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Solar energy utilization patterns for different district typologies using multi-objective optimization: A comparative study in China

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ABSTRACT

Currently, solar energy technologies are in the stage of intensive development. With booming solar industry, there is a challenge to seek for appropriate solar energy solutions for different district typologies. This paper presents a comparative study on solar energy utilization patterns for different types of districts located in Kunming, China. Four district typologies are investigated: residential district (RD), official district (OD), commercial district (CD) and industrial district (ID). For each district, the objective is to identify such solar energy utilization patterns that result in an optimal design and operation of solar energy system. The optimum system is defined and obtained through minimizing life cycle CO_2 emissions and costs as well as maximizing exergy efficiency. To that end, a multi-objective optimization approach based on Genetic Algorithm is proposed. The results of the case study suggest that solar energy is to represent 3.7%, 5.9%, 7.9% and 21.4% of annual energy consumption for RD, OD, CD and ID, respectively. For each district, the portfolio of solar energy technologies is different. Solar power systems factually contribute to the energy supply of ID only. The final work aims at investigating the effects of different solar energy parameters on the solar utilization patterns for these districts.

1. Introduction

Solar energy, as the light and heat from the sun, has been harnessed by humans using a range of evolving technologies since ancient times (Lu, 2013). Solar energy is regarded as environment-friendly source of power and thermal energy. As shown in Table 1, the International Energy Agency (IEA) predicts solar technology to be the strongest growing technology in future. According to the IEA, the average growth rate of solar energy utilization could reach to over 12% (IEA, 2010).

Currently, a significant proportion of energy is used within the building sector. For example, about 38.9% of the total primary energy requirement (PER) in the U.S. was consumed by buildings (Yang et al., 2008). Likewise in China, more than 35% of the PER was applied to provide energy for buildings (Yao et al., 2005). Along with rising living standards, energy consumption in buildings has significantly increased over the past decades. For instance, the energy use of buildings in China has been increasing at more than 10% per year over the past 20 years (Cai et al., 2009). It is hard to match (meet) such an increasing energy demand only by traditional fossil fuels, wherefore renewable energy should be introduced to provide energy for buildings and districts. As mentioned above, when the availability and the penetration of solar energy presumably increase, solar energy conversion technologies will play an essential role in designing and operating energy systems for buildings and districts (Lu et al., 2014).

Several types of solar energy conversion systems are available, such as solar thermal collector heaters, solar photovoltaic (PV) systems and concentrated solar power systems (CSP). One of the challenges is to predict the solar energy conversion technologies with the greatest potential to be widely applied for buildings and urban districts in the future. Building districts are categorized by their main functions into typologies such as official district, industrial district and commercial district. Different district typologies have their unique energy consumption patterns, which is why some more complicated questions will be raised: "Which type of solar energy technology will be the most preferred for the industrial area?" or "Is there any justification to replace the existing PV system by new PV/thermal system in a specific official district?"

To answer the aforementioned questions, first steps is to identify the most appropriate solar energy solutions for given district typologies. Several studies have been conducted to investigate

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Nomenclature

C	cost, c €/kW h
C_0	cost of component, c €/kW h
$CO_2(C)$	CO_2 equivalent of component, g/kW h
$CO_2(I)$	CO_2 equivalent of installation, g/kW h
$CO_2(O)$	CO_2 equivalent of operation, g/kW h
$CO_2(M)$	CO_2 equivalent of maintenance, g/kW h
$CO_2(R)$	CO_2 equivalent of recycling, g/kW h
d	discount rate
E	energy, MJ
$\dot{Ex}$	exergy, MJ
F_Q	Carnot Factor
i	inflation rate
P	power, kW
Pr	present worth factor
PW	present worth, c € /kW h
Q	energy demand, MJ
T	thermal source temperature, K
T_0	constant ambient temperature, K
ω	weight of benefit

Subscripts

CC	cooling capacity demand
DHW	domestic hot water demand
EL	electricity demand
ele	electricity
H	heat load demand
heat	thermal energy
in	input
int	installation
ke	kinetic energy
man	maintenance
out	output
recy	recycling
rep	replacement
waste-H	waste heat used for heat load
waste-DHW	waste heat used for domestic hot water
waste-CC	waste heat used for cooling capacity

Abbreviations

AC	air conditioner
BCHP	bio-fuel micro-turbine power and heat
CC	cooling capacity
CD	commercial district
DHW	domestic hot water
EE	exergy efficiency
FN	linear Fresnel concentrating solar power generation
FST	linear Fresnel concentrating solar thermal energy
EH	electricity heater
EL	electricity
GA	genetic algorithm
GB	biogas boiler
H	heat load
HP	air source heat pump
ID	industrial district
LCC	life cycle cost
$LCCO_2$	life cycle CO_2 equivalent
OD	official district
PE	public electricity grid
PST	parabolic trough solar thermal energy
PT	parabolic trough solar power generation
PV	solar photovoltaic
PVT	solar photovoltaic/thermal
RD	residential district
SAC	solar absorption cooling
SH	space heating
SPS	solar power subsidy
STH	solar thermal heater
WHU	waste heat utilization
WT	wind turbine

Table 1
World renewable energy utilization 2007–2035 (billion kW h) [2].

Source	2007	2015	2020	2025	2030	2035	Average annual percent change (%)
Hydro	2999	3689	4166	4591	5034	5418	2.1
Wind	165	682	902	1115	1234	1355	7.8
Geothermal	57	98	108	119	142	160	3.7
Solar	6	95	126	140	153	165	12.7
Other	235	394	515	653	773	874	4.8
Total	3462	4958	5817	6618	7336	7972	3.0

the feasibility of a single solar energy technology (such as PV and solar thermal collector) within a district (e.g. Skjølstrup and Søndergaard, 2016; Khayet et al., 2016), whereas there is a lack of studies dealing with the optimization of a hybrid solar energy system. Accordingly, this paper presents a comparative study on solar energy utilization patterns for different types of districts located in Kunming, China. The following four types of districts are considered in this paper, namely: official district (OD), residential district (RD), commercial district (CD) and industrial district (ID). To identify the most feasible solar energy utilization patterns, it is necessary to find out the optimum energy system which contains solar energy technologies for each type of district. Specifically, the optimization process aims at designing the energy system with minimum economic cost and environmental burden as well as maximum efficiency. Life cycle CO_2 emissions (LCCO2), life cycle cost (LCC) and exergy efficiency (EE) are chosen as objective functions for the optimization process. Hence, a multi-objective optimization method based on Genetic Algorithm (GA) is proposed in this paper. GA has been applied to a diverse range of scientific and engineering problems (Holland, 1975) and is suited to handling complicated optimization problems with nonlinear, discrete and constrained search spaces (Stanislav, 2003). Through the optimization process, it is found in the present study that the preferred technological solutions vary according to the unique characteristics of individual districts.

After confirming the current solar energy utilization patterns, it is meaningful to investigate how these patterns change along with the variations of solar energy parameters. With the assistance of