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Renovation of NZCB in a poor solar irradiation zone: An investigative case study of residential buildings in Chongqing urban areas

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Abstract
The energy requirements of Chongqing, a major economic hub of Southwest China, have increased annually with at an average of 10.49% per annum since 1997. The predominant primary source of energy is coal. China's long range goal is for a green economy and solar energy is considered a prime renewable energy source. This investigation assessed the feasibility of solar energy utilization in existing residential buildings in Chongqing Urban Areas. The main objectives of the research were to see "available solar renewable energy resource for utilization" and "how much CO_2 emission could be abated by using solar energy from these residential buildings". On the basis of average 3.47 $kWhm^{-2}d^{-1}$ and per capita 20.46m^2 residential areas in 2012, the feasibility study found the availability of 1250 $kWhm^{-2}d^{-1}$ irradiation. In addition, 15% yielding from this availability had the potential of 2.88 MWh annual clean energy generations abating 89.6% of CO_2 emissions from current electricity consumption. The investigative case study in three residential buildings of the Shapingba district of Chongqing found the 0.089, 0.086 and 0.126 tce of CO_2 emissions for per capita 187.89 kWh, 182.23 kWh and 265.37 kWh monthly energy demand. Although the long cash pay back periods (46, 43 and 31 years) don't suggest immediate strong PV utilization in this area this form of renewable energy in Chongqing could form a distinctive substitute as a flanking measure for zero carbon residential buildings.
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Keywords: Renewable energy; PV energy; CO_2 abatement; nZCB; Residential buildings.

1. Introduction

The term "Net Zero Carbon Buildings (NZCBs) means 'nearly zero (0 $kWh.m^{-2}a$) primary energy' fossil fuels consumption i.e., the annual energy balance will be zero or close to zero [1, 2]. Buildings are close to net-zero where energy is utilized efficiently and also harvested on-site and utilized from alternative energy sources such as ground source heat pump, solar photovoltaic (PV), wind, hydro-electric energy generation and day-lighting modifications towards meeting net-zero energy utilization [3, 4].
Buildings are considered as the major source of energy use and important contributor to 30% of all carbon emissions [5]. The current estimated figure for China is 27.8% [10] but China's rapid

urbanization has been gradually accelerating this emission e.g., one-third in 2010 from 27.6% of 2001 and predicted to be 35% by 2020 [6], 110 -150% by 2050 and 160-220% by 2095 [7-10].
Currently, China's total energy efficiency is about 33% which is about 10% lower than most developed countries [11]. However some recent studies revealed that 20% of energy requirements (120 billion kWh) could be saved within 15 years by the replacement of out dated household appliances [12] with 28% emission reduction by means of citizens' energy efficient appliances by 2020 [13]. Dematerialization could save 21,000 Mtce TPES as well through abating 45 billion tons of CO_2 emissions and 15% of cost reduction over 45 years from 2005 to 2050 [14]. Consequently, energy-efficient renovation plan in buildings sector [15] could be an important strategy to reduce the 22% of CO_2 emissions [16].
Solar energy is considered to be a effective and reliable, environment-friendly economic renewable energy resource, having the potential to be one of the major clean energy sources world [17, 18]. As the fastest renewable energy technology, it grew very rapidly with an annual average growth rate of 58% from 4 GW in 2004 to 70 GW in 2011 [19]. It is predicted that by 2050 11% of global electricity production and 20% and 60% of the world's total primary supply by 2050 and 2100 respectively [20]. China's earth surface is abundant with solar radiation with an average 2000 h yearly sunshine receives between annually 930 to 2330 $kWh.m^{-2}$ (3340-8360$MJ.m^{-2}$ and 90% area receives > 4500 $MJ.m^{-2}$) with an average daily radiation 4-7 $kWh.m^{-2}$ (110-250kg standard $coal.m^{-2}$) that is 2.4 trillion tons coal equivalent theoretical reserves [21-25].
Utilization of roofs for off-grid solar energy consumption increased from 8.8 MW in 2004 to 20 MW in 2011 in rural China [26] reaching 7800 km^2 [27, 28]. Furthermore, available estimated Building Integrated Photo-Voltaic (BIPV) areas are 5 billion m^2 of total 40 billion m^2 urban floor areas and aggregated 4 billion m^2 roof areas. However the amount of solar energy varies from region to region. This case study examined the potential of solar energy to reduce primary energy needs in the city of Chongqing. It uses both primary and secondary data to estimate energy requirements and the opportunities to reduce CO_2 emissions.

2. Methodologies

2.1 Data collection methods

Primary data was collected from two sources. One was from the occupants of residential buildings, i.e., international students, the other the management authority of these buildings. Student data comprised data from 110 questionnaires (60 in Xuelin Hotel, 40 in Songlingpo and 10 in Doctoral apartments) conducted to assess the daily energy demand of these residents. Most of the survey documents were completed by residents in the presence of author who assisted completion of the survey document through intensive discussion. For the Management Authority**,** three interviews were conducted with 'in-charge' for accommodation to gain information on the use of room appliances. The survey documents were completed by author himself with the help of a Chinese interpreter. Other relevant data were collected from personnel in-charge of accommodation within the international office of Chongqing University. These data were obtained by the help of ISU chairman. Relevant secondary data were gathered from the Chongqing Statistical Yearbook (2012), National Bureau of Statistics (NBSs), and Meteorological Department of Chongqing, China.

2.2 Data analysis methods

The 'total energy demand' for these buildings was estimated by using Mata and Angela [29] equation. The total and per capita CO_2 emission from these buildings and residents were calculated by using the IPCC (2007) guildlines of CO_2 Emission Factor. The available Solar Renewable Energy was calculated from Renewable Energy System Equation given by Cleland [30]. HOMER computer based software was used for producing radiation graph with considering clearness index of the Shapingba District urban area. The renovation or feasibility of the solar energy solution was calculated by estimation of the available total solar renewable energy for use for each building in contrast to its demand. The CO_2 emission from the integrated solar energy system was considered as zero to reveal the emission abatement than fuel burning electricity generation. The Kurnitski, Allard [2] model was used to feasibility study for achieving nZEB. The amount of maximum solar energy output from PV system and the cash payback period in years were calculated based on the general economic payback equations used for economic assessments globally.

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2.3 Energy demand calculation

Primary energy demand by the residential buildings were calculated by the following equation [29]:

$$E_{Total} = D_{El} + D_{Heat} + D_{Cool} + D_{HotW} - Q_{HR} \quad (1)$$

where, D_{El} is the annual electricity demand (kWh.yr^{-1}), D_{Heat} is annual heating demand (kWh.yr^{-1}), D_{Cool} is annual demand for cooling (kWh.yr^{-1}), D_{HotW} is annual heat demand for hot water (kWh.yr^{-1}) and Q_{HR} is annual heat recovered (kWh.yr^{-1}).

2.4 CO_2 emission factor

The CO_2 Emission Factor was calculated from the proportion of supplied fossil fuels used for generating electricity in 2004 [31, 32].

Electric power carbon emission= Standard Coal Equivalent mass×(39.8%(coal)×0.982×0.732 57+19.6% (natural gas)×0.982×0.732 57×0.561+6.7% (petroleum)×0.982×0.732 57×0.813) (2)

where 0.982 is the virtual oxygenation fraction, 0.73257 is the carbon rate of standard coal per ton, 0.561 is for per therm of natural gas and 0.813 for per gallon of petroleum burning.

2.5 Availability of solar renewable energy

HOMER computer based software was used for producing radiation graph with considering clearness index of Shapingba District. The following Renewable Energy System Equationwas used to calculate renewable solar energy [30].

$$Y_n=R_N*\theta_N*\Sigma_H \quad (3)$$

where Y_n is the yield of any one Collection Device in KWHr.y^{-1}, Y is yield of the Renewable Energy System in KWHr.y^{-1}, R_N is the Nameplate Rating of each Collection Device, θ_N is the Usage Factor of each Collection Device, Σ_Y is the Total Yield of the System, in KWHr.y^{-1} and Σ_H is the Total number of hours in the year (365 x 24 = 8760).

2.6 Renovation calculation

The renovation or feasibility was calculated by the available total solar renewable energy to use for building in contrast to its demand. The CO_2 emission from integrated solar energy system has considered as zero to reveal the emission abatement than fuel burning electricity generation. Following model was used to feasibility study of nZEB in this regards [2].

$$E = \sum_i (E_{del,i} f_{del,i}) - \sum_i (E_{\exp,i} f_{\exp,i}) \quad (4)$$

where $E_{del,I}$ is the delivered energy for energy carrier *i; $E_{exp,I}$* is the exported energy for energy carrier *i*; $f_{del,i}$ is the primary energy factor for the delivered energy carrier *i*; $f_{exp,I}$ is the primary energy factor for the exported energy carrier *i*, which may or may not be equal to the factor of the delivered energy, depending on national definition;

2.7 Solar energy output from PV system

$$E=A*r*H*PR \quad (5)$$

where, E is energy (kWh), A is total solar panel Area (m²), r is solar panel yield (%), H is average solar radiation.yr^{-1} and PR is the Performance ratio

2.8 Cash back analysis

The cash back analysis was calculated using universally recognized economic payback calculations.

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$$Cash\ Back\ Time = \frac{\sum (I - S)}{E \times C} \tag{6}$$

where I is the Total Initial Investment representing the total cost for 180 watt solar panels, rail kit, watt inverter, 250 amp DC disconnect, AC Kilowatt-Hrs electric meter, copper wire and junction box, grounding wire, maintenance and labor cost; S is the assumed all returned values such as Salvage value after 20 years, any grants or subsides during this time etc.; E is the total yearly generated electricity; and C is the grid price for per kilowatt-hrs.

3. Results and discussions

3.1 Population growth

As with the growth of many Chinese cities urbanization in Chongqing has progressed rapidly. Established as a municipality in 1997, urbanization has increased from 31% to 57.5% in 2012 with an increasing annual growth rate of 4.20% although the population size is expected to slightly decrease in near future. This extensive urbanization has resulted in accelerating the energy consumption intensity from 4.4% to 8.97% by the growth rate at 12.94%. (This is shown in Figure 1).

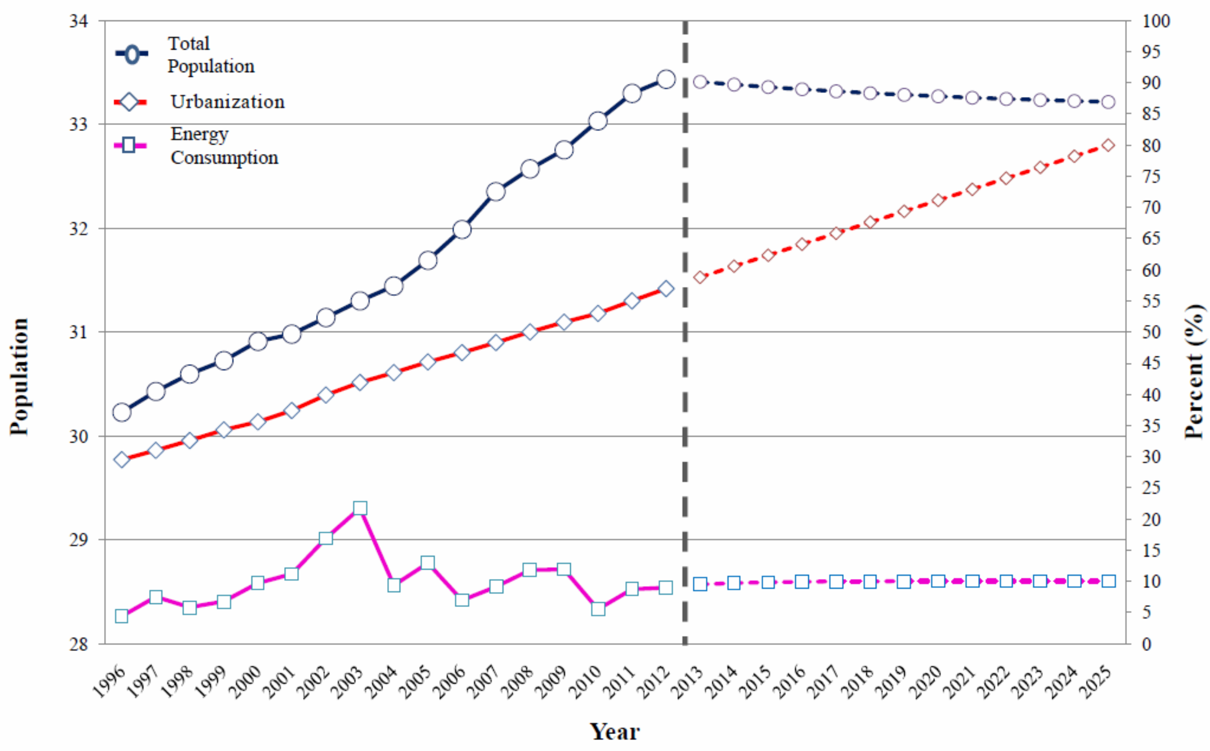

Figure 1. Population, urbanization and energy consumption of Chongqing

3.2 Energy consumption

The total energy consumption of Chongqing has increased consistently since 1980 with an annual average growth rate at 10.49% from 9.9 Mtce to 82.8 Mtce in 2012. It is forecast to rise to be 255 Mtce in 2025. Chongqing's mix energy consumption pattern is coal dominated. Coal based consumption increased 7-times with a growth rate at 6.6% from 7.53 Mtce to 55.21 Mtce and is forecast to climb at 150.15 Mtce by 2025. Besides coal, natural gas, oil and electricity consumption are sources of energy. Their growth is shown in Figure 2.

Energy consumption by industrial sector is shown in Figure 3. This has doubled since 2005, with a maximum of 46.6 billion kWh of total energy in 2012.

In 2007, its' overall energy consumption was 24 Mtce in which 15% represented residential energy [31] with monthly 2132 MJ/household electricity and gas [6] increased 10% since 2005 and 13.5% of the total energy consumption [33] in which household consumed at an average 41.1 GJ annually [34]. This sector has been recognized as the second highest consumer in 2012 increasing from 6.09 billion kWh to 12.34 billion kWh.

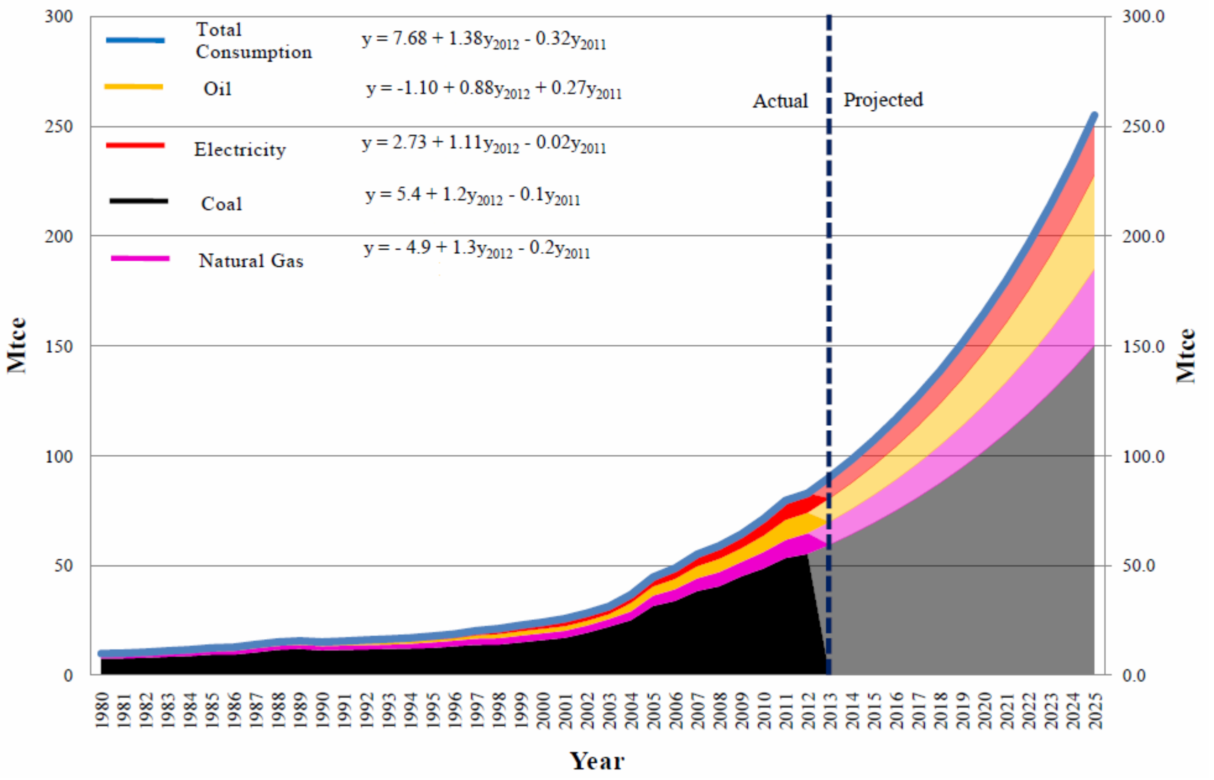

Figure 2. Energy consumption by sources in Chongqing

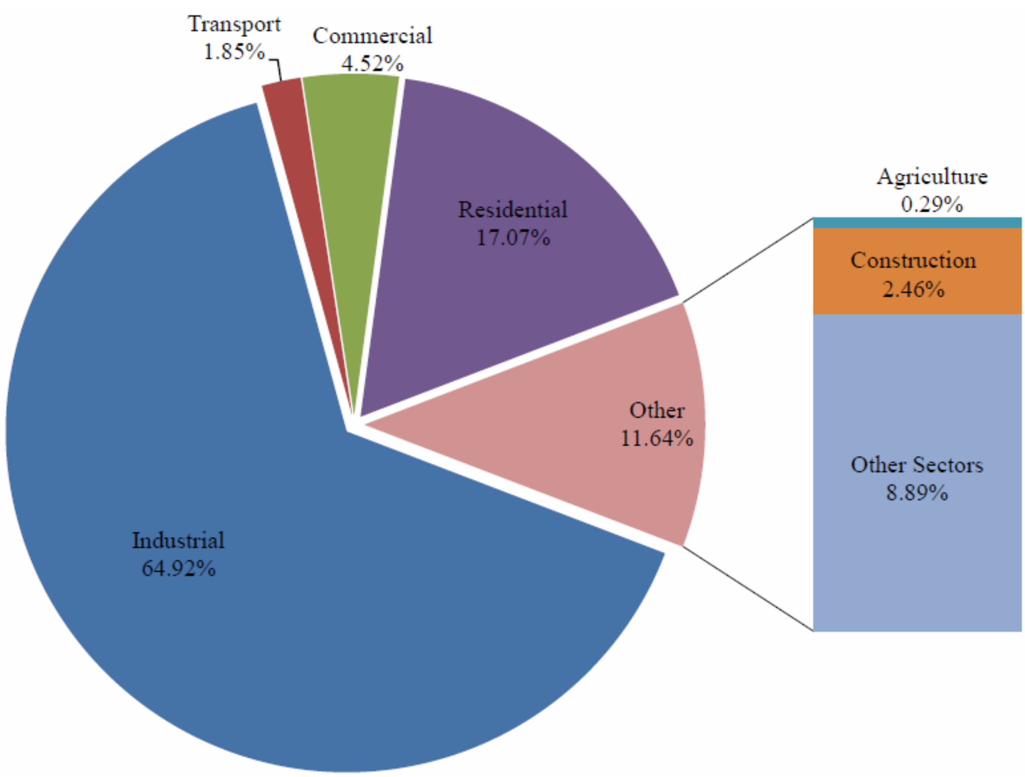

Figure 3. Chongqing Energy Consumption by Sector in 2012

3.3 Potential solar energy and CO_2 abatement

Chongqing is located in Southwest China, situated in 28° 10' to 32° 13' N Latitude and 105° 17' to 110° 11' E Longitude with an area of 82,403 km^2. The municipality is 259m above sea level with approximately 34 million people including estimated 3.9 million urban residents. Its' average maximum temperature is 35ºC in Summer and minimum 18ºC along with cloudy and 104 foggy days [23]. Its energy strategies are efficient use of energy, together with eco-design and maximum utilization of renewable energy to enhance energy security with reduced risk of price fluctuation. It has already achieved 82% energy efficiency along with 31.5% potential probability in residential sector [35]. There is 343.3 Million m^2 of residential floor space in Chongqing (a per capita figure of 20.46m^2) together with a potential source of 116.33 MWh solar of energy of 70.98 kWh per day. (Data from 2012) Per capita electricity consumption increased 3.22% from 2.14 MWh in 1998 to 3.22 MWh in 2012 with 0.19 tce to 0.28 tce emissions which expected to be 24.73 MWh by 29.1% growth rate along with 2.19 tce CO_2 emissions.

Chongqing lies in scattered distributed solar irradiation deficient zone of China [36]. Solar irradiation is highest, approximately 500 MJ.m^{-2}, in July and lowest, 100 MJ.m^{-2} in December [37] with an average 80-200 MJ.m^{-2} in Winter and 1270 MJ.m^{-2} in 5 months of summer that presents 41% of total yearly radiation [23] and utilization rate is around 4% [38]. Shapingba is a district of Chongqing municipality, situated in poor solar radiation zone with in an annual average of 3.47 kWhm^{-2} per day from lowest of 1.78 kWh/m^2/d in December to highest of 5.23 kWh/m^2/d in July along with annually average of 0.38 cloud clearness index (Figure 4).

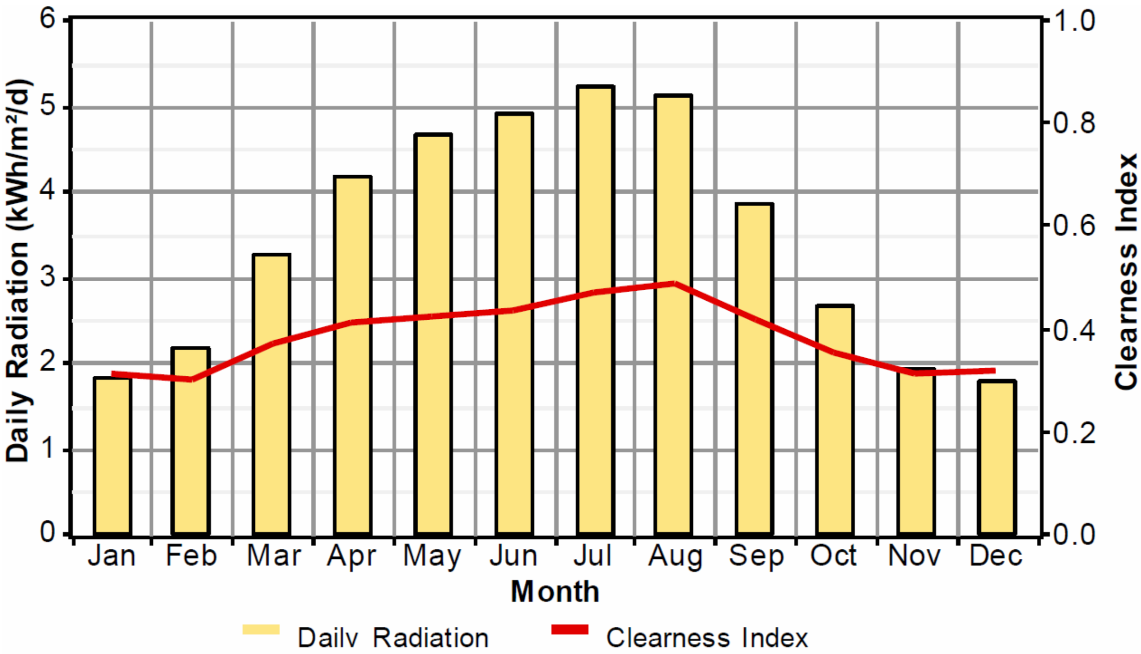

Figure 4. Chongqing horizontal radiation

The solar energy availability assessment was tested according to PV systems with 200 south facing panels without any tracking (Table 1). The study revealed that the annual efficient solar available resources are almost same as the energy requirements of the residential buildings of the city. On the basis of per capita available 20.46m^2 residential areas as considering the solar panel in 2012 with 15% yield of 1250 kWh/m² annual average irradiation on tilted panels, the clean energy generation potentiality was 2.88 MWh that could abate 89.6% of CO_2 emissions from current electricity consumption.

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Table 1. Solar system specification for Shapingba city

Specification	Value	Specification	Value
Latitude	29°33"N	Electricity Cost	¥0.92
Longitude	106°27"E	Altitude	287.43m
DC Rating	80	Azimuth	0^0
AC Rating	10	Slope	20^0
Array Type	Fixed (South Facing)	Array Azimuth	0° Northern Hemisphere
Array Tilt	20°	Ground reflectance	20%
Tracking system	No	De-rating factor	80%

The study focused on three international student dormitories of Chongqing University situated in the Shapingba district. There were three interviewees with management authorities, 110 questionnaires (60 in Xuelin Hotel, 40 in Songlingpo and 10 in Doctoral apartments) conducted to assess the daily energy demand of these residents.

The daily energy demand of the apartments studied was 707.21 kWh/day where Xuelin Hotel consumes highest 375.78 kWh/day in contrast to 242.97 and 88.46 kWh/day by Songlinpo and Doctoral buildings (Table 2). The highest amount (31.65%) of energy consumed for hot water and 28.05% for AC by these buildings while others like daily using appliances (hair dryer, iron machine, TV, sound systems, laptop etc) responsible for 6.13%, lighting 3.49%, refrigerator 12.95%, kitchen 9.39%, elevator 3.98% and washing and drying machine 4.35% of total energy consumption. The monthly per capita demand by Xuelin was 187.89 kWh, 182.23 kWh by Songlinpo and 265.37 kWh by Doctoral buildings with monthly cost of an average ¥172.86, ¥167.65 and ¥ 244.14 and responsible for 17.79 tce, 9.92 tce and 15.07 tce of CO_2 emissions with per capita 0.089, 0.086 and 0.126 tce of CO_2 emissions respectively.

Table 2. Energy demand and CO_2 emissions by selected dormitories

Items	Xuelin Hotel	Songlingpo	Doctoral
Total Residents	200	115	120
Sample Residents	60	40	10
Total Daily Energy Demand (KWh)	375.78	242.97	88.46
Room Electrical Appliances	22.62	10.42	10.33
Lighting	11.60	10.02	3.06
Refrigerator	43.96	38.64	9.00
Cooking/Kitchen Appliances	47.75	10.13	8.52
Air Conditioner	104.80	74.40	19.20
Hot Tap Water and Heater	115.17	87.40	21.27
Elevator	17.78	0.00	10.40
Washing Machine and Dryer	12.10	11.97	6.68
Per Capita daily demand (KWh)	6.26	6.06	8.85
Total Monthly Energy Demand (KWh)	37578.48	20956.23	31844.24
Monthly Per Capita Demand (KWh)	187.89	182.23	265.37
Monthly Total CO_2 emissions (tce)	17.79	9.92	15.07
Monthly Per Capita CO_2 emissions (tce)	0.089	0.086	0.126
Monthly Per Capita Electricity Cost (¥)	172.86	167.65	244.14

3.4 Available PV energy to utilization and CO_2 abatement

The feasibility has been observed by the solar energy availability on the roofs of dormitories. The 646m^2 roof spaces of Xuelin hotel contains a potential 7.14 MWh/month installed capacity with 15% yield and 29.654 MWh/ month by 60% yielding capacity that could lead to abate 20.20% and 80.79% of CO_2 emissions. Besides, Songlingpo's 504m^2 roof spaces has the installed capacity of 5.78 and 21.11 MWh/month with the capabilities of reducing 28.23% and 100% CO_2 emissions from energy consumption. In terms of the Doctoral building, its 836m^2 roof can produce 9.59 and 38.34 MWh/month with 15% and 60% efficiency along with 30.82% and 100% CO_2 emissions abatement (Figure 5).

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3.5 Cost-benefit analysis (CBA)

The Cost-Benefit Analysis was based on daily average 10.8 hours of sun duration of a month with peak 3.47 kW/m^2, 20% estimated energy losses, 12V of system with 3 days retention capability along with 385 (Amp-Hrs) of battery rating and maximum 50% discharge level, 80 amps and 10 amps of charge controller rating and solar panel current with 180 Watt panel module. It demonstrated that there are 37solar panels were required for the Xuelin building, (6,775.27 wattage), 24 solar panels for the Songlingpo building (4,315.76 wattage) and 8 solar panels for the Doctoral building (1,454.37 wattage) (Table 3).

3.6 Cash-back period

The initial installment cost (composed of all relevant expenses for typical 180 watt solar panels, rail kit, inverter, DC disconnect, electric meter, wire and junction box, grounding wire and labor) was ¥27,246 for each 60% efficient panel with taking account of 25% salvage value and 3.5% annual electricity inflation rate (Table 4). The cost of electricity in Chongqing is ¥ 0.92/kW. The cash-back period has been found to be 46 years for Xuelin, 43 years for Songlingpo and 31 years for Doctoral building (Figure 6).

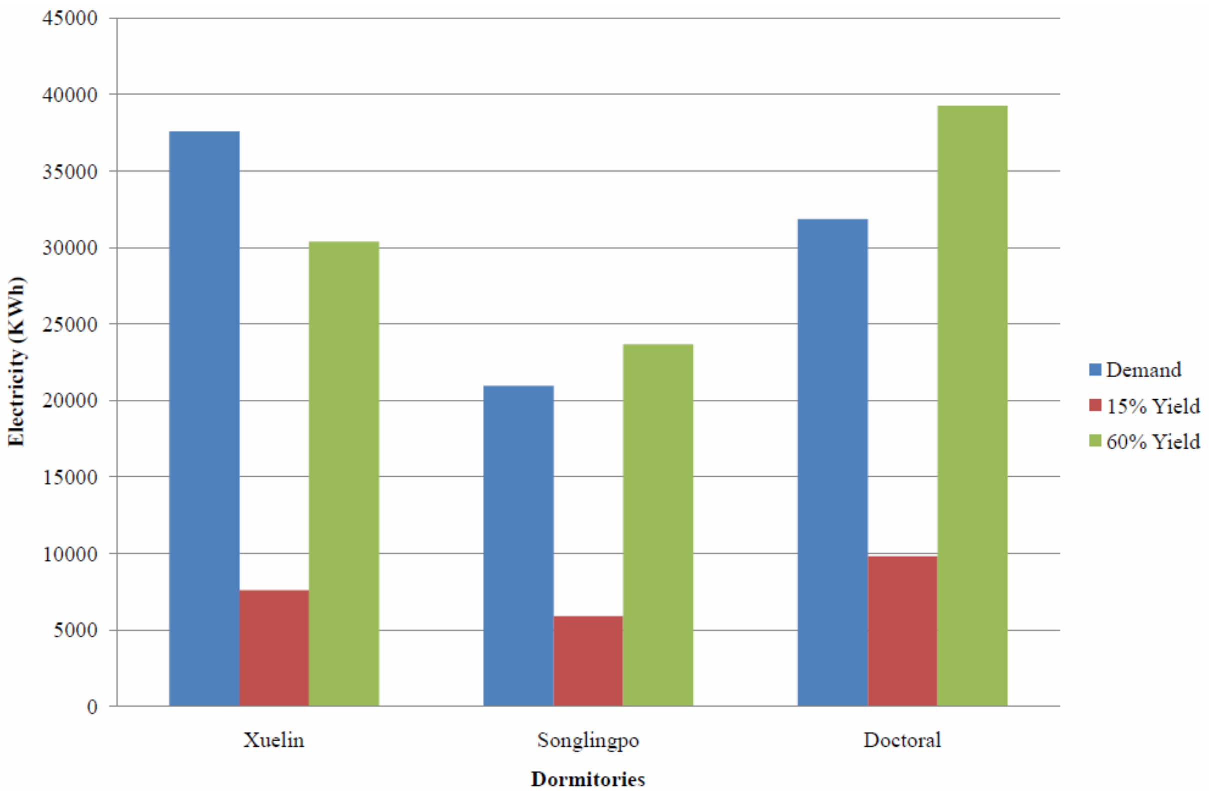

Figure 5. Comparison of electricity demand and PV energy to yield (kWh)

Table 3. Required instruments for total PV systems

Items	Xuelin Hotel	Songlingpo	Doctoral
Total Required Wattage of PV panels	6,775.27	4,315.76	1,454.37
Required Solar Panel	37	24	8
Required Charge Controller (Amp)	564.61	359.65	121.20
Total Required Charge Controller	7	4	2
Battery Bank Capacity (Amp – Hrs)	20,325.82	12,947.27	4,363.12
Number of Parallel rows	53	34	11
Total Battery Bank (Amp-hrs)	20,325.82	12,947.27	4,363.12

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Table 4. Systems cost and cast back period

Items	Xuelin Hotel	Songlingpo	Doctoral
Initial System Cost (¥)	939,258	413,502	69,612
Salvage Value, 25% (¥)	221,778	93,312	10,368
Total watt.hr^{-1} (Total panel*STC Rating)	6,660	4,320	1,440
Performance	60%	60%	60%
Adjusted watt.hr^{-1}	3,996	2,592	864
Estimated watt-hr.day^{-1}	15,185	9,850	3,283
Estimated Kilowatt-hr.year^{-1}	5,542	3,595	1,198
Chongqing electric rate (¥)	0.92	0.92	0.92
Estimated Income (Year 1) (¥)	5,099.06	3,307.50	1,102.50
Electrical Rate Annual Inflation Assumption	3.5%	3.5%	3.5%
Cash-back Years	46	43	31

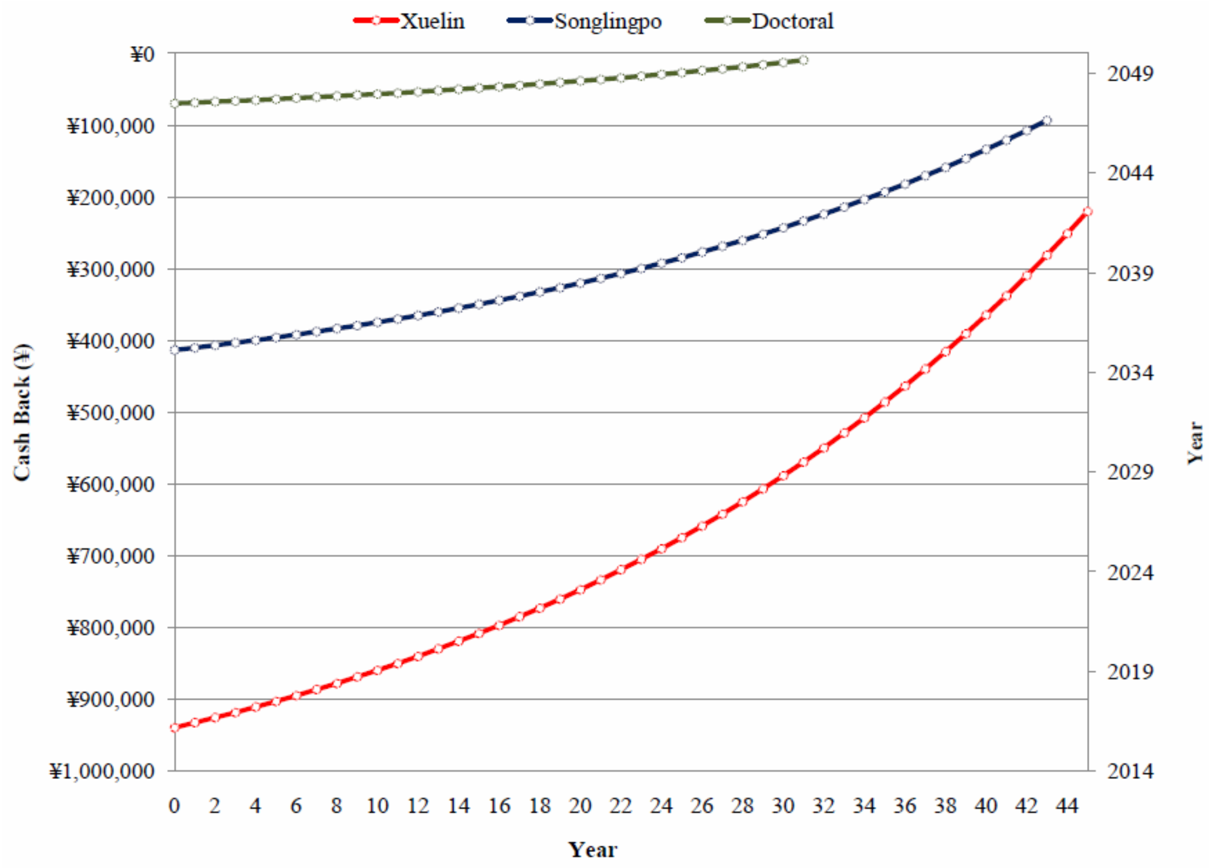

Figure 6. Cumulative cash back with year

4. Conclusions

This study revealed that at 60% yielding capacity of solar PV systems in Chongqing there is the potentiality for abating 80.79% to 100% of total CO_2 emissions. But, based on current electricity prices, the long (46, 43 and 31 years) pay-back periods on the investment required will prevent strong PV utilization for whole buildings of this urban area. Nevertheless, this research could be helpful to make an outlook for renewable solar energy for zero carbon residential buildings. The study may be regarded as an investigative case study. Chongqing is a hot summer and cold winter region where temperature varies from 8.0^{0}C to 28^{0}C. This research was conducted from October - March. Therefore, it did not accrue all the data required for making decisions for a complete calendar year. Amalgamating both winter and summer data is obviously important for energy design and formulation. More data would refine the calculations. Also, consideration needs to be given to the life styles of Chongqing people. These life

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styles would be different in some cases from that of the international students reviewed in this study. Although this is a limitation of this study, it is argued that the study is helpful in making an initial assessment of the overall scenario of CO_2 emissions and its abatement from utilization of solar renewable energy in the urban residential areas in Chongqing, China.

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