Renewable Energy 130 (2019) 130–138

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Estimation of building energy consumption using weather information derived from photovoltaic power plants

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ARTICLE INFO

Article history:
Received 27 January 2018
Received in revised form
26 April 2018
Accepted 18 June 2018
Available online 18 June 2018

Keywords:
Photovoltaic
Partial mutual information
Empirical mode decomposition
Extreme-learning machine

ABSTRACT

Photovoltaic power must be measured for billing purposes and to provide power injection information. To emphasise the importance of weather information derived from photovoltaic power data, we consider how building energy consumption is estimated. Photovoltaic power can be treated as an input to an energy consumption model rather than weather information (solar insolation, temperature, and/or relative humidity). We use a partial, mutual information algorithm for selection of the input variables required by a building consumption model; the data are derived from adjacent photovoltaic power stations. When weather information imparted by photovoltaic power is inadequate, the accuracy of energy consumption estimations can be improved by combining an empirical mode decomposition algorithm and an extreme-learning machine algorithm. Our energy consumption estimations, based on partial mutual information, empirical mode decomposition, and use of an extreme-learning machine, were verified using real data from Beijing and Guangzhou, China. The simulations show that the precision of estimation can be increased by fully exploiting the interdependence of photovoltaic power and building energy consumption.

1. Introduction

We estimated building energy consumption using the interdependence of photovoltaic (PV) power and building heat gain/loss. Three topics are considered: building energy consumption analysis, prediction of energy needs, and previous works exploring the connection between PV power and building heat gain/loss.

Building energy consumption is a major issue in China; rapid urbanisation is associated with ever-increasing consumption [1]. Efficient energy consumption is essential for sustainable urban development. Edwards et al. investigated energy consumption in typical Caribbean office buildings; good management and careful operation enhanced energy efficiency [2]. Cellura et al. developed a building energy input-output model affording environmental benefits; the model has been successfully applied in Italy [3]. Refahi and Talkhabi investigated the effects of green rooves on energy consumption in residential buildings; consumption fell dramatically in hot/dry, warm/dry, and mixed/dry climates [4]. Li et al. emphasised the importance of energy conservation and emissions reduction, but the life-cycle cost of reduction is very difficult to calculate [5]. Mauser et al. found that adaptive building energy management can have a good effect on building energy saving [6]. High energy costs mean that buildings must use renewable energy, as Chwieduk emphasised [7]. Katsaprakakis developed several energy-saving methods for a natural history museum in Crete, insulating the building envelope and generating renewable energy on the roof [8]. Basso et al. developed small-scale hybrid energy systems (combining heat and PV power) for historic buildings; different scenarios were analysed during optimisation [9]. Oller et al. explored the interdependence of weather information and building energy consumption; the use of weather data significantly reduced errors in building energy simulations [10].

Before considering energy consumption predictions, it is useful to evaluate prediction techniques for power systems. Amjady et al. [11] focused on non-smooth, nonlinear load behaviour when developing a bilevel predictive strategy affording accurate short-term load forecasts, verified using the real-world data from a Canadian university campus. Future trends in smart grids were discussed in Ref. [12]; various predictive models for microgrids were presented. Sáez et al. developed fuzzy, interval predictive models of solar and wind generation and load, verified using the real-world

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https://doi.org/10.1016/j.renene.2018.06.069
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power system of Huatacondo, Chile [13]. Other authors [14] engaged in ultra-short-term power prediction combined with feed-forward control of energy management to effectively control power output. Prediction of building energy consumption is essential. Expensive weather forecast information has traditionally been used to predict air conditioning (AC) loads [15]. Physical modelling methods and an artificial neural network were compared in Ref. [16]; both methods accurately predicted building energy demand. Compared to physical modelling, artificial intelligence is making advances in predicting building energy consumption [17]. Hsu developed clustering methods modelling energy consumption; predictive accuracy and cluster stability were interrelated [18]. Naji et al. described an adaptive, neuro-fuzzy inference system that accurately modelled energy consumption based on the physical characteristics of the building envelope [19]. Naji et al. also developed a predictive model using an extreme-learning machine (ELM) to analyse the interdependence of building parameters and energy consumption [20]; the ELM efficiently predicted energy demand.

Here we take a further step in exploring the interdependence of PV power and building energy consumption based on previous works [21–27]. PV plant output depends principally on solar radiation, temperature [21], the system installation angle, atmospheric pressure, relative humidity, and wind speed. The total building heat load comprises internal and external contributions; the external load is affected by solar radiation, environmental temperature, building orientation, humidity, and wind speed [22]. A copula-based approach can be used to model the interdependence of PV power and building energy consumption [23,24], greatly assisting the analysis of distribution networks. A first-order reliability method [25] and a central moment method [26] effectively analysed the reliabilities of distribution networks, including the interdependence of PV power and building energy consumption. Weather information is of vital importance [27].

The novel contributions of this paper are: (1) To the best of our knowledge, this is the first time that weather information hidden in PV power data has been excavated to estimate building energy consumption based on the dependence thereof on PV power. (2) When the hidden weather information is redundant, partial mutual information (PMI) is used to select certain PV stations as inputs to a building energy consumption model. (3) When the hidden weather information is insufficient, empirical mode decomposition (EMD) is used to improve estimations of building energy consumption, employing an ELM.

2. Physical mechanism

The interdependence of PV power and building heat gain/loss, particularly the AC and heat pump loads, are analysed by reference to weather conditions. As shown in Fig. 1, the heat gain/loss and adjacent PV generation are affected by the same temperature, solar radiation, and other factors.

The sensitivities of AC/heat pump requirements and PV power to weather variations differ. There is a substantial time interval between PV power generation and building heat gain/loss. PV power variations follow weather variations immediately, but heating/cooling systems are insensitive to weather. If the change in the weather endures, the AC/heat pump loads will change later than the PV power. If the change in weather is brief (for example, clouds cover the sun for a few seconds), the AC/heat pump loads will not change with the variations in PV power. We emphasise that variations in weather data, including duration and amplitude, are hidden in PV power variations.

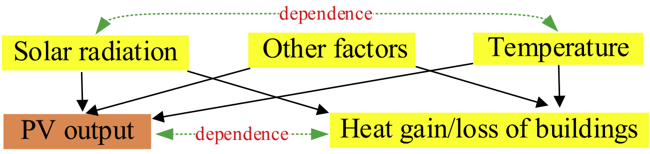

Fig. 1. Interdependence of photovoltaic (PV) power and building heat gain/loss.

3. Methodology

3.1. Research continuity

The principal problem is how to estimate the total energy consumption of a building with major AC/heat pump loads using the interdependence of such energy consumption and PV power. This article is a follow-up of [22], which showed that this interdependence substantially impacted power loss, static voltage stability, and voltage deviation in distribution networks, as shown in Fig. 2.

3.2. The concept

Our new method is best explained by comparing it to traditional methods. In the past, the history status of energy consumption were used to calculate future consumption. In our new method, consumption history and present/history PV power serve as inputs for estimation of present/future consumption. The weather information in the PV power history significantly affects future energy consumption when the interval between the history and the future is short. Therefore, the essence of the method is the estimation of energy consumption using the PV weather data, which directly impact consumption. We use an ELM, PMI, and EMD to this end. The ELM simulates the relationship between inputs and the output (i.e. future energy consumption). PMI selects the input variables using maximum relevance/minimum redundancy criteria. EMD decomposes PV power signals into different scales to improve estimation accuracy. A schematic diagram of the method is shown in Fig. 3.

3.3. The need for the new method

The method can be widely applied to evaluate power systems. A theoretical intraday building power load is calculated using the intraday PV power and the PV history. A comparison of the theoretical and actual intraday power loads identifies wasteful abnormal electricity consumption behaviour. Accurate predictions

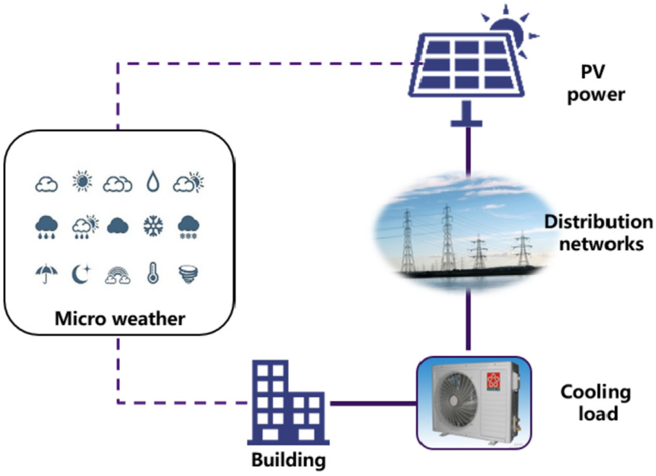

Fig. 2. Interdependence of building energy consumption and PV power.