Urban energy system management for enhanced energy potential for upcoming smart cities

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Abstract
Scientific and industrial development has given rise to a rapidly increasing energy demand. Alternative and augmented energy resources are expected everywhere due to scarcity and depletion of other non-renewable resources. During recent years wind and solar had emerged as a promising cleaner energy source to offer a favourable solution with better efficiency. Hence, the attention has now diverted towards scaling up of hybrid system of energy generation. Numerous attempts have been taken to demonstrate the technological development concerning the requirement of the region. Whilst some research has already started to evaluate the working of the prototype, insignificant attention has been paid towards it. The current work also focuses on the simulation with hybrid urban renewable energy systems for techno-economic feasibility analysis. There were earlier attempts to report the advancement occurred in the technological, scientific and industrial sector due to hybrid renewable energy system. In some regard, it was an attempt to showcase the modelling of a typical urban requirement in an hourly load profile to identify in the energy potentials of the urban region. These will help to summarize the past, present and future trends of the hybrid energy system design, development and implementation for the urban region, which can be later on replicated to other parts of the world.

Keywords
Hybrid energy system, techno-economic, urban energy
Introduction

Advancement of cities and urban regions is facing several challenging issues towards energy security, energy poverty and maintaining a low carbon rating (Lamrani et al., 2019). To drive its economic growth, these were primarily dependent on conventional fuel to support future development. However, despite utilizing the conventional sources of energy (Basir et al., 2013), it has failed to keep up the requirement of the existing demand. There is the critical challenge towards energy deficiency due to a huge increase in demand, expansion of industries, the rise in population, poor management of energy resources, lack of energy plans and orphaned implementation of energy policies (Dong et al., 2013). The conventional energy system market is going through paroxysms everywhere in the world. These critical challenges have diverted the attention of the stakeholders towards the search for alternative energy sources to secure its progressive objectives (Lins, 2007). These search for energy technologies have created open space to provide solutions for long-lasting energy problems with the combination of several renewable energy resources such as solar, tidal, wind and geothermal (Gifford and Grace, 2011). These sources of energy have a high potential to earn dividends also. Combination of all energy sources results in hybrid renewable energy system (RES)/technology and this technology has promising and long-lasting possibilities for on-site clean energy production along with reduced CO₂ emissions (Luqman et al., 2015). These types of energy systems typically enable us to transform the freely available energy resources to a usable energy system like electricity. The adoption of these technologies will help to cater the future demands (Klemes et al., 2012).

Current residential/domestic energy system depends only on conventional energy sources like coal, oil, natural gases or uranium (Ramachandra, 2007). These are causing various problems including (a) contribution towards various types of greenhouse gasses ignoring the influence of atmospheric pollution, climate change or nuclear waste towards our better living condition on the earth, and (b) all these conventional sources of energy will be exhausted after several years and leaving no energy resources. Thus, there is a requirement of clean energy system technology to fulfil the future energy generation from various sources (Al Mamun et al., 2016). During recent years, the capital and costs of energy have condensed due to improved reliability of the system and use of other non-conventional sources of electricity such as wind and geothermal energy (Hosseini et al., 2013). But in urban areas, there is having only the possibility of utilizing the wind along with the traditional solar energy system to develop a hybrid RES (Bright et al., 2018). Traditionally, any energy utilizes the freely available wind in the form of airflow to rotate the wind turbines to mechanically turn the electric generators to generate electrical energy (Stampolidis et al., 2006). This wind energy has also high potential as an alternative to burning fossil fuels. It is also plentiful, renewable, widely distributed, and clean, zero greenhouse gas emissions during operation with no water consumption and little space/land requirement (Shirley et al., 2012). A typical hybrid energy system set-up for urban area will essentially comprise of a generator, photovoltaic system, wind energy set-up, a supporting frame to mount the photovoltaic panels on the ground, on a building or any building structure, a system for power control and conditioning, a possible energy storage system, electrical switchboards and switchgear assemblies, a switching and protection equipment and by the connection cables (Rustemli and Dincer, 2011). As available solar radiation on the Earth’s surface is highly spatially and temporally variable. Therefore, exploring and exploiting the true potential at locations is a complex task requiring knowledge and expertise in various disciplines.
(Reno et al., 2012). This variability also affects the predictability and manageability of the required energy for various applications (Kumar, 2019). The current work tries to address the issues like (1) formulating hybrid urban energy system (HUES) for improving urban energy potential, (2) detailed analysis of HUES, (3) assessing various costs involved in the hybrid urban RES and (4) cash flows and sensitivity analysis for the most substantial physical and economic parameters.

Thus, the current work tries to design architecture for HUES for renewable energy-related projects (Alafita and Pearce, 2014), extracts distinct challenges from these previous efforts and, finally, defines a set of core future research avenues for geospatial technology-based energy infrastructure planning (Ramirez et al., 2015) with a focus on the use of HUES in urban areas (Resch et al., 2014).

Data and methods

Study area for pilot research

The current pilot work was attempted at the metropolitan city of Delhi (the capital city of India) as shown in Figure 1. Geographically, it is located in northern part of India and lies at latitude 28°36′36″N and longitude 77°13′48″E with a flat topography with an altitude of

Figure 1. Location of the study area.
200–250 m (650–820 ft) (Singh, 2006), and covering an area of about 1484.0 km². According to a report of the Population, Union Territory of Delhi had a population of 16,787,941 with a population density of 11,312/km² (29,298/sq mi) (Singh, 2017). Delhi experiences an extreme climate with a very hot summer (April–July) and cold winter (December–January). The average temperature varies from 25 to 45°C during the summer and 22 to 5°C during the winter.

It is also a second most populous urban mega-metro city of India; it has extensive tree cover in several managed green spaces including parks, educational institutions, government and military areas and archaeological sites (Chaves, 2009). The city also harbours a wildlife sanctuary, namely the Asola-Bhatti sanctuary, covering an area of 19.91 km². The area is divided into nine administrative districts, with 27 administrative sub-divisions or tehsils. The city is controlled by three local bodies: (i) New Delhi Municipal Council, (ii) Delhi Cantonment Board and (iii) Municipal Corporation of Delhi. Delhi encompasses the regions of old and new areas. The inherent vegetation of Delhi State is a tropical dry thorn forest (Kumar et al., 2008). But, being a major economic hub, the city is experiencing extreme urbanization pressure (Wihlborg et al., 2019). Extensive industrialization and urbanization are transforming land cover with the degraded natural ecosystem (Tripathy and Kumar, 2019).

Software, tools and datasets

1. **Tools:** Hybrid Optimization of Multiple Energy Resources (HOMER) toolsets for analysis of the energy and geospatial datasets (Anand et al., 2017).

2. **Datasets:** Several geographic and meteorological parameters like daily average incident energy, availability and duration of sunshine, solar power density across various geographic locations (Balasubramanian and Ariffin, 2014). Some of the typical input datasets are the following:
   A. **Elevation:** The elevation data are required to provide information about the terrain (Reno et al., 2012).
   B. **Land use:** The land use data offer information about the land, such as area cover under forest, urban or wetland (Mishra et al., 2006).
   C. **Political boundaries:** The political boundaries are required to provide the demarcation of country, province or state, and district or county level boundaries along with the names of the political units in the attributes (Resch et al., 2014).
   D. **Transportation and electric infrastructure:** The transportation data provide details about roads (paved and unpaved) and railroads (Stampolidis et al., 2006).
   E. **Potential exclusions:** The potential exclusions may include parks, wildlife areas, historic sites and cultural areas.

3. **Technical resource parameters:** These include following a set of datasets required for the toolkit:
   A. **Solar resource:** The solar resource data tell about average energy available from the sun at a location over one year. The data are expressed as an annual average of the amount of radiation available in a single day in kilowatt-hours per square metre of collector surface area per day (kW h/m²/day) (Lund et al., 2015). These datasets are in series of monthly and seasonal solar resource data in addition to the annual data (Gils et al., 2017). Apart from these it also includes the following sub-forms of solar resource data:
B. **Global horizontal radiation (abbreviated as GLO or GHI):** GHI data are treated as appropriate for estimating sites for flat solar collectors, including most photovoltaic and solar hot water systems (Mahtta et al., 2014). These represent the quantity of solar energy reaching one square metre of a flat surface parallel to the ground in a single day (Reno et al., 2012).

C. **Global radiation at latitude tilt (abbreviated as TILT or PV):** Generally a flat collector is tilted at an angle from the horizontal which equals to the latitude of the system’s geographic location for preliminary analyses (International Renewable Energy Agency, 2012). In some of the set-up using the latitude as the tilt angle also results in the maximum collection of solar energy.

D. **Direct normal radiation (abbreviated as DNI or CSP):** These kind of datasets are suitable for assessing sites for parabola-shaped concentrating solar collectors, such as parabolic trough, power tower, dish-Stirling, concentrating photovoltaic systems and some types of solar hot water systems (Stellenbosch University, 2011). DNI contains only radiation in a direct line from the sun (Mendoza and Prabhu, 2000).

E. **Wind resource:** These types of datasets describe the average energy in the wind at a particular location over one year (Ajayi et al., 2016). The wind power density defines an amount of available wind energy available for conversion to electricity by a wind turbine. It depends on the speed of the wind and the density of the air (Natural Resources Canada, 1997). Wind power density is generally denoted in watts per square metre (W/m²) of rotor swept area for a tower height of 50 m above the ground (Wafa and Taha, 2014).

F. **Economic parameters:** These parameters involve various costs like an investment, maintenance, servicing and insurance costs against damages (Considine et al., 2012; Hayat, 2016).

**Methodology**

The current work utilizes the HOMER toolkit to evaluate technology for an off-grid HUES for any location shown on the map (Verma et al., 2015). This toolkit processes the renewable energy data from the toolkit’s renewable resource database for the analysis. The present study considers the case of Community I (in HOMER tool) typically representing an area/region having an annual average load of about 5 kW h/day. These kind of communities may also consist of a group of smaller residences. The residences can be linked to a central system via a micro-grid with wire. The load profile shows a small continuous load with two brief daytime peaks, one in the early morning, and one around noon, and a peak period between sundown and midnight. All costs are in units of U.S. dollars due to predefined currency units in the model and it is restricted to be edited in the model as input (Gifford and Grace, 2011).

The monetary considerations for deployment of the HUES can be quite diverse in developed regions than the undeveloped regions (Bawah et al., 2013). In new regions, the situation is more likely that the economic return will be very much trivial with tiny or no cash flow. The key element of the current study includes economic modelling and simulations for economic analysis using constraints and economic indicators for economic considerations on energy system installations (Van Gevelt and Holmes, 2015). As a result, it can be established that if the installed system that does not recover installation and maintenance costs within a justifiable period then it is not suitable for implementation. The suggested approach also considers various aspects of the problem including the energy and economic ones.
Even if it is important to evaluate the energy cover factor of a hybrid RES, it could happen that the system does not harvest economic advantage from the operational phase. The combined analysis of the energy and economic aspects is of elementary prominence for evaluating real outcomes of investments. In justifying and testing the proposed methodology, the following phases were considered:

1. **Techno-economic feasibility analysis**
   a. Configuration of the system
   b. Technical specification of the system
   c. Evaluation of costs of the HUESs (investment costs and costs for maintenance, servicing and insurance against damage).
   d. Benefits due to the gains for the avoided bill costs, the incentives and the sold electricity.
   e. Cash flow analysis.
   f. Estimation of the energy cover factor concerning economic analysis.
   g. Sensitivity analysis for the most significant physical and economic parameter

2. **Proposed system architecture set-up for simulations**

   The proposed system was set up in HOMER toolkit; the data for solar irradiance and the wind were downloaded from required data archived, and HOMER results have been shown in the ‘Results and meta-analysis’ section. In results, different combinations consisting of a different number of hybrid energy system components along with the ancillary equipment were calculated in HOMER toolkit and, finally, the most economical system was selected considering the factors such as initial capital cost, cost/kW h, net present cost (NPC), surplus electricity generation and the efficiency of the system. The proposed system architecture set-up for simulations with actual schematic diagram is exhibited in Figure 2. It demonstrates a schematic connection diagram of the HUES connected with the DC bus. There is provision for a converter which converts DC into AC and ensures the power quality (reduce the harmonics). The trial simulations of the proposed system were performed through HOMER toolkit, as shown in the block diagram. Table 1 shows the details of system configuration as shown in Figure 1 for the cash flows the simulations for the presumed sets of values. The illustration encapsulates the major equipment being used for energy systems development.
Results and meta-analysis

The present case considers a typical house in Delhi (capital city of India) for calculating the load profile, PV sizing and system design. As a case study of Community I was taken (to represent a small urban house) with an annual average load of about 5 kW h/day. The load profile has a small continuous load and two brief daytime peaks, one in the early morning, and one around noon, and a peak period between sundown and midnight. Because of the planned urban area, each of the houses will have similar individual house’s load profile. All costs are given in U.S. dollars due to the restriction of the toolkit that it takes currency only in U.S. dollars. The location was selected because most of the developed countries like India have high solar energy resource and huge power requirements and face long load shedding hours.

Technical feasibility of the system

The current system architecture analyses the size and cost of current per kilowatt-hour to estimate the cost of renewable energy. As the efficiency and output power of any energy system usually depends on the availability of solar irradiance, location, face angle of the photovoltaic panel, variety of photovoltaic cell (like monocrystalline, polycrystalline, micro amorphous silicon and amorphous silicon) and the efficiency of the components. But the other available sources of energy like the wind energy along with alignments of the location play a very significant role for the energy system. Therefore, in implementing urban energy systems to meet the domestic load demand revealed that wind and diesel would be operationally viable and to be installed then a stand-alone photovoltaic energy system. There are following system architecture considerations before simulating the parameters:

a. Monthly baseline average wind speed average data

Table 1. System architecture configuration details.

| System architecture | Cost summary |
|---------------------|--------------|
| PV array            | 1.25 kW      |
| Generator           | 1 kW         |
| Battery             | 12 Trojan T-105 |
| Inverter            | 0.75 kW      |
| Rectifier           | 0.75 kW      |
| Dispatch strategy   | Cycle charging |
|                     | Total net present cost $25,105 |
|                     | Levelized cost of energy $0.976/kW h |
|                     | Operating cost $718/yr |
|                     | Total net present cost $25,105 |

PV: Photo Voltaic.
b. Monthly global horizontal solar radiation data

Figure 4 displays the monthly variability of the typical global horizontal solar radiation data every month. The average global horizontal solar radiation profile for the complete year was generated as shown in Figure 4. It unveils that the energy generation potential is relatively better in March, April, May and June due to longer sunny days.

c. Simulation results of monthly average excess electrical production

Typically, in any urban areas, people are accustomed to electric appliances for several purposes, so these play a significant role to decide the feasibility of any hybrid
energy system. Therefore, in some of the months, we require a surplus amount of energy resource to compensate for the required energy demand. Hereby, it is mandatory to quantify the excess amount of electrical energy available every month. In this context, Figure 5 displays the scenario of excess electrical production every month. The trends in the Figure 6 show that the average excess electrical production potential is relatively better in March and April.
d. **Simulation results of monthly average electric production**

The actual values of the energy production obtained from HOMER simulation toolkit were analysed for technical analysis of the designed/configured systems. Figure 8 exhibits that the monthly average electricity production to be accounted for the technical feasibility assessment to reduce the cost of installations. The current configured systems contribute to the production of electricity using PV array with 2363 kW h/yr and generator with 285 kW h/yr, with typical consumption through AC primary load of 1825 kW h/yr. The monthly average energy production profile for the complete year shown in Figure 8 illustrates that there is relatively ample potential for better energy production in March, April and May.

e. **Simulation results of PV output**

For proper valuation of any energy system, it is very much essential to weigh the actual values of the energy in the form of PV output. Thus, this simulation was carried and the results obtained from the simulation process showed mean energy output of 6.47 kW h/day with 21.6% of capacity factor and totalling to an amount of 2363 kW h/yr of energy. The simulation provided a value of 0.256$/kW h as levelized cost of production. Figure 9 provides complete details of potential PV output production every month.

f. **Economic feasibility of the system with simulated cash flow**

To illustrate the economic feasibility, Figures 9 and 10 illustrate the detailed summary of cash flow (NPC) of the different components like PV, Trojan T-105 Battery, wind energy system and converter. It tries to rationalize the various effective costs like capital investment, replacement cost, operation and maintenance cost, fuel cost and salvage.
Figure 8. Cash flow summary of NPC for each component. Source: Simulated through HOMER toolkit. PV: Photo Voltaic.

Figure 9. Cash flow summary of annualized cost for each component. Source: Simulated with HOMER toolkit. PV: Photo Voltaic.
cost involved with the operation of any hybrid energy system at the defined set of the configurations. The proposed system architecture set-up for simulations in Figure 2 encapsulates the principal equipment to be used in actual energy systems. Whenever an investment is proposed to install hybrid energy systems in the urban area, the main problem arises in defining a criterion to assess the actual feasibility of the project, because in urban scenario it exhibits complex phenomena due to varied energy demands of various sectors. The majority of paybacks are related to the gain to avoid energy bill cost of the electricity. The total expenses were due to the expenses in costs for investments, system devices replacement, maintenance and management, and insurance. To evaluate the economic feasibility, the costs of the investment were obtained from the market prices of each component, considering the labour costs and fitter’s wages. All these factors were linked to the cash flows for evaluation of the effective HUESs for estimating the cost of the net present value (NPV), the internal rate of return and the payback periods.

The cash flows were calculated for 25 years. The economic analysis was performed and the following results were generated:

- The NPCs of each component were expected as 8521$, generator cost was expected as 4943$, battery (Trojan T-105) cost for storage was expected as 10,835$, converter cost was expected as 807$ and system cost was 25,105$.
- The annualized costs of all components like PV were expected as 605$/yr, generator cost was as 351$/yr, battery (Trojan T-105) cost for storage was 769$/yr, converter cost was 57 $/yr and system cost was 1781$/yr.
- The PV array panels produce 2363 kW h/yr of energy every year.
- The generator was expected to provide 285 kW h/yr of energy every year.

**Figure 10.** Summary of nominal cash flow. Source: Simulated with HOMER toolkit. PV: Photo Voltaic.
Figure 10 exhibits that the majority of paybacks are possible in the last year only. Out of the total expenses required as costs of investments, system design requires the majority of investment in PV array followed by the battery.

**Conclusion**

The ability of renewable energy technologies is evolving faster due to the capability of upcoming energy technologies to empower a fast evolution of low-cost carbon energy system. The several constraints were considered in the present study before endorsing for the implementation of the concept. It was presumed that energy supply to the people in developing countries is a multifaceted activity and there are only limited approaches to resolve it. As for the current study Community I was taken to represent a small urban house with an annual average load of about 5 kWh/day. Figure 3 reveals the monthly average variability of wind speed from datasets obtained from open archive datasets. Typically, in the urban areas, as people use electric heaters or air conditioner for various purposes including heating/cooling, due to that hourly load profile for the complete year will be relatively higher in the months having longer nights. Figure 4 displays the monthly variability of the typical global horizontal solar radiation data every month. The average global horizontal solar radiation profile for the complete year was generated as shown in Figure 4. It unveils that the energy generation potential is relatively better in March, April, May and June due to longer sunny days.

The simulation was carried and the results obtained from the simulation process showed mean energy output of 6.47 kW h/day with 21.6% of capacity factor and totalling to an amount of 2363 kW h/yr of energy. The simulation provided a value of 0.256$/kW h as levelized cost of production. Due to the continued acute energy shortage, it will also play a vital role in economic development. Thus, a HUES has significant potential to source energy along with local jobs creations to promote economic growth, avoiding the peripheral environmental costs associated with traditional electrical generation technologies. The evaluation of any real and economically viable energy systems for reaching ambitious targets in the field of energy has a dominant prominence in addressing issues of decision-makers. It can be observed seen that the battery bank requires a significant capital cost which affects the overall economic viability of the system. In the future, large-scale implementation of another HUES (including compressed air, hydrogen gas, flywheel, pumped hydro and other options) study can be performed to explore the implementation of other combinations for energy storage systems along with the battery bank to provide clean and cheap energy.

**Author's Note**

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