Renewable and Sustainable Energy Reviews 67 (2017) 1331–1344

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Economic disparity and CO_2 emissions: The domestic energy sector in Greater Bangalore, India

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A R T I C L E I N F O

Article history:
Received 8 July 2015
Received in revised form
3 April 2016
Accepted 9 September 2016

Keywords:
Electricity consumption
Greenhouse gas (GHG) emissions
Spatial patterns
Socioeconomic
Bangalore

A B S T R A C T

Energy consumption constitutes one of the important sources of carbon dioxide emission which cause global warming. This paper analyses greenhouse gas (GHG) emissions due to energy consumption in the domestic sector considering household activities and socioeconomic parameters. A stratified random survey of 1967 households in Bangalore pertaining to the energy consumption reveals that annual per capita electricity consumption ranges from 9.64 to 2337 kW h/year with an average of 336 ± 267 kW h/year. Emission from most of the wards (66 wards) is about 10–15 Gg/year, while wards in peri-urban areas emit less than 10 Gg/year. Extrapolation of these, show that total carbon dioxide from all wards of Greater Bangalore accounts to 3350 Gg/Year. The energy consumption analyses reveal a proportional increase in the per capita energy consumption with the family income suggesting that economic levels in respective wards is an important parameter in the domestic energy consumption and also GHG emissions. Suggested interventions through large scale penetration of renewable sources of energy and energy conservation would help in reducing greenhouse gases and consequent warming of the Earth.

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http://dx.doi.org/10.1016/j.rser.2016.09.038
1364-0321/

1. Introduction

Energy constitutes a fundamental and strategic tool to attain the minimum quality of life and energy consumption patterns are closely linked to the agro-climatic conditions and socio-economic factors [1,2]. Recent estimates indicate of sharp escalation in the energy demand, increasing by one-third over the period to 2035 [3]. The study also highlights of an increase of approximately 56% during next two decades of energy demand, which are mainly from the domestic sector (raise from 524 quadrillion Btu in 2010 to 820 quadrillion Btu in 2040 [3]. Exploitation and conversion of natural resources through various energy conversion devices for heating, lighting, etc. have made significant improvement in lifestyles. The dependency of human on energy has increased from 2,500 kJ/day to more than 2 lakh kJ/day. India is the seventh largest geography and ranks fourth among high energy consuming countries in the world with over 1.27 billion population. During past three decades, energy consumption has increased from 18 MTOE (in 1980) to 104 MTOE (2011) in India [4]. The per capita energy consumption is higher in the developed nations (USA-7.3 TOE, Canada- 7.6 TOE, Japan 3.7 TOE) compared to the developing (India-0.6 TOE, China- 1.8 TOE, Brazil-1.4 TOE) and less developed nations (< 0.4 TOE). Energy consumption per capita versus GDP per capita among the countries (Fig. 1) reveals Norway is high in GDP per capita (99,933 million USD) followed by Switzerland (79,024 million USD), Australia (65,430 million USD) and Sweden (55,341 million USD) which shows the effective utilization of energy. The per capita GDP value of India is 1555.50 million USD, which is lowest among these countries. Energy intensity of India is about 0.42 kgoe/million USD which is more than 12 times that of Switzerland (0.033 kgoe/million USD), more than 4 times that of Germany (0.092 kgoe/million USD), more than 3 times that of USA (0.137 kgoe/million USD) and about 1.3 times that of China (0.325 kgoe/million USD) in illustrated in Fig. 2. Most of the Asian countries have high energy intensity (energy/GDP) and lower per capita consumption, which illustrates the inefficient use of energy [5,6]...

However, over exploitation of natural resources especially fossil fuels for meeting the ever increasing energy demands and unplanned developmental activities has affected the environment and health [7–9]. Conventional fossil fuels in the form of coal, diesel, petroleum (gasoline) and electricity used by road, rail and air are responsible for emission of 80%, 13% and 6% respectively [10]. Consumption of fossil fuels is the prime reasons for enhanced greenhouse gases (GHG) in the atmosphere trapping heat and light in the earth's atmosphere, resulting in the global warming. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluorocarbons (HFCs), per fluorocarbons (PFCs) and sulfur hexafluoride (SF6) are the major greenhouse gases. Among the GHG's, carbon dioxide is the most predominant gas causing global warming [11].

In developing countries like India, the urban population is growing at rate of 2.3% per annum and global urban population is increasing from 220 million in 1900 to 3.2 billion in 2005 and is

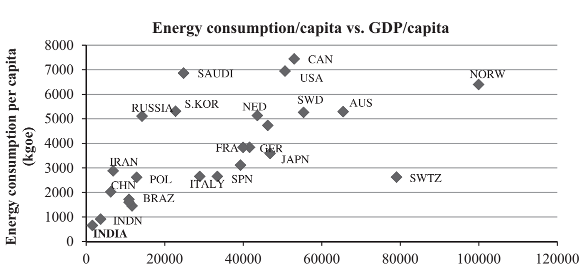

Fig. 1. Country wise energy consumption per capita versus GDP per capita.

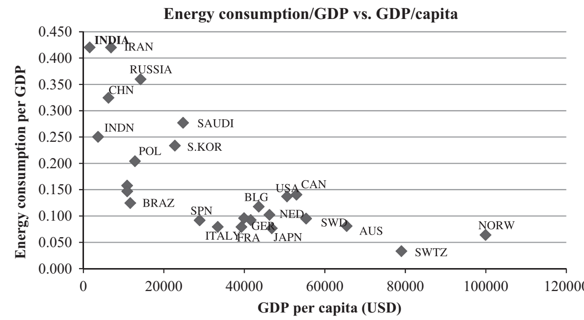

Fig. 2. Country wise energy consumption per GDP versus GDP per capita.

projected to step up to 4.9 billion by 2030 [11]. In terms of the global total anthropogenic GHG emission, cities contribute roughly 75–80% and the domestic sector is one of the major energy consumer in cities [10]. Assessment of GHG footprint (Aggregation of Carbon dioxide equivalent emissions of GHG's) across major cities in India reveals of emissions to the tune of 38633.2 Gg, 22783.08 Gg, 14812.10 Gg, 22090.55 Gg, 19796.5 Gg, 13734.59 Gg and 9124.45 Gg CO_2 eq respectively in Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad and Ahmedabad. Sector-wise synthesis indicate that transportation sector (contributing 32%, 17.4%, 13.3%, 19.5%, 43.5%, 56.86% and 25%), domestic sector (contributing 30.26%, 37.2%, 42.78%, 39%, 21.6%, 17.05% and 27.9%) and industrial sector (contributing 7.9%, 7.9%, 17.66%, 20.25%, 12.31%, 11.38% and 22.41%) of the total emissions in Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad and Ahmedabad respectively [11]. Macro-level analyses emphasized the need for detailed investigations to major sectors such as transportation [10] and domestic sectors.

This communication focusses on the GHG emissions due to energy consumption in the domestic sector considering household activities and socioeconomic parameters. Domestic energy consumption has various interrelated characteristics (ex. regional climate, building architecture, etc.). During the last decade, empirical studies have been receiving good attention in terms of domestic consumption and have included factors that are economical important such as fuel prices and economic stability [12] and variants of analytical techniques [13]. Most of these studies use aggregated time series data, and only a few research involves household-level data [14]. In India, these studies are limited [15] focusing on household socio-economic, demographic, geographic factors role in energy consumption. Estimation of residential energy demand in Seoul [16] based on 380 household samples revealed that the energy consumption pattern depends on the variables such as size of a house [17,18], family size, level of affluence, etc. [13,19,20].

Urban areas support 50% of the world population and are responsible for 67% of the world's energy demand and these region are under acute problem of energy consumption and GHG emissions [21]. It is estimated that by 2030, 73% of the world energy use will be in cities [22]. Urban households in India, for example, are responsible for about 45% of total primary energy use nationwide [23]. The sector wise temporal electric energy consumption in India (Fig. 3) shows that the industries sector is the highest consumption with 44.8%, followed by agriculture (17.3%), domestic (22%) and commercial sector (9%) [24]. Socio-economic growth coupled with urbanization, industrialization and burgeoning population lead to increase in the residential energy consumption for heating, lighting, electric appliances in many towns and cities in India [10] and the increase in energy demand is proportional with the urban growth [25]. Energy is required for heating, lighting, and motive power (to pump water, compressors, etc.) in the urban domestic sector and the increase in energy

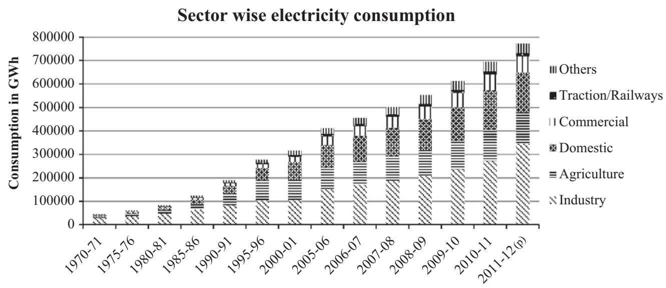

Fig. 3. Sector wise electricity consumption in India.

consumption in recent times has necessitated studies on carbon emissions due to energy consumption [26,27], in the residential sector [28,29]. The looming threat of climate change, urban household energy consumption and GHG emission have become a focus of investigations [30] for evolving appropriate adaptive and mitigation strategies to reduce warming of the Earth [31].

In this backdrop, the current communication examines the household energy consumption and CO_2 emission in Bangalore city, Silicon Valley of India. Bangalore has been experiencing rapid unplanned urbanization since 1990 resulting in the clumped growth with intense economic activities at some pockets and dispersed (sprawl) growth at outskirts. Circumstantial evidences show that some wards have higher energy consumption and CO_2 emission than others, but an understanding of the spatial patterns is yet to be acquired. Thus, the objectives of the current research are to 1) analyze the spatial patterns carbon dioxide emission due to energy (electricity and LPG) consumption in the residential sector; and 2) assess the effect of socioeconomic factors such as household size, income level on the energy consumption and emission.

1.1. Literature review

The review of literatures reveal that the household sector is one of the largest users of energy with about 30% of final energy consumption (excluding energy used for transport) [32]. The buildings sector accounted for more than one-fifth of total global consumption of delivered energy [33]. Energy use in the domestic sector accounts for energy for heating, cooling, lighting and many other household demands excluding transportation. Domestic energy consumption is influenced by various factors including the region, location, end-use efficiency of equipment [34–37], lifestyle [38–40], physical characteristics of a house and socio-economic aspects of the family [41–43] and regional energy policies [33,44–47]. Role of these factors is widely acknowledged across the globe even in similar structural households [48–52]. It is estimated that by 2040 the global residential energy demand would increase by 57% [33]. Financial stability and growth major driving force in energy consumption [53–55]. It is projected that the energy consumption would grow by one-third to 2040 with higher GHG emissions, primarily based on practices in Asian and African countries [56–58]. Reduction of 10–30% domestic energy consumption is reported just by changing occupants' behavior [59]. An understanding of the empirical links between lifestyles and the associated energy consumption and carbon emissions in order to devise strategies to reduce the energy consumption towards the sustainable lifestyles [60,61]. This helps to mitigate GHG emissions and the resultant warming of the Earth's biosphere [62,63]. Study based on the analysis of temporal data of 1971–2011 indicates energy consumption is positively influenced by proportion of urban population growth that uses the most available energy. India has seen unprecedented unplanned urbanization associated with dispersed growth or urban sprawl. Karnataka is one of the major states in India with higher energy consumption due to increase in urban population [64,65]. The annual electricity consumption of 6.20 billion kW h in the domestic sector, which accounts to 16.5% of the total electricity in the State [66], necessitating a study to understand the emissions in the domestic sector.

The analysis of domestic energy use and energy behavior considering demographic variables indicates limited awareness of energy saving from the adoption of energy efficient devices [67]; this is contrary to the claim of awareness of environmental issues. Household survey in different wards and zones of Lucknow city covering various income groups, reveal of enhanced energy (electricity and LPG) consumption in higher income families [68] and similar results were reported from the survey of French households [69]. GHG emissions due to energy consumption have been quantified for Tianjin city, China [70] using methods of IPCC (2006). Variations in CO_2 emissions across different income level households were assessed in Chinese cities [71] and the results indicate income and emission linkages similar to a study in Irish households [72], Haryana, India [73]. Carbon footprint assessment of 12 metropolitan areas of Beijing, Jakarta, London, Los Angeles, Manila, Mexico City, New Delhi, New York, Sao Paulo, Seoul, Singapore, and Tokyo considering emissions from vehicles, building energy use, industry, agriculture and waste sectors reveal of lowest per capita carbon footprints in cities with low per capita income [74,75].

Investigations of strategies towards carbon footprint reduction in the households and communities for 12 income brackets in 28 cities of United States of America reveal of intra and inter variations in carbon footprint based on demography [76,77]. The analyses of the energy consumption and driving factors (climate, geographical, architectural, economic and social) was carried out in urban households through the questionnaire survey in three districts revealed that electricity consumptions was almost twice in summer than in spring and autumn months. The CO_2 emissions per capita for household was 1.97 t in 2010, of which CO_2 emissions from electricity consumption comprised 1.15 t (58%) and per capita CO_2 emissions from natural gas consumption was 0.05 t (3%) and petrol consumption for transport was 0.77 t (39%) [78]. The households' electricity consumption survey in Bandung and Yogyakarta through the stratified random sampling of households reveal of statistically significant relationship between the monthly electricity bill and driving factors (income, family size, education level, daily activity, floor area and home appliances) in Bandung [79]. Similar studies in Bangladesh [80], Ouedraogo [81], Zimbabwe [82], Mozambique [83] and federal states of India [15,84–86] also confirm that domestic energy consumption depends on factors such as economic condition, household density and quality of life in human settlements. Urban heat island (UHI) and its consequences on household energy consumption study revealed of an increase in mean temperature by 1.97 °C during the past three decades [87] and positive correlation between UHI and level of energy consumption, which depended on the income and the number of air conditioner units, floor area of house, etc. Analyses of household energy consumption and expenditure in India based on NSS survey: national sample survey show 30% of monthly per capita expenditure (MPCE) is towards energy for fuel and light [88]. Lighting contributes 30% of total domestic electricity use followed by various applications such as refrigerators, cooling and heating etc. and higher consumption is reported in nuclear families with income elasticity [89–91] and found the threshold at which energy consumption increases with income [91]. All these studies emphasize the increasing contribution of GHG emissions by domestic energy consumption in urbanizing landscapes (towns and cities in India).

2. Data and methods

2.1. Study area

The study has been carried out for a rapidly urbanizing region in India. Greater Bangalore is the administrative, cultural, commercial, industrial, and knowledge capital of the state of Karnataka, India with an area of 741 sq. km. and lies between 12 °39′00” to 13 °13′00”N and 77 °22′00” to 77 °52′00”E (Fig. 4). Bangalore city administrative jurisdiction was redefined in the year 2006 by merging the existing area of Bangalore city spatial limits with 8 neighboring Urban Local Bodies (ULBs) and 111 Villages of Bangalore Urban District. Bangalore has grown spatially more than ten times since 1949 (~69–741 square km) and is the fifth largest metropolis in India currently with a population of about 8.5 million [92,93]. Bangalore city population has increased enormously from 65,37,124 (in 2001) to 95,88,910 (in 2011), accounting for 46.68% growth in a decade. Population density has increased from 10,732 (in 2001) to 13,392 (in 2011) persons per sq. km [94,95]. The per capita GDP of Bangalore is about $2066, which is considerably low with limited expansion to balance both environmental and economic needs Table 1.

Table 1 and Fig. 4 gives an insight to the temporal land use changes during 1973–2013 (based on the analyses of spatial data acquired remotely at regular time intervals since early seventies through space borne sensors). The built-up area has increased from 7.97% (in 1973) to 58.33% in 2012 and 73.72% in 2013. The sudden increment in urbanization during post 1990's was due to the globalization and consequent industrialization (in Peenya, Rajajinagar, Koramangala). Post 2000, Government's push to software sectors led to the large scale land use changes with urbanization at White field, Electronic city, Domlur, Hebbal, due to

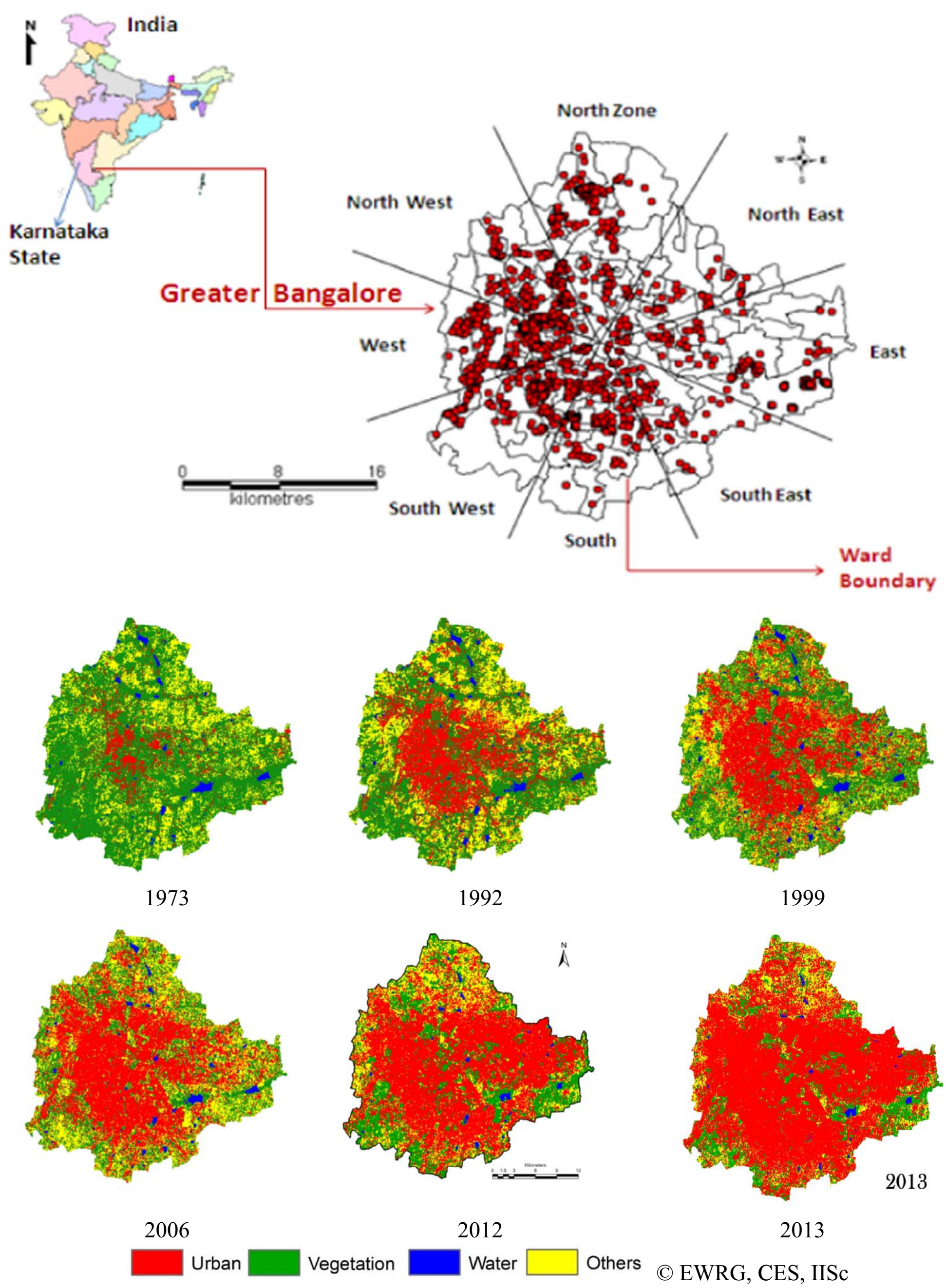

Fig. 4. 1. Study area. 2. Land use dynamics.

Table 1
Temporal land use dynamics in Bangalore.

Class	Urban		Vegetation		Water		Others	
Year	Ha	%	Ha	%	Ha	%	Ha	%
1973	5448	7.97	46,639	68.27	2324	3.4	13,903	20.35
1992	18,650	27.3	31,579	46.22	1790	2.6	16,303	23.86
1999	24,163	35.37	31,272	45.77	1542	2.26	11,346	16.61
2006	29,535	43.23	19,696	28.83	1073	1.57	18,017	26.37
2012	41,570	58.33	16,569	23.25	665	0.93	12,468	17.49
2013	50,440	73.72	10,050	14.69	445.95	0.65	7485	10.94

private players and development of Special Economic Zones (SEZ). Bangalore, once branded as the Garden city due to dense vegetation cover, which has declined from 68.27% (1973) to less than 15% (2013). The temporal analyses of spatial data also reveals of 925% increase in built-up (building, roads, etc.) with the decline of 78% vegetation and 79% of area covered with water bodies [96,97] during 1970–2013. Developments in various fronts with the consequent increasing demand for housing have urbanized these regions evident from the drastic increase in the urban density during the last two decades. Bangalore grew intensely in the north-west (NW) and south west (SW) regions in 1992 due to the policy of industrialization consequent to the globalization [97]. The industrial layouts came up in NW and housing colonies in SW and urban sprawl was noticed in others parts of the Bangalore. This phenomenon intensified due to impetus to IT (Information Technology) and BT (Biotechnology) sectors in south-east (SE) and north-east (NE) during post 2000. Subsequent to this, relaxation of FAR (Floor area ratio) in mid-2005, lead to the spurt in high raise buildings in residential and commercial sectors, paved way for large scale conversion of land leading to intense urbanization in many localities. This also led to the compact growth at central core areas of Bangalore and dispersed growth at outskirts. These sprawl regions are devoid of basic amenities and infrastructure. The analysis showed that Bangalore grew radially from 1973 to 2014 indicating that the urbanization has intensified from the city center and reached the periphery of Greater Bangalore.

Similar trends of urbanization are noticed in other major metropolitans – Kolkata, Mumbai, Chennai and Delhi, which recorded an urban growth of 425% [98], 467% [99], 650% [100] and 850% [101]. Mumbai is the commercial capital of India has a GDP of 209 Billion USD, followed by Delhi (167 Billion USD), Kolkata (150 Billion USD). Bangalore (85 Billion USD) and Chennai (66 Billion USD). Assessment of GHG footprint (Aggregation of Carbon dioxide equivalent emissions of GHG's) of Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad and Ahmedabad are found to be 38633.2 Gg, 22783.08 Gg, 14812.10 Gg, 22090.55 Gg, 19796.5 Gg, 13734.59 Gg and 9124.45 Gg CO_2 eq respectively. Chennai emits 4.79 t of CO_2 equivalent emissions per capita, the highest among all the cities followed by Kolkata which emits 3.29 t of CO_2 equivalent emissions per capita. Also Chennai emits the highest CO_2 equivalent emissions per GDP (2.55 t CO_2 eq/lakh Rs.) followed by Greater Bangalore which emits 2.18 t CO_2 eq/lakh Rs. [102].

2.2. Data collection

Assessment of the spatial patterns in GHG emissions due to domestic energy consumption involved i) primary survey of sample household through the pretested and validated structured questionnaire and ii) compilation of ward wise electricity consumption data from the government agencies. Bangalore with a spatial extent of 741 sq. km has 198 administrative wards. Wards were prioritized for sampling based on type, economic activities and social aspects. The survey was carried out during 2011–12 in select households chosen based on stratified (economic status) random selection and validation of sampled data was done during 2012–14. Survey covered 1967 households representing heterogeneous population belonging to different income, education, and social aspects. Fig. 4 gives the spatial distribution of sampled household (marked as red dots in the study area – Bangalore). The questionnaire was designed to explore key drivers which affect household energy consumption, physical characteristics of dwelling (residential status, type of building, year of house unit built), attitude towards surrounding environment and other parameter includes household size, annual income, age, energy consumption behavior of households. Energy consumption in a household is an outcome of various household behavior such as type of water heating systems (solar, electricity, LPG, etc.), type of fuel used for cooking (electricity, LPG, fuel wood), details of electrical gadgets (lighting, electric fan, refrigerator, washing machine, water treatment units, computers, television, computers, laptop, etc.). Secondary data of ward wise annual electricity consumption for the period 2001–2013 was collected from the BESCOM (Bangalore Electricity Supply Company).

2.3. Method of analysis

Spatial patterns in energy consumption and GHG emission is assessed considering various growth poles based on the extent of urbanization. The study area was divided into 8 zones (/regions) based on directions –North, Northeast (NE), East (E), Southeast (SE), South, Southwest (SW), West (W), Northwest (NW), respectively (Fig. 4) based on the Central pixel (Central Business district, CBD). The electricity and LPG consumptions were computed for each zones based on the compiled data through sample surveys in each zones.

Emission due to electricity use in the domestic sector is quantified using Eq. (1) considering quantity of electricity consumption and emission factor. The emission factors and net calorific values (NCV) for different sectors are listed in Table 2.

$$C = \beta E \quad \ldots \tag{1}$$

Where, C is carbon dioxide emission; β is emission factor (Table 2) and E is consumption of electricity.

Liquefied Petroleum Gas (LPG) is the principal fuel used for cooking in the residential sector. Emission due to LPG consumption is computed using Eq. (2).

$$\mathrm{E} = \mathrm{Fuel} * \mathrm{NCV} * \mathrm{EF_{GHG}} \quad \ldots \tag{2}$$

Where E is the emission; Fuel quantity consumed; NCV is net calorific value; EF_{GHG} is the emission factor of LPG (given in Table 2)

3. Results and discussion

Population census of 2011 [103] shows that majority (56%) of urban households have four or less members. The analysis of 1967 sample households reveals a similar trend of 4.5 persons per household. Fig. 5 illustrates the distribution of household family size in urban areas – 4 persons per family dominates the sample

Table 2
Emission factors and net calorific values (NCV).

Source	Emission Factor	Net calorific value (NCV)	References
LPG	63 t/Tj	47.3 Tj/Gg	[61]
Electricity	0.81 t/MW h		[62]

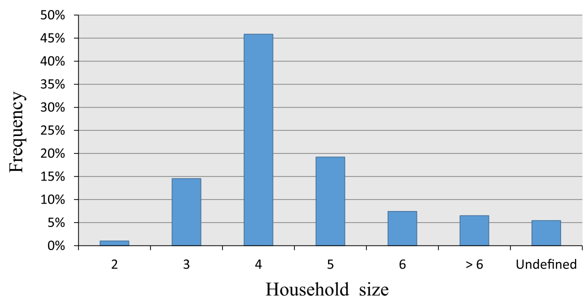

Fig. 5. Household size in surveyed area.

(45.9%) followed by 19.2% family having 5 persons, 14.5% family with 3 persons. A larger family of greater than 6 constitutes 6.5% of the total sample. Spatial distribution of size of the households in the study area i.e. different wards of Greater Bangalore illustrate that majority of the households (902) have household size of 4, while 128 households have more than 6 persons indicating the prevalence of joint family in Bangalore.

Age structure composition forms an important characteristic of any population, which varies significantly with age. Demographic variables such as population expansion, rapid urbanization, aging society and shrinking household size drives carbon emissions [104] evident from higher consumption of energy and higher emissions in the population aged between 15 and 64, [105–107] and lower energy consumption by senior (> 65 years) citizens [108] and contrary results are reported by some [109–111]. The influence of demographic agents on energy consumption and carbon emissions was comprehensively established in macro-level analysis which highlight that higher population density is associated with lower levels of energy consumption and emissions [112]. Similar analyses [113,114] in developing countries considering household size conclude that larger size of household were associated with lower levels of aggregate carbon emissions. Thus, demographic data is useful in regional planning when it is cross classified by variables like marital status, literacy educational attainment, economic activity, etc.

In sampled households of 1967 households, children and youth (< 21 years) dominate (39.2%), followed by age group 41–60 with 31.3%. Middle age individuals (21–40) constitute 21.2% and senior citizens (> 60 years) is about 8.1%. The distribution of various age groups shows that senior citizens is one per house in 271 households, while 141 samples had 2 senior citizens per house Age group distribution reveal that the individuals of 40–60 of one person per house in 702 samples and two persons per house in 731 samples, illustrates the age group of 21–40. 790 households are with only one member followed by 248 houses (2 members), 51 households (3 members), and 23 households (4 members). Children and youth form the major section of the society (39.28%). Large proportion of the households have two children (839 samples) followed by 511 (one child), 162 households (3 children), 40 households (4 children), 10 households (5 children) and about 5 households have more than 6 children per family.

Earlier studies have revealed the linkage of family income with the level of energy consumption, evident from 3 times higher consumption of electricity in high income category compared to low income homes [1]. Earlier studies also highlight the linkage between economic growth of a family and emissions indicating as the income increases the emissions increase and at a stage it stabilizes and subsequently decreases [115–117]. Income is one of the major parameter influencing household energy consumption and Fig. 6 gives the distribution and grouping of households based on annual income. Middle income (Rs. 1–5 lakh per year) with 64.6% (1278 samples) constitutes the major category among the surveyed households. The spatial distribution of various income categories is given in Fig. 6. 132 households have the annual income > 1 million Rs. in wards such as Doddanekundi, Raja Rajeshwari Nagar, Ullal, Chowdeswari, etc.

Most of the sampled residential houses have floor area < 1200 sq. ft. (135 sq. m), while 775 samples are between 1200 and 2400 sq. ft. and 6.2% of them having the floor area in the range of 2400–5000 sq. ft. mainly in the southern part of Bangalore. Small fraction of the sample (1%) have floor area > 5000 sq. ft. at Doddanekundi, HSR layout, Laggere etc. Higher energy consumption and per capita emissions is in residential households with larger floor area.

Bangalore grew rapidly subsequent to the globalization and consequent opening up of markets leading to unplanned urbanization. This is evident from intense urbanization at city center and dispersed growth at outskirts. Zone wise distribution of houses (depending on the year of construction) is given in Fig. 7, which illustrates that about 52% of houses in all zones except NW are have been constructed recently (explained before, due to IT and BT boom). Industrial layouts, residential townships spurted in S and SW zones.

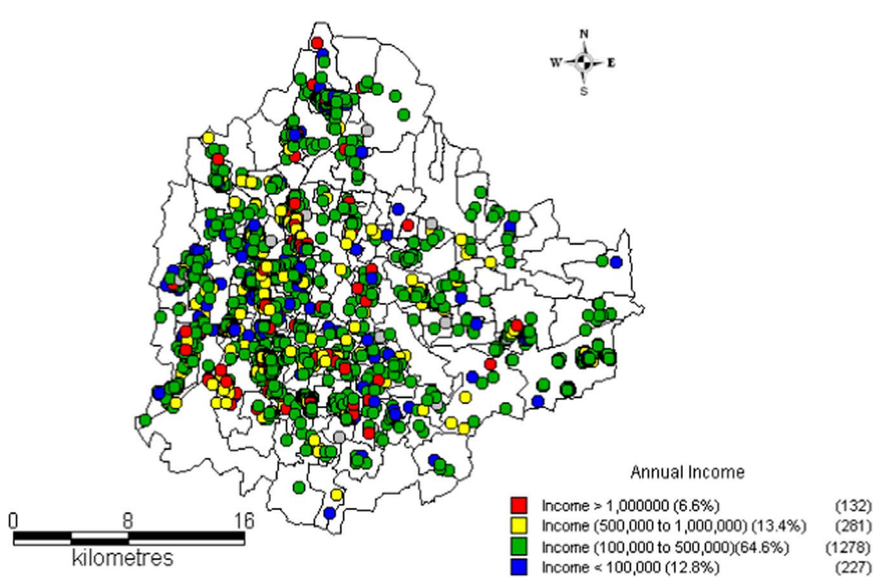

Fig. 6. Annual income.

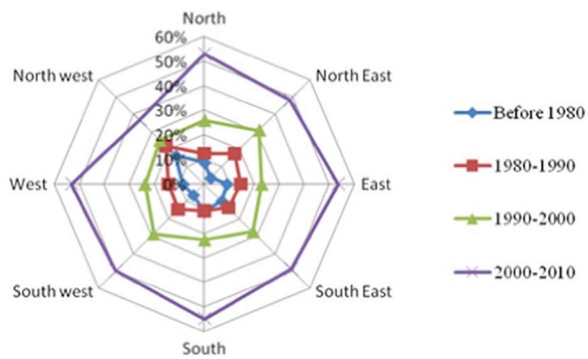

Fig. 7. House unit built.

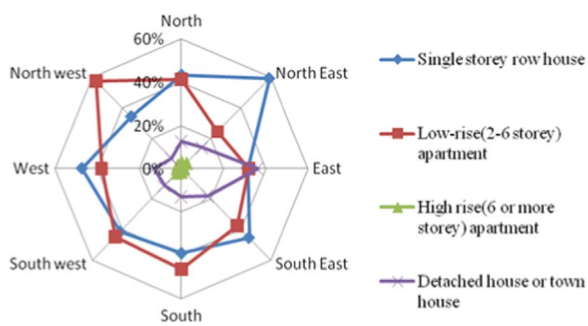

Fig. 8. Type of building.

Most of the buildings in Bangalore are either low raise apartment (41.99%, 826 units) or single-storey row houses (40.72%, 801 units), 15% were detached houses mainly in SE zone and only 2% are high-rise apartment which are concentrated in the center of the city. Zone wise distribution of different types of buildings (Fig. 8) indicate that single-storey row houses are concentrated in the NE (59%) followed by W (47.2%), SE (45.1%), N (43.0%), S (39.0%), NW (33.8%), and E (31.0%) zones. Similarly, 57% low-raise apartments are in NW and 21.1% in NE. E zone has large proportion of detached houses or town houses (35.9%). High raise apartment constitutes 1.1% in E to 3.4% in NE zones. High rise apartments have come up in the recent decade with the relaxation of FAR (Floor area ratio) with rapid urbanization. Higher energy consumption is in nuclear families and buildings with higher FAR. This necessitates exploration of alternate sources of energy to meet the growing energy demand in decentralized way.

Solar energy is the most abundant permanent energy resource on earth and it is available for use in its direct (solar radiation) and indirect (wind, biomass, hydro, ocean, etc.) forms [118]. Solar energy is clean, safe, easy to maintain and sustainable method of generating power. Solar energy is widely accessible and it is free from greenhouse gases emission and does not contribute to global climate change. India has a higher insolation of solar energy due to its favorable location in the solar belt (40°S–40°N) and receives annual sunshine of 2600–3200 h. Solar cookers, dryers, improved cook stoves can be used in domestic sector whereas, solar and wind driven pumps are reliable in irrigation. Captive electric energy generation using solid waste, bagasse, agricultural and horticultural residues, wind and solar are viable in industrial sector. Hence the Renewable sources can replace the present energy mix with higher share with distributed generation and micro-grid (rooftop) generation. Assessment of solar potential in India reveals nearly 58% covering 1.89 million km^2 of the geographical area potentially represents the solar hotspots in India with more than 5 kW h/m^2/day of annual average Global insolation [5]. The identification of solar potential and appropriate policy interventions of the federal governments have hastened the penetration off-grid and grid-connected solar energy based systems. The decentralized electricity generation has reduced T & D losses while meeting the regional energy demand. A techno-economic analysis of the solar power technologies and a prospective minimal utilization of the land available within these solar hotspots demonstrate their immense power generation as well as emission reduction potential. Renewable energy sources and technologies have potential to provide solutions to the longstanding energy problems being faced by the developing countries like India and have potential to offset a huge volume of GHG emissions [119].

The National Action Plan on Climate Change (NAPCC) under Jawaharlal Nehru National Solar Mission (JNNSM) identified the development and deployment of solar energy technologies in the country to achieve parity with grid power tariff by 2022 [120]. Energy is required for heating, lighting and motive power (pump water) in the domestic sector. Water heating for bathing purposes constitutes one of the energy activities in most households. Using clean energy such as electricity for low-end energy inefficient activities such as water heating necessitates the energy auditing in household sector and also the extent of penetration of energy efficient devices. Heating systems used for water heating (bathing purpose) includes fuel wood stove, solar water heater, electrical heaters and others. Majority samples (39.76%) use electric heaters, followed by solar water heaters (24.76%), others (which include LPG, etc.) constituting 20.1%. Higher penetration of solar water heaters in Bangalore could be attributed to the energy policy of the federal government. The Government has mandated compulsory installation of Solar water heaters in the residential and commercial buildings having plinth area of more than 600 sq. ft. in Karnataka [121,122]. About 8.1% of the population still use traditional fuel wood stove for water heating purpose. Improved cook stoves, CFL/LED lamps, energy efficient heaters and coolers will help in reducing the significant amount of energy in the household sector. Solar water heater and rooftop solar PV installation helps in substituting electricity (lighting, etc.) and biomass (water heating) respectively [68].

About 53.4% of samples have adopted solar devices for water heating and these households have adopted solar devices for water heating as the option is environment friendly (17.49%, 344 samples), saving energy (16.73%, 329 samples) or due to subsidy from the government (3.30%, 65 samples). The spatial distribution of use of electric heater, solar heaters, etc. for water heating highlights the success of alternate technologies for water heating especially in some locations such as K.R.Puram, Hosakerehalli, Kengeri and Dasarahalli etc.

Expenditure on heating bill with subsidy indicates majority households (497, 25.97%) spend monthly about Rs. 200–500 whereas 250 households (13.62%) spend less than 200 rupee per month. Energy used for cooking purposes in domestic sector includes electricity, fuel wood, LPG, etc. In India, about 33.6 million households uses the LPG as cooking fuel [123]. The fuel wood, LPG, etc. contribute emissions of greenhouse gases. LPG is used for cooking in the majority (78.75%, 1549) households. LPG and electric heaters are used in 11.54% or 227 households. Most of the households have major rooms towards east (39.76%, 782 samples) and north (22.01%, 433 samples) from better ventilation perspective.

Majority (62.89%, 1237 samples) are keen to conserve energy to reduce the carbon emission while 398 samples for economic reasons and 7.47% want to conserve to save energy as well as money. Analysis shows the deployment of solar appliances in 584 samples. Among these, 430 households have availed the facility of government subsidy. About 55.47% (1091 samples) wants to switch over to solar appliances as they are environment friendly. 14.79% (291) wanted to adopt solar appliances to save money as well as for environment friendliness. About 22.42% of household (441) have

Table 3.1
Total electricity consumption (kW h/Year).

Zones	Minimum	Maximum	Mean	SD
North	150.00	8018.00	1377.24	1135.77
South	169.00	7610.00	1764.03	1362.29
East	104.00	9349.00	1152.34	1226.92
West	100.00	6924.00	1420.84	1075.14
North East	106.00	3000.00	917.21	754.05
North West	108.00	5112.00	1273.28	891.61
South West	155.00	4822.00	1723.83	1006.52
South East	127.66	6023.70	1472.31	1245.31

plan to install solar appliances. However, large proportions of the sample (997, 50.69%) are not sure of installing solar appliances.

3.1. Spatial variations in household energy consumption

The domestic sector plays a dominate role in energy consumption across various income classes in urban areas. [7]. In India, about 30% of total residential electricity is consumed for lighting followed by the refrigerators, fans, electric water heaters, televisions, mobile charging, etc. [21]. Electricity consumption in the domestic sector has been increasing rapidly in Greater Bangalore. Usage of air conditioners and high energy gadgets has enhanced the energy consumption in high income households. The annual per capita electricity consumption variation spatially reveals that about 700 households use annual per capita electricity in the range 100–400 kW h. About 226 households use annual per capita electricity in the range 400–600 kW h. An energy guzzler (1000 units per year per person) happens in 140 households. 36 households are highly energy intensive consuming more than 1000 units (kW h)/Year.

Zone wise analysis of annual electricity consumption given in Table 3.1, shows the variation from 917.21 ± 754.05 (NE) to 1764.03 ± 1362.29 (S) zone. Similar trends are observed in per capita annual electricity consumption (Table 3.2 and Fig. 9), which varies 230.91 ± 210.84 (NE) to 412.30 ± 297.75 (S). Zone wise variation of per capita electricity consumption shows the variation of 30 kW h/year to a max of 1796 kW h/year (SW) followed by the North East with 9.64–750 kW h/Year. East Zone is with minimum per capita electricity consumption 18.57–2337 kW h/year.

Ward-wise electricity consumption details were compiled for 2011–12 from the respective zonal offices of BESCOM (Bangalore Electricity Supply Company) were synthesized to understand variations across zone considering all sectors shown in Table 4. Fig. 10 reveals that about 40 wards have annual per capita electricity consumption of 500 kW h, 23 wards have consumption of 500–1000 kW h. Majority of wards (84) are in the range of 1000–2000 kW h/person/year, 31 wards have the consumption of 2000–4000 kW h/person/year. A very high consumption of more than 4000 kW h/person/year is in 24 wards of SE Bangalore, mainly due to IT and BT industries and large scale high raise apartments [60].

Table 3.2
Electricity consumption per capita (kW h/Year).

Zones	Minimum	Maximum	Mean	SD
North	30.00	1796.00	330.30	276.69
South	28.00	1902.50	412.30	297.75
East	18.57	2337.25	242.85	245.34
West	17.00	1731.00	338.72	262.31
North East	9.64	750.00	230.91	210.84
North West	24.60	1056.25	314.03	220.62
South West	48.80	1577.67	409.65	240.18
South East	31.91	1505.93	352.96	326.62

Per capita annual electricity consumption ranges from 112.16 kW h (Devsandara ward) to 7668.48 kW h (Ejipura ward).

LPG is a dominant fuel used in the domestic sectors. The spatial distribution of monthly LPG consumption (Fig. 11) reveals that majority (1499, 76.2%) consumes one cylinder (of 14 kg LPG) per month while 219 samples require 2 cylinders. The average per capita LPG consumption is 15.5 kg/month. Wards like K.R.Puram, Kengeri, Hoskerehalli, JnanaBharathi consumes 2 cylinders of LPG. Zone wise LPG consumption and per capita LPG consumption are listed in Tables 5 and 6 respectively. The LPG consumption varies from 181.46 ± 57.94 (W) to 208.75 ± 97.50 (SE). Per capita annual LPG consumption varies 42.33 ± 20.02 (E) to 54.02 ± 34.76 (SE).

The annual electricity and LPG consumed in each household were aggregated with common energy unit gigajoules (GJ) and was divided by the respective household family size to get the per capita energy consumption. Analysis shows that 767 households consume < 2 GJ/year while 888 households consuming 2–4 GJ/year. The energy consumption ranges from 0.129 GJ/year to 12.39 GJ/year with the average of 2.9 ± 1.4 GJ/year and this is comparable to earlier reports [63].

Fig. 12 reflects the zone wise monthly electricity consumption. E (19.03 kW h) and NE (19.41) have average lower per capita monthly electricity consumption compared to SW (31.81 kW h) and SE (30.28 kW h). Fig. 13 represents the seasonal variation of electricity consumption in different zones. Bangalore enjoys tropical climate and this is reflected in season wise household electricity consumption. In summer there is a higher consumption than winter and rainy seasons. In summer per capita electricity consumption is minimum in NE zone (20.41 kW h) and maximum in SW (34.69 kW h), whereas in winter and rainy seasons minimum consumption is 19.02 kW h (E) and 19.75 kW h (NE) respectively and maximum is 33.33 kW h (SW) and 34.56 kW h (SW)...

3.2. Spatial pattern of domestic CO_2 emission in Bangalore

Domestic sector plays major role in the emission of greenhouse gases [11]. An emission due to electricity consumption in the domestic sector is computed as explained earlier in the methods section. CO_2 emissions from electricity consumption in 419 households range between 1–2 t/year followed by 379 households with 0.5–1 t/year. 29 households with higher consumption of electricity emit more than 4 t/year. Similarly, emissions due to LPG consumption is computed and results shows that most of the households (1501 households) have emission ranging between 0.4–0.6 t/year followed by 230 households with 0.6 t/year. Fig. 14 provides the CO_2 emission from total energy (including LPG and electricity), which illustrates that 40% households (751 samples) emits between 0.5–1 t/year, followed by 37% households (695) emitting 1–2 t/year. 44 households emit more than 4 t/year.

Based on the survey data, considering the population of the wards, CO_2 emission from electricity and LPG are extrapolated for different wards of Greater Bangalore. CO_2 emissions from electricity consumption show that majority of the wards (71 wards) emits in the range of 10–15 Gg/year while 9 wards in the city center emits more than 20 Gg/year. Wards such as Atturu, Kadugodi located at outskirts of the city emits between 15 and 20 Gg/Year and 16 wards emits less than 4 Gg/Year. The emissions due to electricity consumption in Bangalore is about 11,112 Gg/Year and emission from electricity consumption in domestic sector from the sample of 1907 households is 224;6Gg/Year, which is about 20% of total emission.

CO_2 emission due to LPG consumption (Fig. 15) shows that 48 wards mostly located in the outer zone of the city emits CO_2 in the range of 4–5 Gg/year. 28 wards emit less (4 Gg/year) and 26 wards in the city center like Chickpet, Shanti Nagar, Vijay Nagar emits

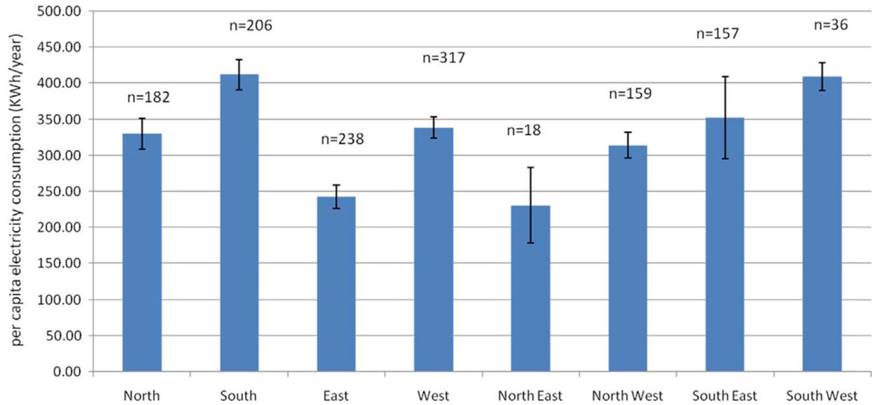

Fig. 9. Per capita annual electricity consumption in different zones.

Table 4
Per capita electricity consumption in zones according to BESCOM.

Zones	*Minimum*	*Maximum*
North	0	1796.00
South	0	1902.50
East	0	2337.25
West	0	13,796.50
North East	0	750.00
North West	0	3252.40
South West	0	5718.75
South East	0	14,849.10

CO_2 more than 7 Gg/year. Wards such as Nandini layout, Benniganahalli, Shettihalli emits 6–7 Gg/year. Fig. 15 depicts the total CO_2 emission including LPG and Electricity from different wards of Greater Bangalore. Emission from most of the wards (66 wards) ranges between 10 and 15 Gg/year, wards located at city center such as Kacharkanahalli, Vijnanapura, Sarvagana Nagra, Malleswaram have emissions more than 25 Gg/year. Maximum carbon dioxide emission is 46.56 Gg/Year in Sarvagna nagar ward and minimum emission is 3.66 Gg/Year in Konena Agrahara ward. Total carbon dioxide emission from all wards of Greater Bangalore is 3350 Gg/Year.

3.3. Role of socioeconomic factors in residential energy consumption and CO_2 emission

Household energy demand and associated carbon emissions depend on many factors, like household size, income levels, attitude towards energy savings which is related to the education level, government policies, etc. Earlier studies have focused on the role of education, family size, climatic parameters on the level of energy consumption in rural area [1] and the role of education on household energy requirement in Australia, Brazil, Denmark, India and Japan [123]. Fig. 16 indicate the decline in per capita LPG as well as electricity consumption with the increase in the number of persons per household and the probable relationship is $Y=9.4007e^{-0.266x}$ ($r=0.973$, $p<0.05$) comparable to the earlier study [124] comparable to the earlier study where the household size had negative correlation with energy consumption [123]. Family income is a key variable in the household energy consumption intensity [15], evident from Table 7, which illustrate the increase of per capita electricity consumption with the increase in income and the probable relationship is $y=-0.0002x^2+29.287x+2E^{+06}$($r=0.983$, $p<0.05$). A proportional increase in the per capita energy consumption with the family income mainly due to dependence on high level energy services (Fig. 17), which suggests that economic level of a family, is an important parameter in the domestic energy consumption and GHG emissions...

4. Conclusion

The spatial patterns of GHG emissions due to domestic energy consumption have been analyzed for Greater Bangalore – a rapidly urbanizing region in India. Domestic sector is the major consumer of energy in a city and understanding spatial patterns of domestic

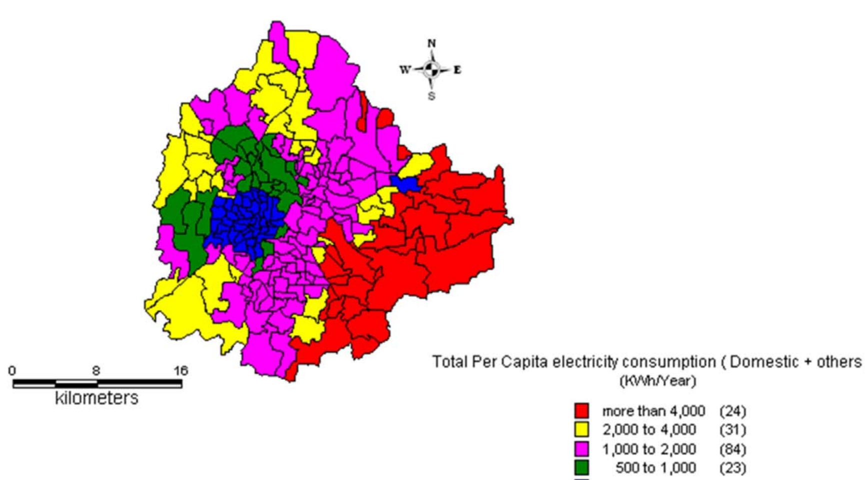

Fig. 10. Annual per capita electricity consumption (domestic and other sectors) in surveyed area (BESCOM data).

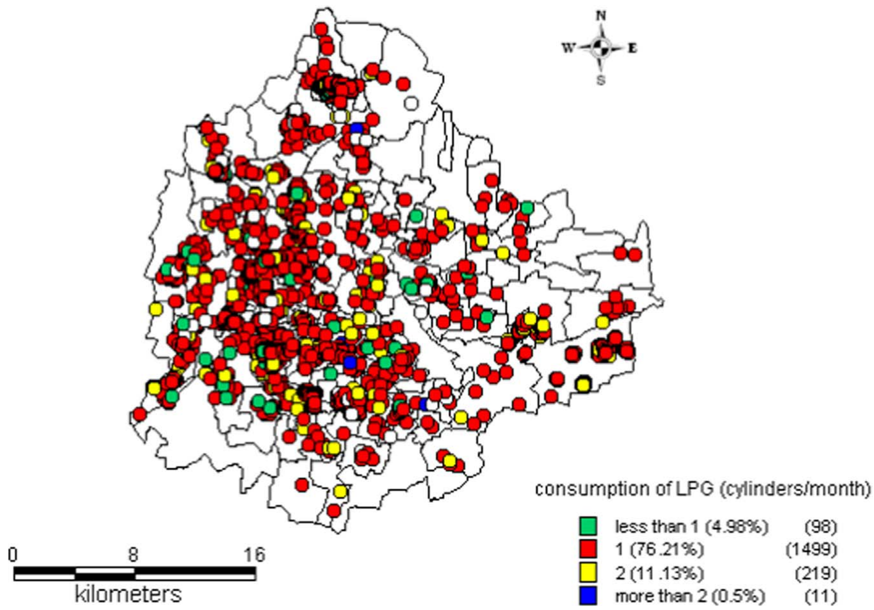

Fig. 11. LPG consumption.

Table 5
Total LPG consumption (kg/Year).

Zones	Minimum	Maximum	Mean	SD
North	84	504	186.40	58.42
South	84	504	183.80	57.57
East	42	504	189.33	83.09
West	42	504	181.46	57.94
North East	84	336	189.78	64.20
North West	84	336	186.47	59.86
South West	84	504	185.27	64.58
South East	84	504	208.75	97.50

Table 6
Per capita LPG consumption (kg/year).

Zones	Minimum	Maximum	Mean	SD
North	12	168	45.11	20.39
South	14	112	43.03	14.39
East	7	126	42.33	20.02
West	5.09	112	42.97	16.51
North East	21	168	46.66	29.96
North West	12	168	47.00	19.04
South West	12.92	168	44.09	18.87
South East	21	168	54.02	34.76

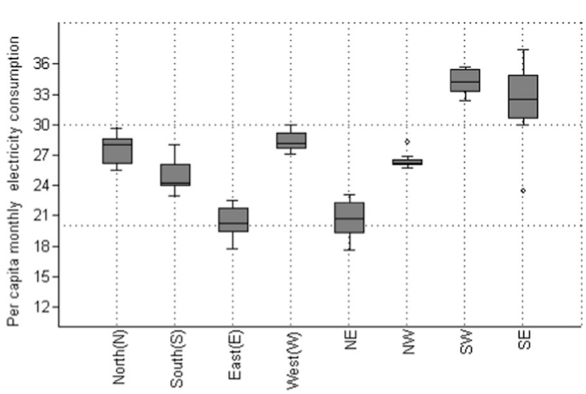

Fig. 12. Per capita monthly electricity consumption in different zones.

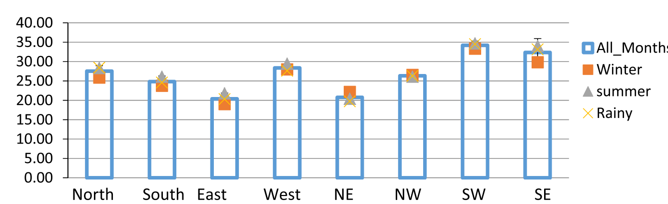

Fig. 13. Seasonal variation in different zones.

energy consumption help in formulating appropriate policy measures to introduce environment friendly alternate energy sources and also to implement energy conservation measures towards low carbon cities. This has been done through multi-stage stratified random survey of households (1967 households) and compilation of ward wise electricity consumption data from the government agencies.

The current analyses provide insights to the neighborhood and community of household, energy consumption pattern and corresponding carbon dioxide emission due to different inside household activities. Present study provides understanding of the trends in CO_2 emission in the urban household sector of different wards of Greater Bangalore. This study illustrates that different segments of population have very different energy consumption depending their socio-economic characteristics. The survey reveals a typical household family size, family income and the extent of adoption of renewable energy devices (Solar water heaters, etc.) play an important role in the energy consumption at households.

Energy used for cooking purposes in domestic sector includes electricity, fuel wood, LPG, etc. LPG is being used for cooking in the majority (78.75%, 1549) households. The spatial analysis of annual per capita electricity consumption reveals that about 700 samples use annual per capita electricity in the range 100–400 kW h and about 226 households use annual per capita electricity in the range 400–600 kW h. Zone wise analysis of annual electricity consumption shows the variation from 917.21 ± 754.05 (NE) to 1764.03 ± 1362.29 (S). Similar trends are observed in per capita annual electricity consumption, which varies 230.91 ± 210.84 (NE) to 412.30 ± 297.75 (S). Ward-wise total electricity (domestic and other sectors) consumption synthesis reveals that about 40 wards have annual per capita electricity consumption of 500 kW h, 23 wards have consumption of 500–1000 kW h. Majority of wards

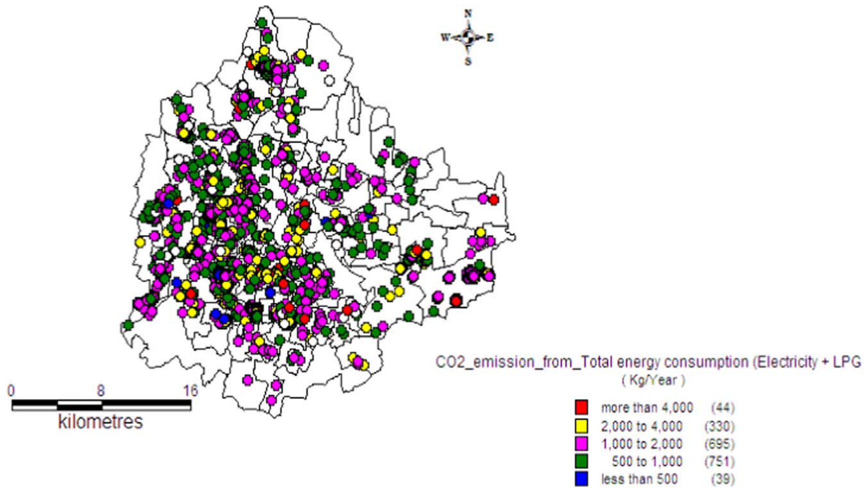

Fig. 14. CO_2 emission from total energy consumption.

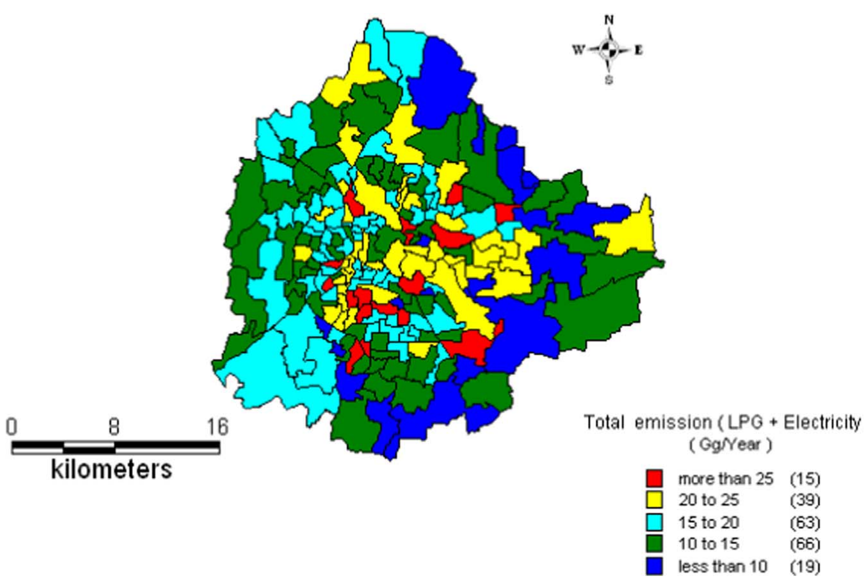

Fig. 15. CO_2 emission from LPG+ Electricity.

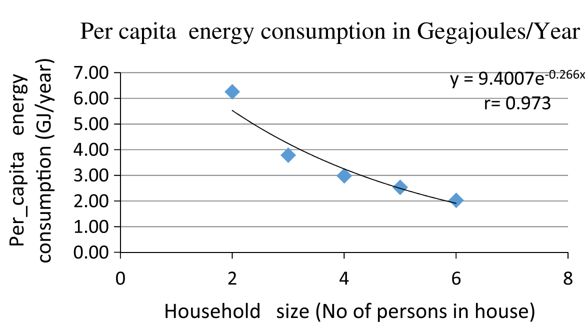

Fig. 16. Relationship between per capita residential energy consumption and household size.

Table 7
Consumption pattern of electricity in the surveyed area of Greater Bangalore.

Income catgory	*Electricity Consumption (kW h/month)*	*No of households*	*Percent*	*Per capita consumption (kW h/month)*
Income < 100,000	3482.50	156	9.0	22.32
Income 100,000–500,000)	22,617.11	816	58.6	27.72
Income 500,000–10,00,000)	8230.42	193	21.3	42.64
Income > 10,00,000	4284.99	92	11.1	46.58

(84) are in the range of 1000–2000 kW h/person/year, 31 wards have the consumption of 2000–4000 kW h/person/year. A very high consumption of more than 4000 kW h/person/year is in 24 wards of South East Bangalore, mainly due to IT and BT industries and large scale high raise apartments. LPG is a dominant fuel used in the domestic sectors. Majority of households (1499, 76.2%) consumes one cylinder (of 14 kg LPG) per month while 219 samples require 2 cylinders. LPG consumption varies from 181.46 ± 57.94 (W) to 208.75 ± 97.50 (SE). Per capita annual LPG consumption varies 42.33 ± 20.02 (E) to 54.02 ± 34.76 (SE). Pertaining to the link between energy consumption with the social factors, negative correlation between household size and energy consumption per capita is observed in the sample analysis. A proportional increase of the per capita energy consumption with income ($r = 0.983$), suggests that economic level of a household is an important factor in domestic energy consumption. The spatial distribution of annual per capita energy consumption shows that 767 households consume < 2 GJ/year while 888 households consuming 2–4 GJ/year. The energy consumption ranges from

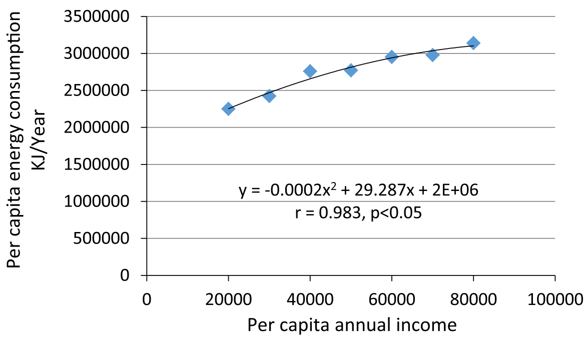

Fig. 17. Per capita income and residential energy consumption.

0.129 GJ/year to 12.39 GJ/year with the average of 2.9 ± 1.4 GJ/year and this is comparable to earlier reports. Emission from most of the wards (66 wards) is 10–15 Gg/year, while wards in peri-urban areas emit less than 10 Gg/year. Wards located at city center emit more than 25 Gg/year with maximum of 46.56 Gg/Year (Sarvagna Nagar) and minimum of 3.66 Gg/Year (Konena Agrahara ward). Extrapolation of these, show that total carbon dioxide from all wards of Greater Bangalore accounts to 3350 Gg/Year. The study illustrate that domestic sector contributes significantly to GHG emissions in the city. Present study provides understanding the trends of spatial pattern of domestic energy consumption and CO_2 emission in the urban household sector of different wards of Greater Bangalore which is necessary for an appropriate policy measures towards low carbon city and present study can be used as basis for policy planning at city level reducing GHG emission and maintain sustainable development in the city.

4.1. Recommendations

Appropriate policy incentives might help in the large scale deployment of solar devices at household levels. There is a need to focus on energy efficient decentralized electricity generation technologies with micro-grid and smart grid architecture, which would go long way in meeting the energy demand. Solar energy based generation seems promising and environmental friendly option to meet the growing demands. India is blessed with the good solar potential and harvesting this potential would minimize the environmental implications associated with the fossil fuels. Solar Photovoltaic (SPV) technology has the potential to meet the domestic and irrigation demands in the decentralized way. In this regard, suggestions are:

1. Electricity generation using SPV (solar photovoltaic) and CSP (concentrated solar power) technologies would bridge the demand supply gap as India receives abundant solar energy of more than 5 kW h/m^2/day for about 300–330 days in a year. The adequate potential with mature technologies and apt policy incentives would help in meeting the electricity demand in a region.
2. Roof top based SPV would help in meeting the household energy demand in rural as well as urban households. Rural household require about 70–100 kW h per month and to meet this requirement 5–6 m^2 rooftop is adequate (at $\eta = 10\%$, and insolation of 5 kW h/m^2/day) and the average rooftop in rural locations in Karnataka is about 110 m^2 and about 155 m^2 in urban localities.
3. Adequate barren/waste land is available in Karnataka as the available waste land is about 7% of the total geographical area less than 1% area is sufficient to generate electricity required for irrigation and domestic sector through SPV installation.
4. Decentralized generation of electricity through renewable energy resources (solar, wind, bioenergy) SPV would help in meeting the respective household's electricity demand apart from the removal of T&D losses. Generation based incentives (GBI) would herald the decentralized electricity generation, which would help in boosting the regional economy. Considering the current level of T & D losses in centralized system, inefficient and unreliable electricity supply, it is necessary to promote decentralized energy generation. Small capacity systems are efficient, economical and more importantly would meet the local electricity demand.
5. Promotion of high energy efficient appliances in households, mainly by replacing conventional heaters and coolers with high energy efficient ones. Government need to improve the end use energy efficiency by providing improved cook stoves, Piped Natural Gas (PNG) usage instead of LPG, CFL/LED lamps, which will help in reducing the significant amount of energy and CO_2 emission from the household sector
6. Using clean energy such as electricity for low-end energy inefficient activities such as water heating (for bathing) necessitates the energy auditing in household sector and also the extent of penetration of energy efficient devices including solar water heaters.
7. Impetus to energy research through generous funding for the R and D activities to ensure further improvements in the grid, technologies, two way communication energy meters (to connect rooftop generation with existing grid), efficient luminaries' production, low cost wiring, switchgears, appliances, etc.
8. Energy education (focusing mainly on renewable energy technologies, end-use energy efficiency improvements, energy conservation) at all levels. School curriculum shall include renewable energy (RE) concepts.
9. Capacity building of youth through technical education for installation and servicing of SPV panels.
10. Mandatory one week capacity building/training programmes to all bureaucrats and energy professionals at the initial stages of the career. This is essential as lack of awareness/knowledge among the bureaucrats is the major hurdle for successful dissemination of renewable energy technologies in India.

Acknowledgement

The authors are grateful to the Asia-Pacific Network for Global Change Research (APN) for its financial support (ARCP2011-07CMY-Han) to this research. We thank BESCOM for providing zone-wise electricity data.

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