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The role of distributed energy systems in European energy transition

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Abstract

This study presents a comprehensive analysis on the energy demand and supply of typical European city centers for present time and 2050 horizon according to the Intergovernmental Panel for Climate Change (IPCC) climatic scenario A1B. Building and urban archetypes are modelled to represent the building stock considering thermal characteristics and local climatic conditions of typical city centres in European cities in order to understand the demand. Subsequently, present and future heating and cooling demands for these urban archetypes are computed considering present and future climate as well as renovation scenarios. Micro-grid systems are designed for the urban archetypes to evaluate the potential for renewable energy integration. Results of the study reveal that a notable reduction in energy demand can be anticipated due to the building renovation. Furthermore, the study reveals that the average renewable energy generation within the micro-grid can be reached up to 52% using solar PV and wind energy after considering grid curtailments for 2050 scenario considering lower grid curtailments.

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1. Introduction

Due to industrialization and globalization activities, rise in greenhouse gas emissions is leaving detrimental repercussions on the global climate. Exhaustive use of the non-renewable resources, particularly fossil fuels play a vital role in this context. On the other hand, urban population has increased rapidly while demanding for more and more energy generation to cater to the energy requirements of the cities [1]. To tackle these challenges, distributed energy systems such as energy hubs play a vital role when integrating non-dispatchable renewable energy technologies such as wind turbines and Solar PV (SPV) panels[2]. However, designing such distributed energy

systems considering the urban conditions and climate change is a challenging task [3]. The EU is persistently undertaking initiatives to combat the rising global warming threats and is trying to reduce its traditional independence on fossil fuels and nuclear power. It is seeking to switch towards a greener, more sustainable and a more environment friendly future with the integration of renewable technologies in its energy mix. There are a number of studies that focus on the energy sustainability at community scale using bottom up models as explained in [4–6]. However, such bottom up models have not been extended beyond national scale considering both energy demand and generation besides their lack of importance to understand the big picture about energy transition in the future. This study aims to address this research gap by considering energy transition path ways by extending the bottom up model approach. Towards achieving this objective, a computational platform is developed combining urban simulation tools and micro-grid optimization tools which are explained in detailed in Section 2. Results obtained from the study are discussed in detail in Section 3.

2. Methodology

A computational platform is developed in this study to consider the impact of both building renovation and energy system improvements. The workflow of the computational platform is presented in Fig. 1.

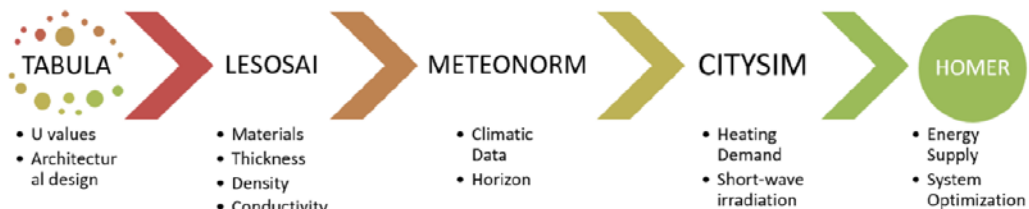


Fig. 1 workflow of the computational platform.

The thermal, structural characteristics of the building such as U values and architectural design for archetype buildings for different European countries are collected from TABULA [7] database. Required characteristics for the future refurbishment scenarios are also taken from the same source. The collected data was translated into a software readable format with the help of LESOSAI [8]. The climatic data for each representative European city is taken from the METEONORM [9] software which is a continuously updated platform for global climatic conditions. The future climatic data collected through METEONORM supposedly follows an assumed climatic scenario (A1B) that predicts the climatic conditions in the future. The energy demand simulations were then carried out using CITYSIM Pro [10,11]. The combination of Tabula database, Lesosai [8], CitySim and Meteonorm was helpful to derive energy demand for future cities along with the archetype proposed by Ratti et-al. [12] (Fig. 2 (a)). This archetype, along with the climatic data and horizon characteristics of the representative European capital, was input into the CITYSIM software where the heating and cooling demand simulation was carried out for each European city. CitySim uses single zone, resistance-capacity models to provide hourly energy demand profiles. Interactions between buildings are taken in consideration through shadowing and radiation effects. Based on the simulations performed in CitySim, annual hourly energy demands for different European cities were obtained which were used to model the micro-grid using Homer Pro Software. The micro-grid (Energy Hub) comprising of wind turbines, flat plate PV panels, storage batteries (Lead Acid and Lithium Ion depending upon cases) is considered in this study (Fig 2(b)). It is assumed that heating and cooling demand is catered using heat pumps and air-conditioners. Due to the magnitude of the study, the cost inputs for all the components of the micro-grid under all considered scenarios were estimated and interpolated/extrapolated (wherever necessary) through several published studies, national reports and the EUROSTAT [13] database.

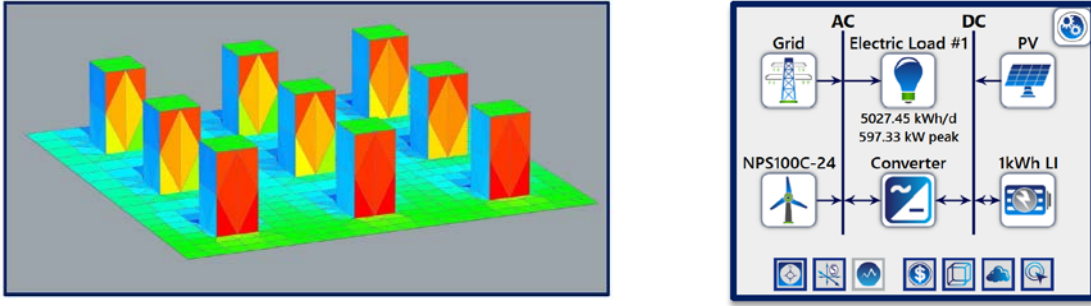


Fig.2 (a) Archetype of a typical city center used for simulating energy demands in various European cities (b) Schematic of Micro-Grid model used for supplying energy to meet the simulated demands.

The performance of distributed energy systems are assessed using a number of performance indicators [14] such as grid sale capacity, net grid purchase, net present cost, levelised cost of energy, renewable energy fraction, carbon emissions etc.

The net present cost is used to estimate the total life cycle cost of the system. It takes into account all the various revenues, investments and costs that occur during the lifetime of the system and reduces into a single lump sum whereas the cash flows in the future are discounted back to year zero with the help of a specified discount rate (5% in our case). The various costs that are taken into account include capital and replacement costs of the components as well as their operating and maintenance expenditures. Revenues are calculated from the income generated by selling power back to the grid along with the salvage value of system equipment at their end of life [15].

The levelized cost of Electricity (COE), as defined by Homer, is the average cost per kWh of useful electrical energy produced by the system. It is defined as follows [16]:

$$COE = \frac{C_{ann, tot}}{E_{served}} \quad (1)$$

where $C_{ann, tot}$ is the total annualized cost of the system (\$/year).

The renewable energy fraction (f_{ren}) pertaining to the micro-grid is calculated using the following equation [17]:

$$\sum_{t=1}^{8760} f_{ren} = 1 - \sum_{t=1}^{8760} \frac{E_{nonren}}{E_{served}} \quad (2)$$

where E_{nonren} is the hourly non-renewable electricity production (kWh/year) and E_{served} is the Net hourly electricity served by the grid (including grid sales). The sale capacity of the grid refers to the maximum amount of power that can be sold back to the grid in each hourly time step [18]. The Net Grid Purchase Limit refers to the maximum value of net grid purchases less the grid sales allowed to the micro-grid and the annual purchase capacity is defined as the maximum power that can be purchased from the grid in each time step [19].

3.0 Results and discussion

Several scenarios are considered for both energy demand and generation.

3.1) Scenarios to simulate the energy demand

Three scenarios were taken into consideration to assess the impact of the demand change. These are

- **Scenario 1:** Net heating and cooling demand for the archetype with present climatic conditions
- **Scenario 2:** Net heating and cooling demand for the archetype with future climatic conditions
- **Scenario 3:** Net heating and cooling demand for the archetype with future climatic conditions and usual building refurbishment

In general, North European cities have larger heating demands compared to the cities in Southern Europe. For instance, cities in the Nordic countries such as Stockholm (Sweden) and Copenhagen (Denmark) were computed to have annual heating demand of 157 kWh/m² and 179 kWh/m² respectively whereas cities in south European

countries such as Madrid (Spain) and Rome (Italy) had annual heating demand of 87 kWh/m^2 and 87 kWh/m^2 respectively for scenario 1 (Fig. 3). Cities in Central Europe fell in between this spectrum. For instance, Brussels (Belgium) experienced an annual heating demand of 120 kWh/m^2 , Paris (France) required 109 kWh/m^2 and Belgrade (Serbia) required 108 kWh/m^2 . This spatial variation can be explained by the concept of Heating Degree day (HDD) which reflect the building's energy requirement to heat the internal environment during a cold climate for a specific city in a given day to a specific base temperature [20]. The Cooling Degree Day (CDD), on the other hand, reflects the building's energy requirement to cool the internal environment during a warm climate for the representative city in a given day to a specific base temperature [20]. Countries in Northern Europe have higher mean ensemble HDDs followed by Central European countries and finally Southern European Countries which have the lowest HDD values [20]. This signifies that, due to climate differentials, cities in Northern Europe have the highest heating energy demands followed by Central European cities while Southern European cities have the lowest heating energy demands as represented in Fig. 3. On the other hand, the observed trend in cooling demand was the opposite. Cities in the Nordic countries had the lowest cooling demands compared to the cities in the southern part of Europe. For instance, Oslo (Norway) and Stockholm (Sweden) had annual cooling demands of only 0.10 kWh/m^2 and 0.40 kWh/m^2 respectively whereas cities in South European Countries had the highest cooling demands such as Madrid (Spain) which had annual cooling demand of 32 kWh/m^2 , Nicosia (Cyprus) required 34 kWh/m^2 and Athens (Greece) required 33.5 kWh/m^2 . Cities in Central Europe experienced cooling demands in between this gamut, higher than Nordic cities but lower than South European cities. For instance, Paris (France) experienced a cooling demand of 5 kWh/m^2 , Berlin (Germany) required 12 kWh/m^2 and Belgrade (Serbia) required 8 kWh/m^2 . The mean ensemble CDDs are highest for Southern Europe and lowest for Northern Europe. In scenario 2, nearly 10 kWh/m^2 or 8.21% average reduction in heating demand was observed due to climate change when compared with scenario 1. With regards to the cooling demand, the simulations indicate that net annual cooling demand throughout will increase by 3 kWh/m^2 or 54.% for the selected cities on average (Fig. 3). However, on comparing scenario 3 with scenario 1, a significant reduction in both heating and cooling energy demands can be observed due to the building renovation accounting for an average decrease by 52.91 kWh/m^2 or 44% and 0.96 kWh/m^2 or 12% in heating and cooling demand respectively. Hence it can be concluded that the impact of climate change can be easily taken off by appropriate renovation strategies.

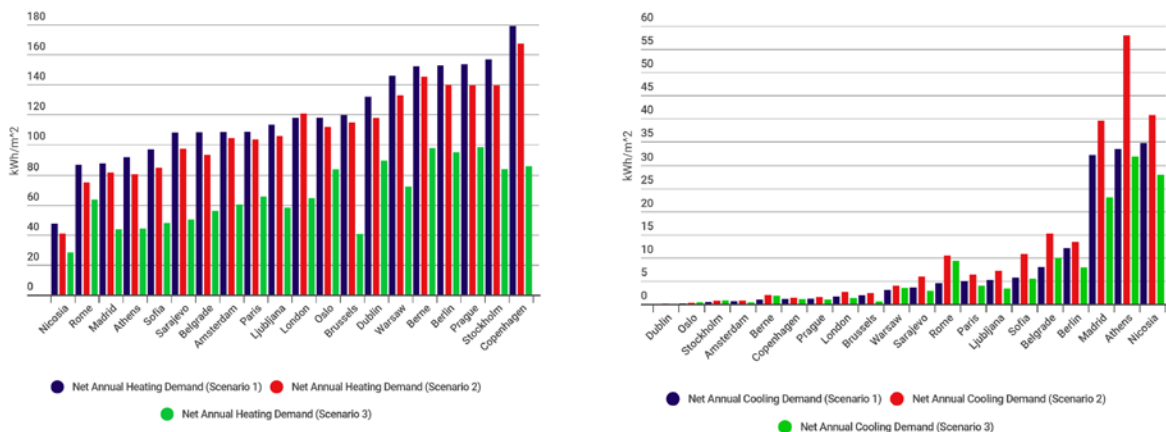


Fig. 3 (a) Net annual heating demands for each city computed in all scenarios (b) Net annual cooling demands for each city computed in all scenarios

3.2 Energy Supply

Two main scenarios are considered for the energy supply (present and future (2050) scenarios). Each of these scenarios are further split into two considering grid curtailments used during the energy system optimization (curtailments introduced as 10% and 70% of annual demand for grid injection). For both cases, 10% scenario (scenario with lower grid curtailments) out performs when considering cost and renewable energy fraction. An average of 22% renewable energy fraction per city was obtained in this case (10%). In terms of costs, there was a 26

% decrease in average COE in the scenario with 10% curtailments. Similar observations were made for the 2050 scenario when considering the grid curtailments. However, the most interesting point is the improvement in the renewable energy fraction. Renewable energy fraction increased from 22% to 52% when moving into 2050 scenario (Fig. 4). When analysing Fig. 4, it is clear that there was a high variability in renewable energy penetration across Europe. This was basically due to two reasons. Firstly, there is a high variability in renewable energy potentials across European cities located at different geographical locations. Secondly, there is a significant variation in the COE of the grid electricity for each European city under study.

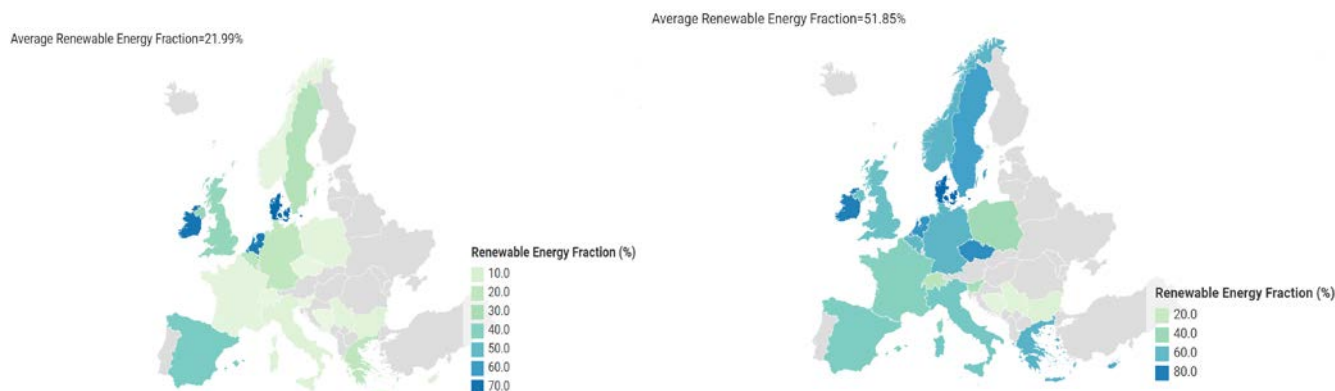


Fig. 4 Renewable energy fraction computed across Europe in the 10% grid restriction case for (a) present scenario (b) future scenario. Note that a single city (capital city) represents the colour of the country.

Conclusion

Scenario 1 presented the current picture about net energy demand across European cities in the present scenario. Scenario 2 helped us interpret the impact of climate change on the energy demands of building systems in the future. Under this scenario, the heating demand across Europe is expected to decline coupled with an increase in the cooling demand which could be attributed to the impact of global warming in the future. Scenario 3 helped to interpret the combined impact of climate change and building renovation on building systems' energy demand in the future. On comparing with Scenario 2, we observed that future refurbishment of the building systems potentially plays a dominant role compared to climate change in the decline of net energy demands in the future. To meet these demands via renewable sources in a cost-efficient and environment friendly manner, we designed micro-grid systems and analyzed two grid restriction levels after which we got to the conclusion that lower grid restrictions (in our case 10%) are better with the perspective of increasing renewable energy fraction as well as reducing costs and carbon emissions. Finally, the study shows that the average renewable energy fraction that is feasible to be integrated into micro-grids increases from 22% to 52% when moving from the present scenario to the 2050 scenario.

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