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Energy and Exergy Quasi-Dynamic Analysis of Building Integrated Photovoltaic System Using Data Analytics

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A B S T R A C T

In this paper, quasi-dynamic analysis of a building integrated photovoltaic (BIPV) system has been investigated by using data mining for a simulated case study. To cover the aim of this research, practical generated energy, power conversion efficiency, energy efficiency and exergy efficiency have been analysed as key performance indicators for evaluation of system dynamics. Results of data analytics can be usefully applied to investigate the performance of system in real conditions of operation in compare to the results of models.

1. Introduction

The efficiency of a solar photovoltaic (PV) cell can be considered as the ratio of electricity generated to solar irradiation. In this definition only the electricity generated by a solar PV cell is considered and other properties of PV modules, which might affect efficiency, such as ambient temperature and cell temperature are not directly considered [1]. Building Integrated PV (BIPV) systems play an important role in generating electricity. BIPV's are defined as PV modules which can be integrated to building envelope by replacing conventional building materials [2]. The performance of such systems can also be evaluated in terms of exergy efficiency [3]. Exergy (sometimes called availability) is defined as the maximum theoretical useful work obtainable from a system as it returns to equilibrium with the environment [4].

Several studies and researches was done to cover the aim of performance evaluation for PV and BIPV systems. Joshi and Tiwari [3] have reviewed energy and exergy efficiencies of a hybrid photovoltaic–thermal air collectors. Dubey et al. [5] have provided analytical expression for electrical efficiency of photovoltaic thermal hybrid air collector in their research. Agrawal and Tiwari [6] have investigated life cycle cost assessment of building integrated photovoltaic thermal systems. In their research, they also analyised system performance using energy and exergy analysis. Mishra and Tiwari [7] have carried out energy and exergy analysis of hybrid photovoltaic thermal water collector for constant collection temperature mode. Hepbasli et al. [8] have done an exergoeconimic assessment of a building integrated photovoltaic system.

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Shakouri et al. [9] have investigated an energy and exergy optimization for water cooled thermal photovoltaic system using genetics algorithm.

This research goes one step forward in compare to the previous studies. In this study, authors have investigated performance evaluation of a simulated BIPV system using data anlytics and considering energy and exergy quasi-dynamic analysis. Results of this study would be useful for investigation of system dynamics in simulation or operation of the system.

2. Materials and Methods

Figure 1 shows the three-dimensional view of the studied BIPV system. The geometry of sections A, C and E provide an application of both glass and PV modules as outer façade. Glass could be used in parallel to glass windows of the existing façade and PV modules could be applied in parallel to connecting small walls between levels. Due to the geometry of sections B and D for the existing façade which is a wall, the proposed outer façade being shaped by integrated PV modules wall. Total available area for PV modules is 60 (m^2) and the maximum power output of the designed system is 10.62 (kW). Type of the selected PV modules is mono-crystalline silicon with reference efficiency equal to 14.96 %. Short circuit current and open circuit voltage of the PV modules are 4.8 (Amp) and 21.7 (V), respectively. In order to investigate the behavior of BIPV system to the climate parameters, hourly data for one year starting by 2017-03-01 and ending to 2018-02-28 have been gathered. Irradiance data have been gathered through Solar Radiation Data (SoDa) [10], European Commission – Photovoltaic Geographical Information System [11] and The World Bank – Global Solar Atlas [12]. Gathered data have been processed and it was understood that the BIPV system is available for generating electricity in 2517 hours of the studied year due to the availability of vertical solar irradiance. The most important climate parameters which have been reviewed are including ambient temperature, vertical solar irradiance and wind velocity. In order to evaluate the effect of different climate parameters on the performance of system, practical generated energy and three PV system efficiencies can be considered including power conversion efficiency, energy efficiency and exergy efficiency.

For solar PV cells, efficiency measures the ability to convert radiative energy to electrical energy. The electrical power output is the product of the output voltage and the current out of the PV device, taken from the current–voltage curve (I–V curve). This conversion efficiency is not a constant, even under constant solar irradiation [1].

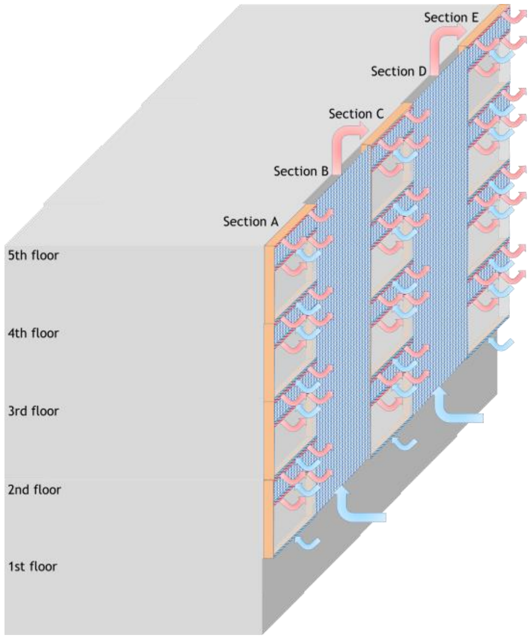

Figure 1. Three dimensional view of the BIPV system

However, there is a maximum power output point, where the voltage value is V_m, which is slightly less than the open-circuit voltage V_{oc}, and the current value is I_m, which is slightly less than the short-circuit current I_{sc}. E_{GH} represents the highest energy level of the electron attainable at maximum solar irradiation conditions ($E_{GH}= I_{sc}V_{oc}$). It is recognized that there should be an active relational curve from I_{sc} to V_{oc}. E_L represents the low-energy content of the electron, which is the more practical energy ($E_L=I_mV_m$). The maximum power point is restricted by a 'fill factor' FF, which is the maximum power conversion efficiency of the PV device and is expressible as [1]:

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{1}$$

The enthalpy of a PV cell with respect to the reference environment, ΔH, can be expressed as [1]:

$$\Delta H = C_p (T_{cell} - T_{amb}) \tag{2}$$

where C_p denotes the heat capacity, T_{amb} the ambient temperature and T_{cell} the cell temperature. The total entropy of the system relative to ambient conditions, ΔS, can be written as [1]:

$$\Delta S = \Delta S_{system} + \Delta S_{surround} \tag{3}$$

or

$$\Delta S = C_p \ln\left(\frac{T_{cell}}{T_{amb}}\right) - \frac{Q_{loss}}{T_{cell}} \quad (4)$$

where

$$Q_{loss} = C_p (T_{cell} - T_{amb}) \quad (5)$$

Here, Q_{loss} represents heat losses from the PV cell. The physical exergy output for a PV cell system can be expressed as [1]:

$$Ex_{physical} = E_{GH} + C_p (T_{cell} - T_{amb}) + T_{amb}\left(C_p \ln\left(\frac{T_{cell}}{T_{amb}}\right) - \frac{Q_{loss}}{T_{cell}}\right) \quad (6)$$

The first term on the right side of this equation (E_{GH}) is the generated electricity at the highest energy content of the electron. The second and third terms are the enthalpy and entropy contributions, respectively.

The total exergy of the PV solar cell can be formulated as [1]:

$$Ex_{total} = Ex_{physical} - \left(\frac{T_{cell}}{T_{sun}} \times (V_{oc} I_{sc} - V_m I_m)\right) \quad (7)$$

where T_{sun} represent the sun temperature.

The BIPV solar cell power conversion efficiency η_{pce} can be defined as a function of E_L and G_{tV} as follows [1]:

$$\eta_{pce} = \frac{V_m I_m}{G_{tV}} \quad (8)$$

where G_{tV} represents hourly total vertical solar irradiance on the surface of BIPV.

The second main energy source is the solar irradiance incident on PV cells. Evaluation of the exergy efficiency of BIPV cells requires, therefore, the exergy of the total solar vertical irradiance. The exergy of solar irradiance, Ex_{solar}, can be evaluated approximately as [1]:

$$Ex_{solar} = G_{tV}\left(1 - \frac{T_{amb}}{T_{sun}}\right) \quad (9)$$

As a result of these formulations, the exergy efficiency ψ can be expressed as [1]:

$$\psi = \frac{Ex_{total}}{Ex_{solar}} \quad (10)$$

The energy efficiency η depends on the generated electricity of the BIPV (E_{GH}) and the total energy input on the vertical surface of BIPV based on the total solar vertical irradiance G_{tV} and can be expressed as [1]:

$$\eta = \frac{E_{GH}}{G_{tV}} \quad (11)$$

The exergy efficiency usually gives a finer understanding of performance than the energy efficiency, and stresses that both external losses and internal irreversibilities need to be addressed to improve efficiency. In many cases, internal irreversibilities are more significant and more difficult to address than external losses [1].

The system has been simulated in PVsyst software and results of monthly and daily energy generation by system have been illustrated in Figures 2 and 3, respectively.

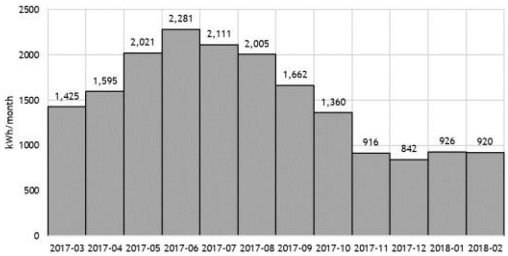

Figure 2. Simulated monthly electrical energy generation of BIPV system by PVsyst software

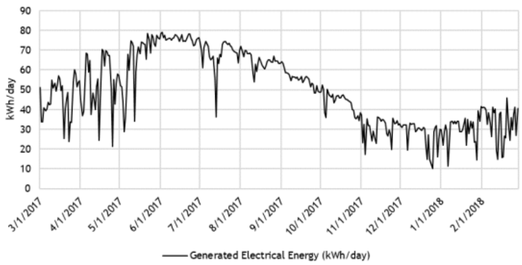

Figure 3. Simulated daily electrical energy generation of BIPV system by PVsyst software

Reference efficiency of the PV modules have been addressed in standard test condition (STC) in which cell temperature is assumed to be 25 degree Celsius. However, in reality the efficiency of PV module will drop if the cell temperature increases. Authors have investigated the effect of different climate parameters based on quasi-dynamic analysis and using data analytics method to provide better understanding of the system dynamics. The method used for data analytics is a liner and non-liner regression analysis. As it has been tested in the analysis, variation of wind velocity has no significant effect on the performance of simulated BIPV system. PV cell temperature has a dependency to the ambient temperature. As the efficiency of PV modules differs with variation of cell temperature and it is relevant to ambient temperature, therefore cell temperature and vertical solar irradiance have been considered as the potential significant parameters.

3. Results & Discussion

Figure 4 illustrates a comparison on theoretical and practical simulated energy generation during one-year application of the system. It is obvious that practical simulated energy generation is lower than theoretical amounts due to differences between reference efficiency and energy efficiency of the PV module cells.

Figure 5 illustrates quasi-dynamic trends for reference efficiency, power conversion efficiency, energy efficiency and exergy efficiency of the PV module for the studied BIPV system. According to the results of this figure, in most cases power conversion efficiency is higher than energy and exergy efficiencies. In addition, the exergy efficiency is also higher than energy efficiency in majority of time and just in some minor periods the variation is different from the above state.

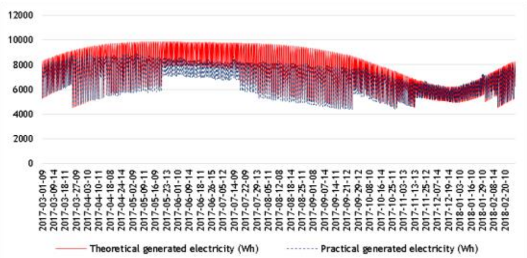

Figure 4. Calculated theoretical and practical energy generation of BIPV modules in quasi-dynamic conditions

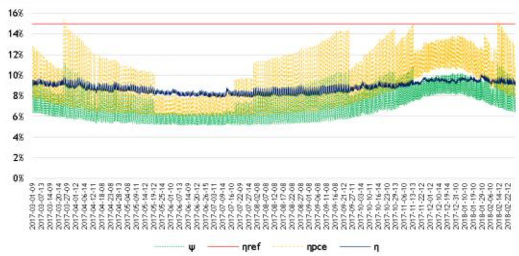

Figure 5. Reference, power conversion, energy and exergy efficiencies of BIPV modules in quasi-dynamic conditions

Figure 6 shows the result of data mining for the studied period which illustrates strong elation between PV module cell temperature and ambient temperature.

Data mining for energy generation in compare to cell temperature and vertical solar irradiance are illustrated in Figures 7 and 8, respectively. According to these figures, energy generation is significantly dependent to variation of vertical solar irradiance. On the other side energy generation has less dependency to cell temperature. This means, cell temperature is not the only significant relevant variable for variation of energy generation.

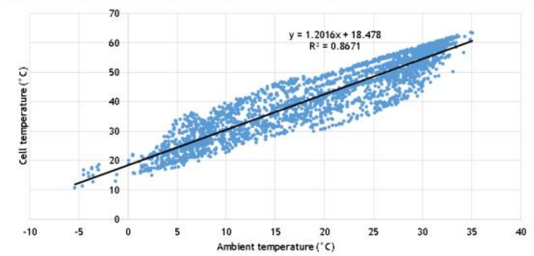

Figure 6. Data mining of PV cell temperature vs. ambient temperature

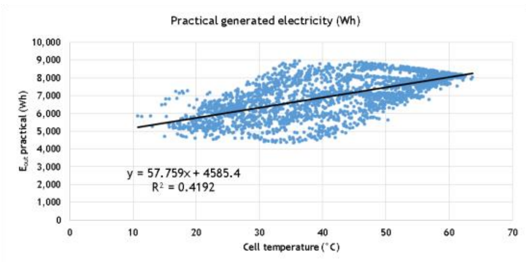

Figure 7. Data mining for practical energy generation vs. cell temperature

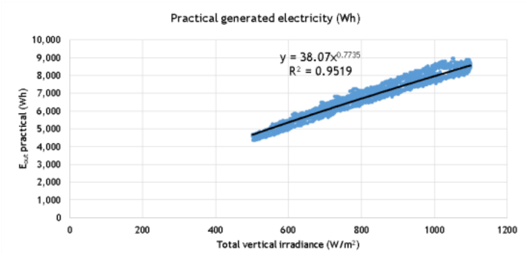

Figure 8. Data mining for practical energy generation vs. vertical solar irradiance

Data mining for power conversion efficiency, energy efficiency and exergy efficiency in compare to cell temperature and vertical solar irradiance are shown in Figures 9 and 10, respectively.

Regarding the cell temperature effect, energy efficiency is completely dependent to cell temperature. Power conversion efficiency and exergy efficiency are both dependent to cell temperature. However, dependency of these two key performance indicators to cell temperature are lower than energy efficiency. Referring Figure 10, power conversion efficiency, energy efficiency and exergy efficiency are significantly dependent on variation of vertical solar irradiance. According to Figure 8, energy efficiency was higher than exergy efficiency.

For the cases with lower irradiation, energy efficiency was higher than power conversion efficiency. On the other side, in higher irradiation, power conversion efficiency was higher than both energy and exergy efficiencies.

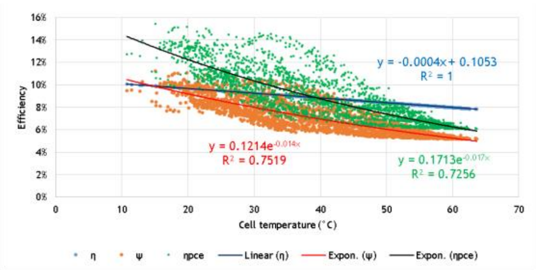

Figure 9. Variation of power conversion, energy and exergy efficiencies with cell temperature

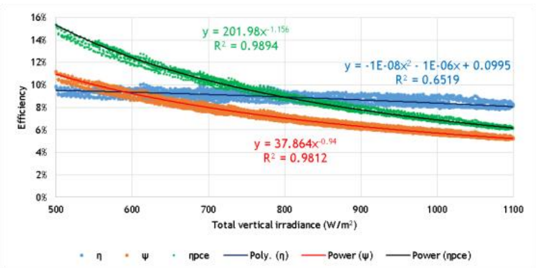

Figure 10. Variation of power conversion, energy and exergy efficiencies with vertical solar irradiance

Results of data analytics for energy generation, power conversion efficiency, energy efficiency and exergy efficiency in compare to cell temperature and vertical solar irradiance are shown in Figures 11, 12, 13 and 14, respectively.

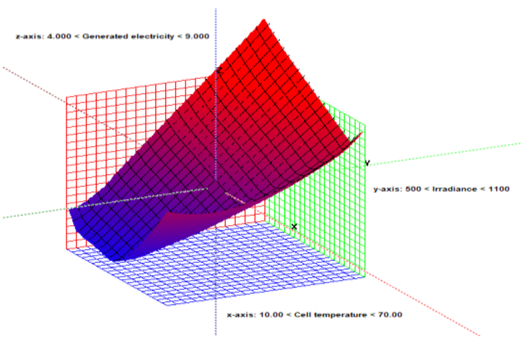

Figure 11. Variation of practical energy generation with cell temperature and irradiance

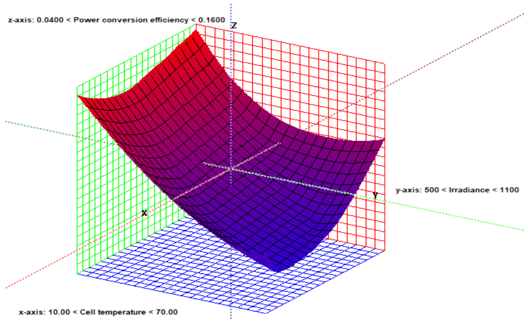

Figure 12. Variation of power conversion efficiency with cell temperature and irradiance

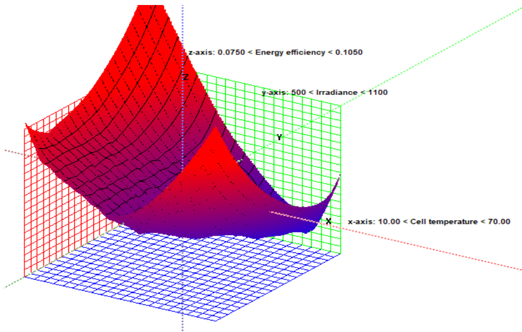

Figure 13. Variation of energy efficiency with cell temperature and irradiance

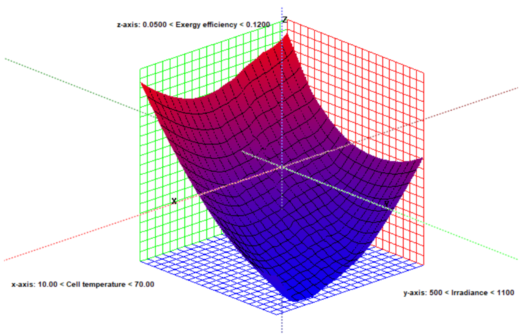

Figure 14. Variation of exergy efficiency with cell temperature and irradiance

According to the results of data analytics, the extracted mathematical functions for the quasi-dynamic analysis of the simulated BIPV system are shown in follows. These mathematical functions can be usefully applied to investigate the performance of system in real conditions of operation in compare to model’s results. In all extracted mathematical functions through data analytics, both vertical solar radiation and cell temperature have been determined as the most significant relevant variables.

$$E_L = (0.0102204 \times G_{tV}) - (0.0415808 \times T_{cell}) \quad (12)$$

$$\eta_{pce} = (0.000163 \times G_{tV}) - (0.0013668 \times T_{cell}) \quad (13)$$

$$\eta = (0.0001501 \times G_{tV}) - (0.00104 \times T_{cell}) \quad (14)$$

$$\psi = (0.0001264 \times G_{tV}) - (0.0010198 \times T_{cell}) \quad (15)$$

Table 1 shows the results of regression models based on data analytics. According to the results of data analytics and based on the statistical analysis test results including R-square and t-statistical, both vertical solar irradiance and cell temperature have significant variation on the extracted mathematical correlations for key performance indicators pf BIPV system.

Table 1. Results of the statistical analysis based on data analytics and regression models

Key performance indicator	R-square	t-stat G_{tV}	t-stat T_{cell}
Energy generation	0.9983	298.6	-60.6
Power conversion efficiency	0.8291	32.7	-13.7
Energy efficiency	0.9475	56.6	-19.6
Exergy efficiency	0.8611	36.1	-14.5

4. Conclusions

In this research, quasi-dynamic analysis of a building integrated photovoltaic (BIPV) system has been investigated by using data mining for a simulated case study. Practical generated energy, power conversion efficiency, energy efficiency and exergy efficiency have been analyzed as key performance indicators for evaluation of system dynamics. Results of data analytics shows that performance of the BIPV system is highly dependent on changes in cell temperature and solar vertical irradiance. In conclusion, developed regression models for all key performance indicators illustrates a significant result for statistical tests including R-square and t-statistical. Therefore, obtained mathematical functions according to the data analytics in quasi-dynamic modes can be usefully applied to investigate the performance of system in real conditions of operation in compare to the results of models.

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Nomenclature

C_p	Heat capacity (kJ/K)
E_{GH}	Generated electricity at the highest energy content of the electron (kWh)
E_L	Practical generated electricity (kWh)
$Ex_{physical}$	Physical exergy for PV cell (kJ)
Ex_{solar}	Exergy of solar irradiance (kJ)
Ex_{total}	Total exergy of PV cell (kJ)
FF	Fill factor
G_{tV}	Solar total radiation on vertical surface (W/m^2)
I_m	Maximum power output point current (Amp)
I_{sc}	Short-circuit current (Amp)
Q_{loss}	Heat losses from PV cell (kJ)
STC	Standard test condition
T_{amb}	Ambient temperature (°C or K)
T_{cell}	PV cell temperature (°C or K)
T_{sun}	Sun temperature (°C or K)
V_m	Maximum power output point voltage (V)
V_{oc}	Open-circuit voltage (V)
ΔH	Enthalpy of PV cell (kJ)
ΔS	Total entropy of system (kJ/K)
$\Delta S_{surround}$	Entropy of surround (kJ/K)
ΔS_{system}	Entropy of system (kJ/K)
η	Energy efficiency (%)
η_{pce}	Power conversion efficiency (%)
η_{ref}	Efficiency of PV cell at standard test condition (%)
Ψ	Exergy efficiency (%)

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