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Performance assessment of a hybrid solar-wind-rain eco-roof system for buildings

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ABSTRACT

A technical feasibility study of an innovative hybrid solar-wind-rain eco-roof system with natural ventilation and skylight for electrical energy generation and saving is presented in this paper. The system integrates and optimizes five green technologies: wind turbine, solar photovoltaic system, rain water harvesting and utilization system, natural ventilation and roof sky lighting. The design was conceptualized based on the experiences acquired from meteorological data for Malaysian application. The V-shape top roof which was designed above the wind turbine was able to increase the wind speed by the venturi effect before the wind interacts with the wind turbine located between the roofs, hence improve the performance of the wind turbine. An automatic cooling and cleaning system with a stream of water was designed to clean and cool the roof which can improve the electrical efficiency of the solar photovoltaic modules. The ventilation vents of the system allow warm air inside the building to be ventilated out from the building by the pressure difference caused by high speed wind due to the roof design. The skylighting in the system improve the living comfort level and reduce power consumption of artificial lighting. Technical assessment of the system showed the estimated annual energy generated was 21205.65 kWh, estimated energy savings was 1839.6 kWh, the estimated annual ventilation rate was 2.17×10^8 m^3 and reduction of CO_2 emissions was 17767.89 kg/yr.

1. Introduction

The high energy demand with the increase of environmental pollution issues including global warming and greenhouse effect have led to a greater interest in the efficient usage of renewable energy. Energy consumption and carbon dioxide emission have become important issues for many researchers, while ensuring a comfortable living environment for humans. It was noted that the emerging economies that supported the development of renewable energy policies have soared more than six times in the past eight years [1]. Governments from many countries have increased awareness on their communities to achieve greener cities; meanwhile many building policies that are concerned on the usage of renewable energy have been introduced. Adopting renewable energy for building construction is a great alternative to achieving energy efficient buildings and building roof is an area which has great potential for application of renewable energy. Therefore, it is important to design an innovative hybrid solar-wind-rain roof system based on local meteorological data that is more effective for the application in buildings.

Wind turbines that are incorporated within a build environment are described as building integrated wind turbines (BIWTs) which are encouraged for urban on-site clean energy generation allowing a notable contribution to a sustainable design of new buildings in terms of energy consumption [2]. In addition, building mounted small-scale wind turbines, including horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) and building integrated turbines are the most utilized types of wind turbines for urban areas according to Lin et al. [3].

There has been a significant progress in VAWTs over the last few years due to the fact that these turbines are better suited to the built environment than the HAWT due to their better performance in turbulent wind flow [4]. A VAWT with an enclosure can be mounted

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Nomenclature

BIWTs	Building integrated wind turbines
HAWT	Horizontal axis wind turbine
VAWT	Vertical axis wind turbine
CFD	Computational fluid dynamics
BIPVs	Building integrated photovoltaic's
IRS	Innovative roofing system
SPVT	Semitransparent photovoltaic thermal
OPVT	Opaque photovoltaic thermal
PAGV	Power augmentation guide vane
ODGV	Omni direction guide vane
LCC	Life cycle cost
ISL	Inertial sublayer
GHG	Greenhouse gas
ρ	Air density
C_p	Efficiency of rotor
η_g	Efficiency of generator
η_{WD}	Wind direction loss
A	Swept area of turbine blade (m^2)
U	Mean wind speed at the height of building roof (m/s)
V'	Augmented wind speed at the height of building roof (m/s)
f_1	Speed increasing factor (experiment)
f	Speed increasing factor (simulation)
u_*	Friction velocity
k	Von karman's constant
z	Building height
z_0	Roughness length
d	Displacement height
C_D	Drag coefficient of a single obstacle
A_0	Coefficient derived from experimental evidence
β	Correction parameter
h	Mean building height
λ_P	Plan area ration
λ_F	Frontal area ratio
G_s	Annual mean global radiation (kWh m^{-2})
A_s	Array active area (m^2)
η_{ps}	Module conversion efficiency
K	Shadow factor
ϵ_{PV}	Effect of surface inclination and orientation on PV output
PR	Effect of surface inclination and orientation on performance ratio
A_c	Rain catchment area (m^2)
I	Rainfall intensity (mm)
C_R	Run-off coefficient
P	Output power (P) of the PV module
A_P	Surface area of PV module
S	Incident solar radiation
n	Number of nozzles
v_n	Velocity at each nozzle
Q_1	Flow rate at the pipe inlet
D	Pipe diameter
d	Diameter of each nozzle
h_{minor}	Minor losses in the pipe
Δh_{total}	Height difference of the head
Φ	Luminous flux (lm)
P	Light power (W)
η	Luminous efficacy (lm/W)
L	Length of room (m)
W	Width of room (m)
H	Height from the ground to ceiling (m)
RI	Room index
N	No. of luminaries/lamp
t	Illumination hours (h/day)
E	Light illuminance (lux)
E_{lamp}	Energy consumed by lamp(kWh/day)
M_F	Maintenance factor
U_F	Utilization factor
Q	Volumetric flow rate
C_d	Discharge coefficient
C_{p1}	Windward pressure coefficient
C_{p2}	Leeward pressure coefficient
V_{ref}	Velocity at reference height
A_o	Area of opening
Θ	Outdoor temperature day volatility
Δt	Average reducing temperature
$\Delta t'$	Average increasing temperature
CO_{2sav}	Amount of CO_2 savings (kg CO_2/yr)
E_s	Total energy (saving) produced by the prototype (kWh/yr)
CI	Malaysia carbon intensity (kg CO_2/kWh)

above a cooling tower's exhaust fan to harness the wind energy, an innovative idea was contributed by Chong et al. [5]. Another architectural shape issue of buildings integrated with wind turbines (BIWT) was introduced by Bobrova [6]. Proposed by Campbell et al. [7], there are several possibilities where wind energy generation systems can be integrated into a building and are categorized into the following three types:

(a) Siting stand-alone wind turbines.
(b) Retrofitting wind turbines onto existing buildings.
(c) Full integration of wind turbines together with architecture.

Nowadays urban building wind characteristics are being studied by the research community, and a number of manufacturers offer turbines for attachment to buildings [8]. The wind aerodynamics and wind flows over the buildings are investigated using the tool of computational fluid dynamics (CFD) [9].

Building integrated photovoltaic's (BIPVs) are photovoltaic (PV) modules integrated into the building envelope and hence also replace traditional parts of the building envelope, e.g. the roofing. BIPVs have a great advantage compared to non-integrated systems. Jelle et al. [10] summarized the current state-of-the-art of BIPVs, including both BIPV foil, tile, module and solar cell glazing products. The main options for building integration of PV cells are on sloped roofs, flat roofs and facades. It was explained and presented in different ways of implementing passive solar systems i.e heating, cooling, and day-lighting into commercial-type buildings by Nikita Morozov [11], who also explained the structure and implementation methods of each system in buildings.

Regarding the building ventilation, Susanti et al. [12] calculated the reduction amount of roof solar heat gained through the use of natural ventilation in a cavity of a factory roof. Later, Kobayashi et al. [13] used simplified estimation and CFD analysis to focus on "monitor roof" which has the potential to promote wind induced natural ventilation, and evaluated its ventilation performance in the urban environment. Inducing natural ventilation can significantly improve the indoor air quality, while also decreasing reliance on air-conditioning, thus cutting energy consumption. Previous works examined the potential of installing a new common roof turbine ventilator onto an existing bathroom system and achieving adequate air change rate [14].