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Daily global solar radiation prediction from air temperatures using kernel extreme learning machine: A case study for Iran

Shahaboddin Shamshirband [a,*], Kasra Mohammadi [b], Hui-Ling Chen [c], Ganthan Narayana Samy [d], Dalibor Petković [e], Chao Ma [f]

[a] Department of Computer System and Technology, Faculty of Computer Science and Information Technology, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, Massachusetts 01003, USA
[c] College of Physics and Electronic Information, Wenzhou University, Wenzhou, Zhejiang 325035, China
[d] Universiti Teknologi Malaysia (UTM), Malaysia
[e] University of Niš, Faculty of Mechanical Engineering, Deparment for Mechatronics and Control, Aleksandra Medvedeva 14, 18000 Niš, Serbia
[f] School of Digital Media, Shenzhen Institute of Information Technology, Shenzhen 518172, China

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ABSTRACT

Lately, the kernel extreme learning machine (KELM) has gained considerable importance in the scientific area due to its great efficiency, easy implementation and fast training speed. In this paper, for the first time the potential of KELM to predict the daily horizontal global solar radiation from the maximum and minimum air temperatures (T_{max} and T_{min}) is appraised. The effectiveness of the proposed KELM method is evaluated against the grid search based support vector regression (SVR), as a robust methodology. Three KELM and SVR models are developed using different input attributes including: (1) T_{min} and T_{max}, (2) T_{min} and $T_{max}-T_{min}$, and (3) T_{max} and $T_{max}-T_{min}$. The achieved results reveal that the best predictions precision is achieved by models (3). The achieved results demonstrate that KELM offers favorable predictions and outperforms the SVR. For the KELM (3) model, the obtained statistical parameters of mean absolute bias error, root mean square error, relative root mean square error and correlation coefficient are 1.3445 MJ/m^2, 2.0164 MJ/m^2, 11.2464% and 0.9057%, respectively for the testing data. As further examination, a month-by-month evaluation is conducted and found that in six months from May to October the KELM (3) model provides further accuracy than overall accuracy. Based upon the relative root mean square error, the KELM (3) model shows excellent capability in the period of April to October while in the remaining months represents good performance.

1. Introduction

Currently, the governments, energy policy makers and researchers are paid further attention towards solar energy since not only it is sustainable, but it is also inexhaustible and environmental friendly. In fact, the exploitation of solar energy would be particularly useful in abatement of the prevalent environmental problems such as global warming and air pollution (Karthikeyan et al., 2014; Benmouiza and Cheknane, 2013). Due to abundant potential of solar energy, a particular priority has been assigned for developing the solar energy technologies to supply the electricity, heating and cooling demands of the world. For the efficient design, simulation and development of solar energy related systems the long-term knowledge of solar radiation is of vital significance (Mellit et al., 2003; El-Metwally, 2005; Nehrir et al., 2011; Capizzi et al., 2012; Vindel et al., 2015). Generally, the superior way of acquiring the solar radiation data at a particular location is to establish the high precision measuring instruments. Nevertheless, because of high costs required to purchase, calibrate and maintain the instruments, horizontal global solar radiation is scarcely observed in many parts of the world (Iziomon and Mayer, 2002; Liu et al., 2012). Accordingly, to overcome this issue, a considerable number of empirical models have been proposed for estimating the horizontal global solar radiation using several meteorological variables (Bahel et al., 1987; Abdalla, 1994; Trabea and Shaltout, 2000; Garg and Garg, 1982; Ojosu and Komolafe, 1987; Ododo et al., 1995; Muzathik et al., 2011; Duzen and Aydin, 2012; Badescu and Dumitrescu, 2014). The developed empirical models may be classified into the following categories, based on the meteorological variables used as inputs:

* Corresponding author. Tel.: +60146266763.
E-mail addresses: shamshirband@um.edu.my (S. Shamshirband), kmohammadi@umass.edu (K. Mohammadi).

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Nomenclature

C	penalty parameter of KELM and SVR
KELM	Kernel Extreme Learning machine
H	daily global radiation on a horizontal surface (MJ/m^2)
H_o	daily extraterrestrial solar radiation on a horizontal surface (MJ/m^2)
$H_{i,c}$, $H_{i,m}$	ith calculated and measured values of H (MJ/m^2)
$H_{c,avg}$, $H_{m,avg}$	average calculated and measured values of H (MJ/m^2)
KT	daily clearness index (dimensionless)
MABE	mean absolute bias error (MJ/m^2)
$n_{d\,a\,y}$	number of days
RMSE	root mean square error (MJ/m^2)
RRMSE	relative root mean square error (%)
R	correlation coefficient
SVR	support vector regression
$Tmax$	daily maximum air temperature (°C)
$Tmin$	daily minimum air temperature (°C)
TB	temperature-based
Greek symbols	
σ	kernel width in KELM and SVR

- Sunshine duration-based models.
- Temperature-based models.
- Cloud factor-based models.
- Multiple meteorological-based models.

Since availability of the meteorological data varies from one location to another, the appropriate models for estimating global solar radiation should be developed on the basis of the accessibility to the meteorological inputs at a desired location. Among all parameters, air temperature is broadly observed in standard meteorological stations because of its importance in several applications. Therefore, developing the models to correlate the horizontal global solar radiation with the air temperature would be an appealing possible option. Over the past years, numerous temperature-based (TB) empirical models have been proposed, and subsequently several modifications and assessments have been performed to estimate the horizontal global solar radiation in many locations across the globe (Meza and Varas, 2000; Abraha and Savage, 2008; Liu et al., 2009; Almorox et al., 2011; Pan et al., 2013; Li et al., 2013; Yacef et al., 2014; Dos Santos et al., 2014). In the TB models, the maximum and minimum air temperatures are mainly used for estimating the atmospheric transmissivity. In fact, these models presume that maximum temperature will decrease with reduced transmissivity, whilst minimum temperature will increase because of the cloud emissivity. Clear skies will increase maximum temperature due to higher shortwave radiation during sunshine hours, and minimum temperature will decrease due to higher transmissivity at night times; so the difference between daily maximum and minimum air temperatures becomes an indicator of cloudiness (Almorox et al., 2013).

Estimating the horizontal global solar radiation using different artificial and computational intelligence techniques including the artificial neural network (ANN) (Tymvios et al., 2005; Mubiru and Banda, 2008; Şenkal and Kuleli, 2009; Solmaz and Ozgoren, 2012), particle swarm optimization (PSO) (Mohandes, 2012), adaptive neuro-fuzzy inference system (ANFIS) (Mellit et al., 2007; Rahoma et al., 2011; Sumithira and Kumar, 2012; Güçlü et al., 2014; Mohanty et al., 2015), support vector machine (SVM) (Chen et al., 2013; Chen and Li, 2014; Ramli et al., 2015; Antonanzas et al., 2015), and etc. has received tremendous attention in recent years. In this regard, a few studies have also focused on prediction of global solar radiation from only measured air temperatures data using the above-mentioned approaches.

Rahimikhoob (2010) employed ANN technique for estimating global solar radiation using air temperatures in a semi-arid location. The ANNs were trained based upon the maximum and minimum air temperatures and extraterrestrial radiation. Then the ANNs were compared with a traditional temperature-based empirical model. The attained results showed that ANN technique offers higher accuracy. Chen et al. (2011) examined the possibility of employing the support vector machines (SVMs) for estimating the monthly mean global solar radiation utilizing maximum and minimum air temperatures at Chongqing station, China. For this study, they applied three different functions of SVM. In another study, Chen et al. (2015) appraised the transferability of SVM to estimate global solar radiation using ambient temperature in subtropical zone in China. They found that global solar radiation at one site can be estimated from air temperatures acceptably by SVM model established for another site.

In recent years, extreme learning machine (ELM) has been introduced for single layer feed-forward neural network (SLFN) architecture (Huang et al., 2004, 2006). ELM can reduce the required time for training a neural network. As a matter of fact, ELM would be considered as an effective algorithm with several advantages such as ease usage, quick learning speed and Higher capability for many nonlinear activation and kernel functions. therefore, so many investigations have been performed in order to apply the ELM algorithm for solving the problems in different scientific domains (Yu et al., 2014; Wang and Han, 2014; Ghouti et al., 2013; Wang et al., 2014; Nian et al., 2014; Wong et al., 2015).

Nevertheless, to avoid the application of time consuming algorithms for the determination of the ELM space dimensionality and overcome the drawback of randomly assigning the weights in the ELM, the kernel extreme learning machine (KELM) has also been developed lately (Huang et al., 2012; Iosifidis et al., 2013). In the KELM method, the hidden layer feature mapping is defined using the kernel matrix. In fact, owing to utilization of kernel function, it is expected that much better generalization performance can be achieved compared to the ELM. Therefore, the KELM technique have been used with higher performance, much easier implementation and faster training speed in many applications including the hyperspectral remote-sensing image classification (Pal et al., 2013; Chen et al., 2014), activity recognition (Deng et al., 2014), 2-D profiles reconstruction (Liu et al., 2014) and fault diagnosis (Jiang et al., 2014).

In spite of great success in some scientific fields, the KELM method has not been utilized for the prediction of solar radiation so far. In our previous investigation (Shamshirband et al., 2015) the ELM technique was used successfully to predict horizontal global solar radiation in a specific location of Iran. In this study, due to particular features and capabilities of the KELM technique, for the first time the KELM method is employed to predict the daily horizontal global solar radiation. The maximum and minimum air temperatures are considered as the only inputs to model the global solar radiation using KELM. The motivation behind the selecting these inputs is their wide availability at most meteorological stations and their favorable correlations with the global solar radiation. To extend the results, three combinations of maximum and minimum air temperatures are served to assess the influence of input attributes on the global solar radiation predictions. The accuracy of KELM method is compared with grid search