.3	0.5	65.5	49.2	5
Child Room	2766.9	376.6	0.42	47.5	58.2	4
Living Room	5664.1	906.7	0.5	137.4	41.2	6

Table 3. Preference order for PV placement with PVLR as criteria.

Zones	**PVE**	**TCE**	**TEC**	**PVLR**	**Order of Preference**
Toilet 1	694.1	102.7	5876	0.12	6
Toilet 2	796.3	107.0	5876	0.13	5
Kitchen	2785	373.2	5876	0.47	3
Master Bedroom	3225.2	432.3	5876	0.54	2
Child Room	2766.9	376.6	5876	0.46	4
Living Room	5664.1	906.7	5876	0.92	1

Table 4. Integrability Index computation for the two chosen alternatives.

Sr. No.	Functionality	Parameters			Integrability Index	
		Name	Value			
			TCE Based	PVLR Based		
1	PV Electricity Generation	Actual PVE/m^2	100.9	106.1	**0.43**	**0.40**
		Maximum PVE/m^2	291.7	291.7		
		Minimum PVE/m^2	33.8	33.8		
		PVE/m^2 Normalized	0.26	0.28		
2	Climateresponsiveness and Thermal Comfort	Actual TCE (kWh$_{thermal}$)	959.5	1339		
		Maximum TCE (kWh$_{thermal}$)	2298	2298		
		Minimum TCE (kWh$_{thermal}$)	0	0		
		Normalized TCE (kWh$_{thermal}$)	0.58	0.41		
3	PV Loading Ratio	PVE	7042.3	8889.3		
		TECe	6166.8	6281.8		
		PVE/TEC$_e$	1.14	1.42		
		Equivalent PVE/TEC	0.07	0.17		
		Normalized Equivalent ratio	0.53	0.58		

3.3. Framework for the Application of Integrability

The two variety of cases that have been discussed might have demonstrated the utility of Integrability as a tool not only for evaluation but also for testing possible intervention strategies to improve BIPV performance. The intended purpose of Integrability has been from the point of view of performance evaluation alone, although it may find its application to compare various design configurations for new buildings. Integrability could also serve as an appropriate indicator that will lead to an integrated evaluation. A flowchart depicting Integrability Evaluation Methodology is illustrated in Figure 9. There are three stages in the application of the Integrability Methodology. It is important to understand that whether the evaluation involves a single BIPV system or multiple systems. In the former case, there can be a multitude of design possibilities that would need due attention. The very basic step of to apply this methodology is to identify the functionalities based on which comparison could be made. The functionalities have to be the same in case comparisons of two or more systems have to be made. Once the functionalities have been decided, instrumentation and real-time or simulation-based monitoring systems have to be set in place to monitor them. In the case of physical measurement, it is necessary to have standardized instruments and standard operating procedures (SOP). The SOP explains the measurement of parameters and the way they have to be carried out. For instance, the measurement of solar radiation would include the selection of the Pyranometer, the placement of the Pyranometer at the appropriate location and setting the interval for data collection embedded into the SOP. Such practices have to be followed in order to ensure repeatability of measurements. In the case of physical instrumentation, it is also necessary to set the frequency interval for data collection for every parameter. For simulation-based measurements, the model has to be validated appropriately. The application and adoption of codes (say for thermal comfort) has to be made carefully. As far as possible the codes applied should be the same for all the comparisons. The final stage of analysis includes the computation of the index and based on that the rating of the systems (in case of comparisons). This can be utilized for further design modifications and improvisations.

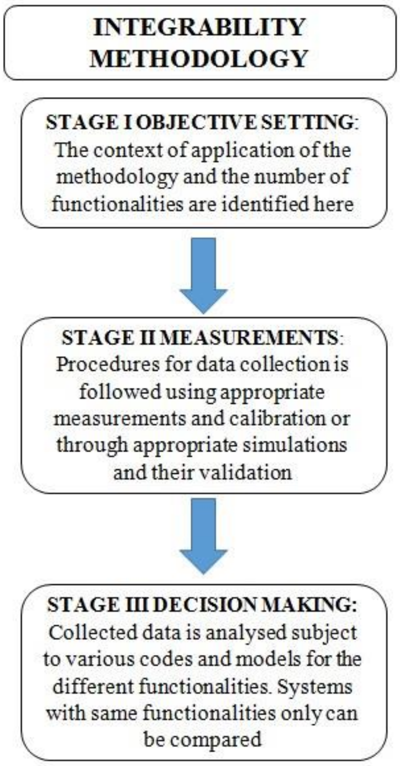

Figure 9. Integrability evaluation methodology as a flowchart

4. Conclusions

BIPV systems, as a technology, is still in a very potent stage in its adoption for tropical countries like India. It certainly has its benefits over many other decentralized energy technologies, however, also has numerous constraints. This paper has tried to develop a methodology that can help in better designing of these systems. The methodology may not directly have intended to the design aspect of the BIPV system. The premise followed here is that the evaluation system in place has a higher bearing on the overall performance of the system. The same consideration of a PV panel is also given to a BIPV system and thus only the electrical performance of the system is classified as the “performance of the system”. The current paper sheds light on a new evaluation technique, Integrability, for BIPV/BAPV systems. Integrability provides an integrated techno-socio-economic assessment platform. The application of Integrability is through two different case studies. The first one discusses the utility of Integrability in assessing a BIPV system and the second case study utilizes Integrability as a decision support tool to locate the ideal PV placement on the building. Different building configurations can be compared using the methodology, provided the functionalities used for the comparison have been the same. The important conclusions that can be inferred from the discussions are that

1. A roof integrated BIPV system need not necessarily be the best configuration in tropical climates as far as the overall performance is of concern.
2. It has been observed that RW configuration (roof and west façade as PV) out of the 31 single room BIPV cases has the highest Integrability Index (0.36) while south wall BIPV system has the lowest value (0.06) based on only two functionalities of PVE and TCE for the climate of Bangalore.
3. An addition of every square meter area of PV panel on the roof of a single room BIPV system (with zero pitch) increases the TCE linearly by 0.73 % on an average for the climate of Bangalore.
4. TCE relations and trends can be generalized only for a particular configuration of the base case model. With a change in the base case model, the TCE trends (with respect to PV area, other surface materials, WWR etc.) also change. The general trend of increasing TCE with increasing PV area may still hold good.
5. Integrability index has been utilized a decision support tool by assisting in identifying the ideal location on the building for PV placement. PV placed on areas (zone of the building either on the rooftop or façade) like the toilets and kitchens (low occupancy zones) show higher Integrability Index compared to PV placed on higher occupancy zones like the living room and bedroom.

5. Future Scope of Work

The current research has initiated the concept of Integrability and so there is a tremendous potential for nurturing it and realizing its maximum potential would require considerable work in that direction. The scope for future work has been identified as follows.

1. Quantification of various other functionalities like the structural rigidity, safety and aesthetic dimensions of a BIPV system need to be done in order to make the index truly multi-faceted.
2. Developing a scheme to compare systems across different time periods and utilization of the methodology as a policy measure to incentivize solar PV residential systems.
3. Understanding the application of Integrability Methodology for decision support systems at a regional level. This will mean understanding the maximum possible limit of residential BIPV systems in a particular locality given the modifications in by-laws and the constraints of the system.
4. Developing pragmatic strategies to improvise the Integrability Index based on building functions specific to locations that can form relevant guidelines and can be incorporated in building standards like the National Building Code and the ECBC.

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