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A Review of District-scale Energy Performance Analysis: Outlooks towards Holistic Urban Frameworks

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Abstract

Over the past few decades, the world has experienced a major population shift towards urban areas resulting in environmental degradation and increased energy consumption. To combat these challenges, energy efficiency measures are being deployed to improve the performance of different entities within urban built environments. However, effective implementation of such measures often requires a holistic approach to account for existing interrelated and complex relationships between entities at the urban scale. This paper presents a distillation of salient facts and approaches for energy performance evaluation of districts. The studies are reviewed in three sections; (1) concepts defining district energy performance, (2) approaches and methodologies for district energy performance evaluation and (3) system interactions between district entities. The state of the art review reveals that several challenges exist in the initial stages of energy performance assessment of districts. The suggested framework in this paper addresses this issue through pre-processing of data related to entities such as transportation systems and buildings. The framework classifies the available information under three potential categories, namely, 'Subject and Scope', 'Input Data Management' and 'Methods'. This categorisation results in easier integration of multidisciplinary aspects of entities involved in district energy performance assessment.

Keywords: Districts, Energy, Built environment, Planning Process, Performance

1 Introduction

Urban environments have grown at a remarkable rate and the world has experienced a major population shift from rural to urban areas. Cities account for approximately 75% and 80% of world's energy consumption and greenhouse gas emissions respectively, even though they occupy only 2% of the total world’s surface [1]. Furthermore, the construction and operation of buildings contribute towards a large proportion of total energy end-use [2,3]. Fossil fuels are known as one of major contributors to greenhouse gas emissions, considerably affecting quality of life. To reduce the overall energy consumption and thereby greenhouse gas emissions, energy efficiency measures are being implemented worldwide. Alongside, existing energy systems are being transformed to increase the penetration of renewable energy sources [4–7].

Energy performance evaluation of buildings has experienced a major boost over the past decade as advanced techniques and methodologies are being developed. Since, the building sector accounts for a noticeable part of overall energy consumption and greenhouse gas emissions [8], many studies have developed approaches to evaluate the environmental impacts of existing buildings as well as new constructions. For instance, the “Nearly Zero Energy building (NZEB)” approach is becoming quite popular and generally implements scenarios for balancing the consumption and production of energy, especially through compensating energy use by renewable resources [9]. Alongside, new policy measures have come into practice to raise the existing energy standards of buildings [10].

In the current modelling domain, districts are usually modelled as consisting of one or two subsystems, often neglecting the interdependencies involved [10]. However, districts are composed of several subsystems where accurate and effective models need to consider the different subsystems together such as buildings and transportation systems [11]. Consequently, a comprehensive framework is required to use the district level models as an intermediary that would fill the gap between the modelling of entire city and individual elements and integrate all the components for energy performance analysis.

This study presents a literature review of key findings/research gaps, methodologies, results and further research suggestions in energy performance analysis of the built environments. Moreover, investigating upon academic literature and successful experiences, the paper reviews the role of different factors influencing the evaluation of energy performance at district/neighbourhood scale. The review reveals various challenges and constraints in different steps of the evaluation process with a critical role in the early stages of energy assessment process such as gathering required data for defining scope or determination of effective parameters in various methodologies. To address this gap, a framework is proposed to integrate the overall process through pre-processing of various categories of required information and actions related to relevant components of districts.

To entail a deeper understanding of the existing literature, section 2.1 discusses the concept definition of energy performance indicators employed at the district/neighbourhood scale. Section 2.2 discusses the significant approaches towards achieving the optimal solution in energy analysis with environmental, economic and social objectives. Effective components of energy performance in built environments are introduced in section 2.3. And finally, a theoretical framework is proposed in section 3 to address the difficulties which may occur in the early stage of analysis. This framework determines three main issues; first considering the precise and clear definition of subject and its scope, second, defining different types of input data which should be gathered and finally making decision towards the effective methods to handle the interactions and effects of these inputs.

2 Literature Review

2.1 Concept Definition

Energy performance analysis includes a wide spectrum of research areas in which different disciplines focus on the energy domain through specialised approaches and methodologies. Concepts such as “zero energy” have been applied in the existing literature to determine different aspects of energy performance in the built environment. In addition, the scale of the built environment also offers a stark separation between these definitions. Defining the metrics such as scale or approach is necessary to specify the subject and scope of energy performance studies. Considering these different dimensions, a short review of the zero energy building concept is presented in section 2.1.1. Section 2.1.2 highlights the issues related to scale evolution from buildings to districts. The key concepts of zero energy districts/neighbourhoods are discussed in Section 2.1.3.

2.1.1 Zero Energy Building

The most commonly articulated basis for zero energy definition is the compensation of the annual energy demand with renewable energy sources based on social and political characteristics of contexts and the availability of technology [12–17]. The European Energy Performance of Buildings Directive Recast (EPBD) has introduced “nearly zero-energy building” as a “building that has a very high energy performance where the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” [18]. Torcellini and Crawley proposed four basic elements for balancing energy in buildings, namely, primary energy, site energy, cost and emissions [13]. Sartori et al. developed a systematic framework for “net zero-energy buildings” which considers the purposes and political targets that lay behind those purposes [12]. In this framework, the “net zero-energy buildings” are defined through the concept of import/export balance with emphasis on the exchanged energy flows between individual buildings and the grid to provide load match over different time steps [12].

2.1.2 Scale Evolution

Buildings as one of the lower level entities in the built environment are affected by the plans and frameworks of higher aggregated entities such as districts, cities and countries [19–21]. As buildings are the end-use entities in the energy flow process, they determine the energy usage patterns [22–24]. Although building assessment is considered as an essential stage in assessing the energy performance of built environment, focusing solely on such assessments may lead to unreliable results.

On the other hand, due to the cooperation at international level through policies and conferences such as “Rio de Janeiro Earth Summit” and “Our Common Future” [25], studies at mega-scales, world and country, have attracted more attention and budget in recent years [26,27]. These mega-scale studies integrate different data categories including building geometry, consumption patterns, generation profiles etc., which often result in conflict, ambiguity and uncertainty. Additionally, general findings from the mega-scale studies should be validated before the implementation at smaller scales. In this regard, an intermediate scale is required to handle the shortcomings of the modelling procedures at these two scales, i.e., building and mega-scales. Neighbourhood/district level is regarded as an appropriate scale, incorporating all the necessary components as well as providing means for the verification of results [28,29]. This scale facilitates the application of optimization tools with the goal to improve the energy performance and minimize the cost for energy infrastructure [30].

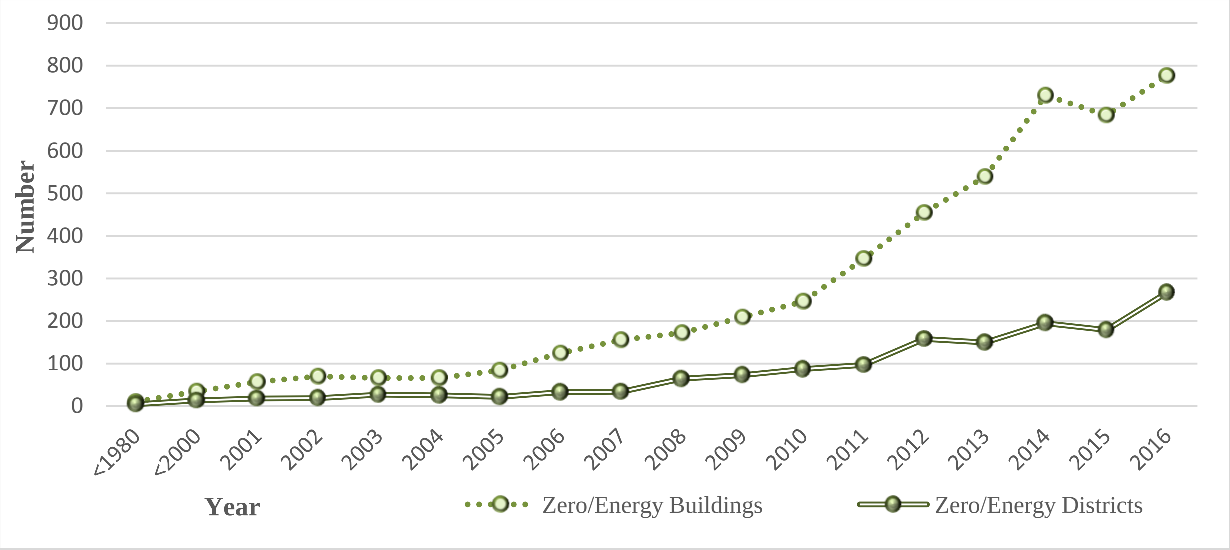

Figure 1- Number of papers published in Scopus database for the considered scales of buildings and districts with energy-related subjects.

The review of past literature demonstrates that although a limited number of studies exist at neighbourhood or district scale, the growing interest in this domain has been significant. Searching the databases can affirm this evolutionary trend. The Scopus database was chosen to perform an extensive search for the two scales, building and district, with similar keywords. To facilitate the search process, two categories were defined, first category (1) for buildings and second category (2) for a larger scale. Two criteria were applied to improve the results of the search attempts: first, filtering the results by excluding the irrelevant subject areas (for instance Biochemistry) and second, limiting the results to journal and review papers and omitting the conference papers. In the first run for category 1, by using keywords, *energy or zero and building*, 6031 papers were found published between 1954 and 2016. 66% of these papers were published after 2010, confirming the fact that interest in this study field is growing at a fast pace in this decade. For category 2, 1994 papers were found after applying the filters. The number of search results is significantly less than category 1. A similar pattern for both categories points out that the interest for studying energy performance in the built environment is growing and hence affirming that this field has a great potential for future research (Fig. 1). The important concepts to define energy performance at district scale are outlined in Section 2.1.3.

2.1.3 Zero Energy Districts

Urban settlements spatially comprise smaller units, for instance, districts or neighbourhoods [31]. There are different definitions for concepts such as neighbourhoods and districts based on researchers' points of view and approaches. Hallman defines a "neighbourhood" as combinations of "geographical boundaries, ethnic or cultural characteristics of the inhabitants, psychological unity among people who feel that they belong together, or concentrated use of an area's facilities for shopping, leisure and learning" [32]. Barton with focus on spatial aspects, considers neighbourhood as "an area of distinctive identity, normally named, which may coincide with either a local catchment area or/and an environmental area, and is geared towards pedestrian/cyclist access" [33]. "Districts" are usually regarded as one of the fundamental organizing elements of new urban planning theories [34]. Urban districts might be formed of 4-5 neighbourhoods and their primary activity is supported by typically neighbourhood-scale uses [35].

Since the 21st century, planners and environmentalists have defined initiatives to pave the way for sustainability assessment at the neighbourhood scale [36–40]. Zero energy district is one of the important concepts in this domain and has been broadly researched. This section categorises the “zero energy district” concept based on three major features; scale, theoretical-practical, and finally benefits-constraints. The most cited references constitute a combination of all these three categories (Fig. 2). Sections 2.1.1 and 2.1.2 state the first feature, Scale, in details. The remaining two features are discussed in the following section.

A-Theoretical-Practical

The theoretical studies mainly concentrate on developing the framework definitions and thereby, casting a foundation for practical implementation [39,41,42]. In this regard, a significant body of literature such as review papers provide theoretical definitions of zero energy built environments based on the practical and theoretical orientations (Fig. 2). A study by Carlisle et al. (2009) summarises the different zero energy definitions for the individual buildings [43]. Sartori et al. applied the concept of zero energy to a cluster of buildings to present a possible framework for balance between weighted demand and supply based on the quantities that are of interest and available [12]. Another study by Kennedy and Sgouridis proposes a framework to define the carbon-neutral urban development using hierarchical emission categories including internal emissions depending on the geographical boundary, external emissions by core municipal activities, and internal-external emissions of non-core activities [44].

As far as practical implementation is concerned [45–53], the United States Department of energy (DOE) has classified the zero energy definitions based on the differences between end-use sectors and the function of the each place, for instance, function-specific definitions for residential communities or campuses [54]. Another definition for “zero energy community” (ZEC) by “National Renewable Energy Laboratory” [43], combines energy efficiency methodologies and renewable energy applications for thermal and electrical end-uses. The green district is one of the leading concepts with a focus on the environmental impacts of energy consumption [55]. A study by Bouton et al. has affirmed the growing opportunities and interests in green districts [56].

One of the prominent projects in this domain is Leadership in Energy and Environmental Design-Neighbourhood Development (LEED-ND) rating system, which comprehensively considers the sustainability concept [56]. In Europe, according to “European Performance of Buildings Directive” (EPBD), all new buildings have to meet the requirements of “nearly zero-energy” buildings (NZEB) by 2020 [57]. These attempts will result in CO_2 emission reduction by 50%, energy systems cost reduction by 15% and energy usage reduction by 30% [58]. Beddington Zero Energy Development (BedZED) for sustainable neighbourhood is considered to be the UK’s largest mixed-used zero-carbon community [59]. Also, the West Village in Davis, California is a working example of zero energy community in the US [60]. Previous and ongoing projects in this domain have been well documented by the International Energy Agency’s Energy in Buildings and Communities Programme (IEA-EBC) to increase the dissemination of information at a global level [61]. The European Commission has invested in an international research project, Ecocity, which aims to develop a sustainable framework for seven countries with specific legislative, socio-cultural, economic and climatic conditions [62].

B-Benefits-Constraints

Working at the neighbourhood scale involves significant benefits and poses numerous constraints as discussed briefly in this section (Fig. 2). Although studies have considered cities as an aggregation of disconnected energy consumer units, cities often consist of complex subsystems with varied energy performance metrics. A study by Choguill aptly concludes that “no single city can contribute to the overall sustainability if its own components are found not to be sustainable” [36]. In fact, neighbourhoods are regarded as an intermediate scale to fill the gap between the entire city and individual elements [63] and are often regarded as the backbone of cities [11]. Neighbourhood-scale studies add on to the results of individual building analysis, especially in the implementation of energy management [36] and to identify energy supply and demand patterns [64]. Additionally, problems at the micro scale arise due to poor planning at the macro scale, which deems it mandatory to define principles at the neighbourhood scale to prevent further inconsistences and dilemmas at other scales [65]. Consequently to acknowledge these benefits, more focus is required to develop assessment frameworks and tools for this scale [66].

The benefits of working at district level incorporate various economic, social and environmental aspects of sustainability concept [10,64,66]. Zero energy districts result in economic growth especially through national policies in long term outlooks; for instance, governments can push national energy targets by district scale policies or intensify their optimal national outcomes by district scale interventions [67–70]. Furthermore, these practices enhance community participation in neighbourhood planning [67,71–73] and address the macro scale problems such as macroeconomic prospective, regional accessibility, low carbon cities and power and energy supply and generation [11,36,63,64,68,74]. Many studies, as presented in Fig. 2, have highlighted the benefits and constraints of analysis at district level.

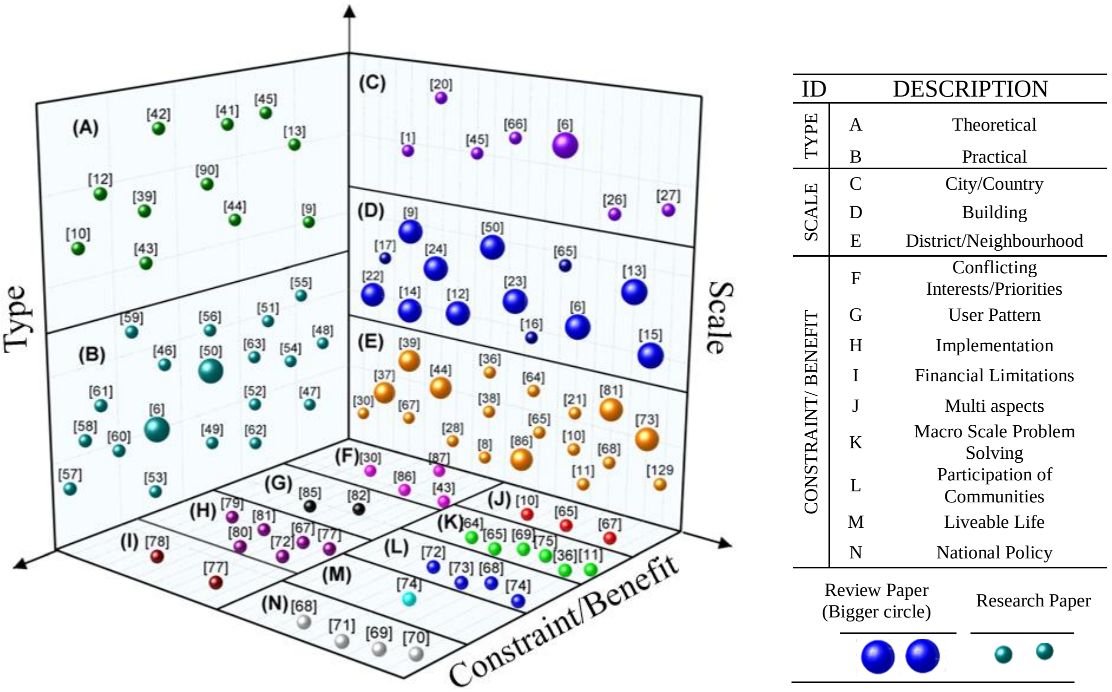

Figure 2- Different aspects of energy analysis definitions of built environments based on their Scales, Types and Constraints and Benefits. Each circle shows a reference with focus on that specific aspect.

However, working at district scale involves difficulties due to the existence of varied sub-systems, their interdependencies and direct/indirect impacts on overall energy performance [75]. Site specific characteristics such as financial context, technological aspects, society, policy, and legal frameworks and on-site conditions such as existing buildings, infrastructure and landscape can create constraints as well as opportunities for planning, which makes the neighbourhood scale more complex to work with. The most important constraints include financial limitations [76,77], implementation of theories and plans [66,71,76,78–80], different user patterns [81–84], and finally multiple goals and priorities, which may result in conflicting interests [30,42,85,86].

2.2 Performance Evaluation Approaches

Numerous approaches have been devised for energy performance evaluation of districts. Such approaches tend to identify optimal scenarios for energy usage based on their initial themes and objectives. However, due to the various kinds of available data relating to districts, it is necessary to specify a set of classification metrics to define the main theme and objectives of energy performance analysis. The following section reviews the predominant objectives of district energy performance approaches including social, economic and environmental aspects (Fig. 3).

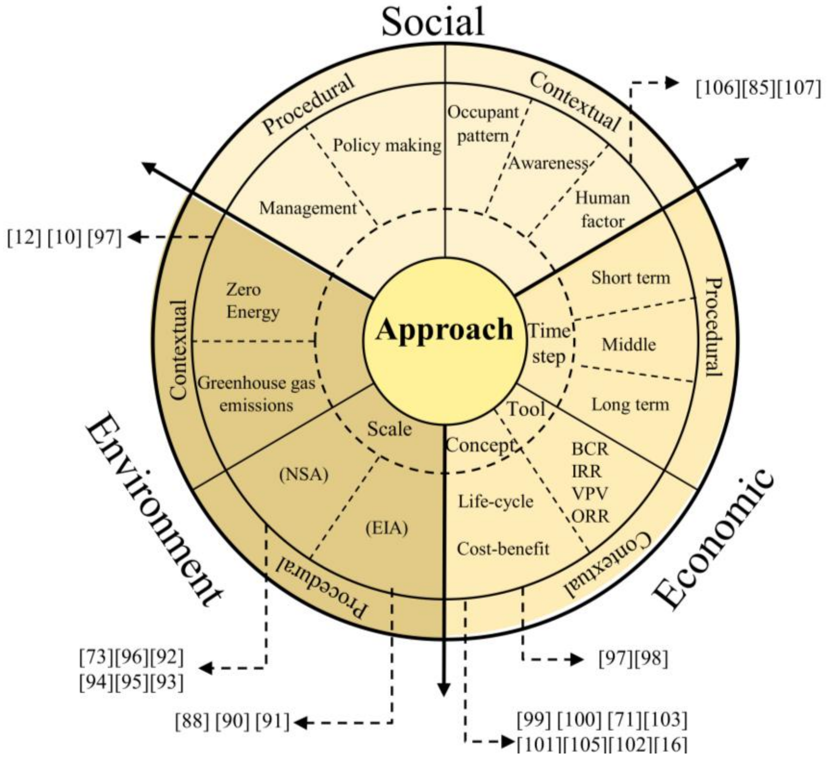

Figure 3- Existing approaches for energy performance analysis of districts classified based on social, economic and environment factors

2.2.1 *Environmental Aspect*

Improper use of the existing resources and increased population rate has led to growing environmental concerns over the past century [87] resulting in increased CO_2 emissions from both the building and transportation systems [10,12]. Such environmental concerns have led to establishment of policy frameworks such as Strategic Environmental Assessment (SEA) and Sustainability Assessment (SA) for assessment of projects impacts in different countries [88]. After the introduction of National Environmental Policy Act (NEPA) in 1969 as the main United States environmental law, there was a growing interest for evaluating the consequences of projects through Environmental Impact Assessment (EIA) tools [89,90]. Initially, the EIA approach focussed on human impacts of the environment, which was further complemented with inclusion of social and economic factors. Most of these methods provide sets of criteria to assess the existing condition of the environment and further develop appropriate guidelines for planners and local stakeholders. Sharifi categorised the existing

EIA approaches into two groups based on the target scale: (1) buildings and (2) neighbourhoods [72]. The latest generation of impact assessment tools such as Neighbourhood Sustainability Assessment (NSA) do not just focus on “zero-energy” objectives but also cover the environmental, social and economic aspects of sustainability [91,92].

BRE Environmental Assessment Method (BREEAM) was introduced as a pioneer building assessment method in 1990s in the UK and provided an independent, third-party standard assessment certification for neighbourhoods [72]. LEED-ND introduced by Green Building Council is considered as one of the most reliable sustainability indices worldwide [93]. Sustainability Tools for Assessing and Rating (STAR) communities provide a broad range of socio-economic topics that define sustainability at the community level [94]. In addition, Comprehensive Assessment System for Built Environment Efficiency (CASBEE) and CASBEE- Urban Development (CASBEE-UD) rating systems have been developed by the Japan Sustainable Building Consortium (JSBC) to provide comprehensive assessment methods for assessing the built environment efficiency both for buildings and communities [95]. In addition to environmental concerns as the eminent focus of these studies, economic and social aspects of sustainability are also attracting more attention during these decades.

2.2.2 Economic Aspect

Economic approaches determine the optimum solution towards costs and benefits related to a specific project for a community or the private sector. The overall objective of the economic analysis should be to minimize total annual energy related costs, which involves the economic assessment (investment and operation costs) of different energy system components in the short, medium, or long term [96]. Numerous studies have established the important concepts for the energy economics domain. The economic aspects are crucial since they allow for feasibility and profitability assessments of projects. Economic concepts such as overall rate of return (ORR), net present value (NPV), internal rate of return (IRR), cost-benefit ratio (CBR), discounted payback period (DPP), simple payback period (SPP), amount of saving to investment ratio (SIR) and life-cycle cost methods have already been applied for economic assessment in the built environment [70,97–101]. Kaynakli used life-cycle cost assessment to determine the optimal thermal insulation required for a building envelop [102]. Goodacre et al. implemented a cost-benefit analysis to upgrade the existing heating system to an energy efficient one for the English building stock [103]. Furthermore, comparing the real estate market value before and after retrofitting is an important factor to assess the viability of a project [104].

2.2.3 Social Aspect

Social factors which involve comfort conditions, activity patterns, occupancy regimes, management, and maintenance methods play a significant role in the success of energy-related projects. Most of the literature in this area addresses the effects of occupants’ behaviour in assessing the energy performance of the entire system. For instance, Owens and Wilhite have demonstrated that 10–20% of energy reductions can be achieved by changing the activity pattern of residents in the Nordic residential sector [105]. A study by Santin et al. affirms the role of occupant behaviour in energy consumption especially in hot water demand in Netherlands [83]. Yohanis argues about the relation between householders’ awareness and domestic energy use [84]. He affirms that awareness of users for temperature control, energy saving and efficacy of systems and household appliances leads to significant energy savings. In addition to studies focusing on occupants’ behaviours, Community Renewable Energy Network (CREN) has presented a holistic socio-energy method to handle the interdisciplinary challenges for a greenfield project [106].

The vast variety of research and practical projects with different methods incorporating social, economic and environmental variables affirms the complexity of analysis at district scale. Hence, it seems mandatory to dedicate considerable time and effort to review related methods to choose and implement the most effective one based on the specifications of a project.

2.3 System Interaction in Districts

For analysis of complex and interrelated systems, the performance of each element and its impact on other members should be addressed to enhance the accuracy results. A study by Haapio introduced the important components and indicators, which are used in well-known international assessment tools such as CASBE-UD, BREEAM and LEED-ND [66]. Infrastructure, transportation, ecology and location were considered as the most effective indicators in energy analysis of districts [66]. Another study investigated the interdependencies between the different system elements through system classification using four layers, namely, void layer, volume layer, functional layer and transportation layer [63]. Implementation of these four layers results in transforming cities to sustainable form by adaptive modification of each layer in addition to collaborative integration with other layers [63]. As proposed by Lund et al., transport energy operation is a key element in the coherent energy system analysis of scenarios at the district level [107]. C´osic´ et al. have proposed a framework for achieving energy reduction considering an entire system involving buildings, industries, and transportation systems to implement a 100% renewable energy plan for Macedonia [27].

Community scenarios have been formulated to connect transportation systems, home energy systems and the electric grid [43]. A framework proposed by Boussauw and Witlox assesses the annual energy consumption for daily mobility (EDM) as an important indicator for sustainability of spatial structures [108]. In this research, they argue about the critical role of regional variations in the energy performance of the whole transport system such as the issue of proximity in home-to-work travels [108]. “Zero-energy neighbourhood” framework (nZEN) articulates the opportunities and challenges for the reduction in energy consumption and increment in on-site renewable energy production for both buildings and daily mobility sectors [37]. To clarify the role of different components, some peer-reviewed articles are introduced with a short summary of their key findings, implementation strategies and components considered in analysis (Table 1). The most important parameters are related to geometry and form of built environment and transportation system characteristics, which are discussed briefly in the following sections.

2.3.1 Design Metrics of Form

Urban morphology and building typology are considered as crucial parameters to evaluate the energy performance of the built environment [63,109] at different design stages for owners, engineers and planners. Hachem et al. investigated the effect of residential districts configurations and density on the electricity generation and consumption pattern [110]. Their results which have to be used in the early stages of design process, show that district configurations can compensate the increased energy consumption by more generation and improve the respond to the demand pattern in peak times [110]. Another study analysed the energy performance through parameters such as density, prominent function of the neighbourhood (mixed-use/residential) and location of the commercial centre relative to residential areas, in addition to the pattern of streets and the transportation system [10]. A similar study has investigated the positive impact of compactness of building distribution and their density on the energy performance of districts in modern developments [111]. Their results reveal that urban sprawl and suburban districts lead to significant energy consumption in both buildings and urban transportation sectors [111,112].

2.3.2 Transportation

To date, literature has addressed the individual role of transportation in energy performance assessment and has often neglected the interactions of transportation systems with the building sector or other components of districts [10]. Although transport and mobility systems are often neglected, these systems have aggravated the process of urban sprawl [113]. Boussauw and Witlox have developed a commute-energy performance index in Belgium to investigate the link between spatial structure and energy consumption for home-to-work travels at the regional scale [108]. They have considered buildings, transportation and public lighting systems as there effective components of energy assessment at the district scale [108]. Transport energy consumption is defined as a composite measure of travel distance, modal choice and journey frequency [113]. Vahabzade Manesh has defined the transportation system through parameters such as porosity, proximity, diversity, interface, accessibility and efficiency [63]. Although, the role of urban architecture in transportation energy usage has been well addressed, it is rarely considered as a component of the entire urban system in districts [86,113,114]. Steemers investigated the interaction link between buildings and transportation system for minimizing energy consumption and air pollution and moving towards compact and connected sustainable districts [115].

Reviewing the existing body of literature affirms this fact that most of the research analyse their case studies based on one or two of these components without considering their interactions [10]. These kinds of approaches result in failure to evaluate districts as a system of various components with internal interactions affecting the energy performance of upper and lower level systems [12,86]. Consequently, specific methods have to be determined based on the system interactions to become applicable in the districts.

Table 1- Summary of reviewed papers for energy analysis of built environment with focus on different effective components.

Ref	Year	Component	Implementation Strategy	Key Findings	City/ Country
[115]	2003	• Building • Urban form: density • Transportation (Car travel) • Function	• Modifying density • Changing compactness	• Energy efficacy • Link between transport and building energy • Quality of urban environment	London
[114]	2008	• Buildings operation • Food • Transportation	• Material flow analysis • Metabolism approach	• Metabolism of components • Urban context as a live creature	Toronto
[43]	2009	• Building's function • Transportation • Community-based infrastructure	• Community as intermediate tool • Multi-year and long-term implementation strategies	• Cost effective balance • Using renewable on three sites: Onsite or brownfield in community; Green space within the within the region; Purchase of new sources	–
[108]	2009	• Infrastructure • Commuting behaviour • Spatial-economic structure	• Home-to-work travel pattern	• A commute-energy performance (CEP) index • Residential density • Role of context characteristics	Flanders
[113]	2012	• Buildings • Transport • Public lighting	• Sensitivity analysis scenarios • Interactive decision-making tool	• Developing a tool on the web	Belgium
[27]	2012	• Industry • Transport • Residential • Public services • Commercial sector	• EnergyPLAN • Defining special set of input and output data	• A 100% renewable energy scenario in Macedonia • Integrating renewable energies • Applying storage technologies	Macedonia
[116]	2013	• Built-up mass layer • Open spaces, streets • Land use layer • Transportation layer	• IMM (Integrated Modification Methodology) • Modification and collaborative integration	• Distinguishing principle and secondary layers • Modification horizontal relation • Collaborative integration vertical layer	Barcelona
[37]	2014	• Buildings: space heating space cooling, ventilation, appliances, cooking and domestic hot water • Daily mobility	• Simplified net "zero-energy neighbourhood" "Energy mutualisation" for energy production and energy consumption	• Energy efficiency • Maximize on-site renewable energy production • Using off-site renewable energy production • Balancing on-site production and load by grid application (send and receive)	Belgium

3 Discussion and Results

The growing interest in low and zero energy concepts has increased the number of district studies over the past few decades. This confirms the necessity for performing energy analysis in districts; however, based on the literature reviewed in the section 2, various challenges and constraints exist in the entire process of energy performance assessment [10,66]. Few of the reviewed studies investigated the challenges in the initial stages of designing different steps of energy performance analysis in districts. Moreover, the multidisciplinary and numerous effective parameters of district scale studies have resulted in the ambiguity of defining methodologies. Since, inaccurate or imprecise assumptions in the basic steps of energy performance analysis may lead to irreparable consequences such as wastage of project resources or unreliable results and solutions; significant attention has to be paid to this issue. Implementation of techniques such as data mining and gathering is required and transformation of inputs to more standard outputs via specific metrics is important to establish the initial stages of data gathering process for energy performance analysis (Fig. 4).

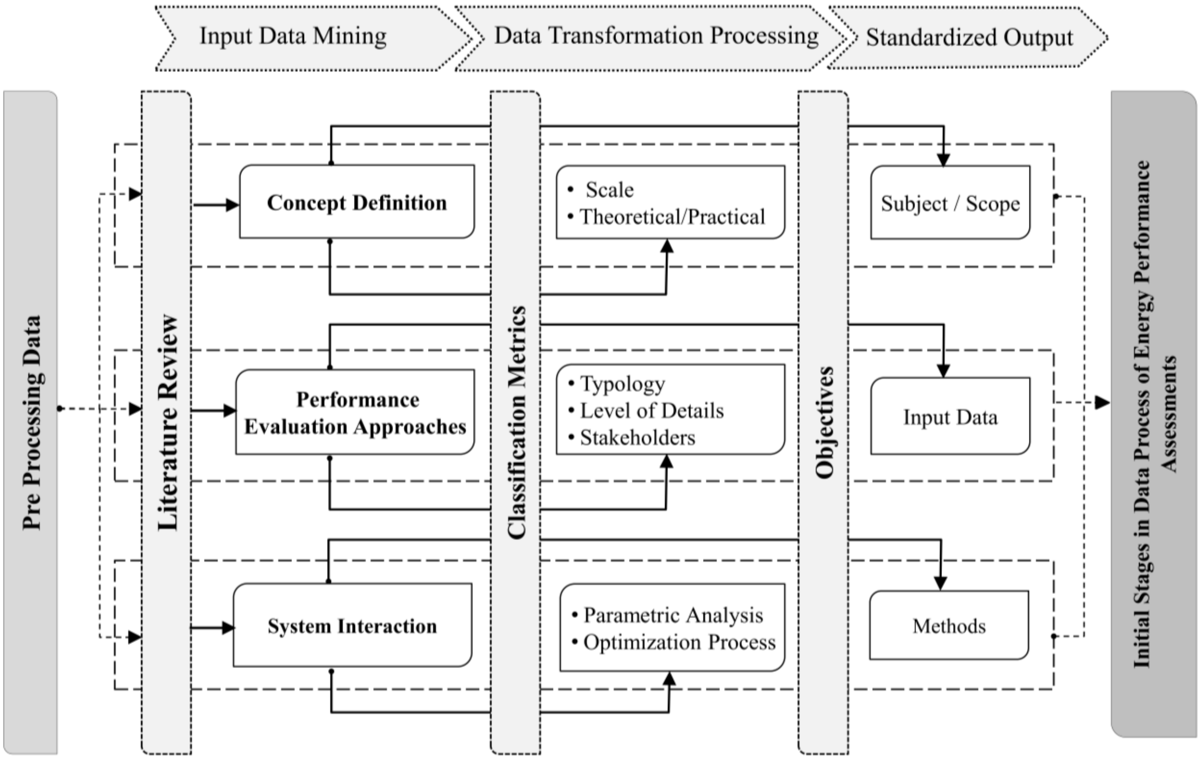

Fig. 4- Initial stages in the data gathering process of energy performance assessment. The effective issues are extracted from the main concepts of literature review and transformed via classification metrics to form the conceptual framework's objectives.

The most important concepts of existing literature for applying in the district energy performance were reviewed and summarised in three sections including; (1) defining concepts relating to the district energy performance, (2) main themes of approaches for district energy performance evaluation and (3) system interactions between district entities. However, there are challenges and issues in each of these three groups which have to be considered before carrying out the analysis. The input data for each group should be categorised based on the related classification metrics and transformed as standard outputs which are necessary to be considered in energy performance analysis. These outputs form the basis of the conceptual framework of this study (Fig. 4).

This framework involves three main steps; “*Subject and Scope”,* “*Input Data Management”* and *“Methods”*. In this regard, further discussion on the reviewed studies and recommendations for combating the identified challenges are presented in three sections as below: 1) defining the effective components as the subject and scope of research, 2) categorising the input data Management by target group, required resolution and specific type and 3) determining methods to handle the interactions of variables. In this section, a preliminary framework is proposed to address these difficulties, which need to be determined in the early stages of the project (Fig. 5).

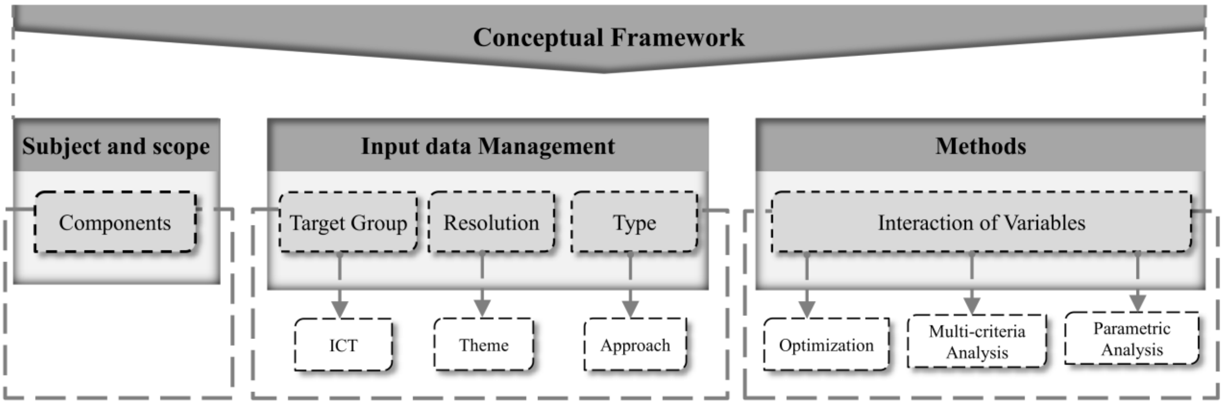

Fig. 5- The conceptual framework to identify the challenges in the early stages of design process in energy performance analysis.

3.1 Subject and Scope

Over the past decade, the research focus has shifted from performance analysis of individual building level to performance analysis at larger scales. As mentioned in section 2.1, 73% of studies have been conducted after 2000 emphasizing the growing interest for district level studies (Fig. 1). Based on the sections 2.1 and 2.2, approaches utilised at the district scale consider the district as a cluster of buildings and neglects numerous other components (Fig. 2). Buildings have received more attention since they are the most tangible and accessible test objects [22]. Working in larger scales involves considering a wide variety of effective parameters that makes the analysis process more complex. Although transportation, public spaces and green fields play paramount role in the energy performance of districts, the integrated effect of these entities has often been overlooked. Neglecting these components leads to inaccurate results and further impedes the objective for achieving zero energy districts [10]; since, energy optimization and efficiency scenarios need to be implemented for the whole district and not just for buildings [43]. Consequently, describing the subject and scope is a basic step to pave the way in determining the other aspects of the framework such as gathering the relevant data and solving system interactions.

3.2 Input Data Management

In the data gathering process, three principal challenges should be resolved: the first challenge concerns the type of data to be gathered. The second challenge describes the mandatory level of details required to ensure the validity and reliability of the research, and finally, the third challenge concerns the stakeholders who would benefit from this data. Sections 3.2.1- 3.2.3 lay out the platform to address the challenges related to the data gathering process.

3.2.1 Type

Owing to the multidisciplinary nature of energy performance in the built environment, different kinds of data are available. Hence, the most challenging part is often to establish a set of criteria for relevant data selection. The amount of input data can be reduced through defining a set of relevant goals. Moreover, goals and approaches have evolved during the past few decades. With the advent of sustainability in projects, initial goals were mainly directed towards reducing CO_2 emissions and other pollutants and conserving fossil fuel reserves. However, end-users and implementation methods are now being considered in defining the goals to account for social and economic aspects respectively. Economic aspects should be thoroughly addressed to avoid conflicts and delays during the project and deliver the initial targets within the specified time. Social features demand special attention and efforts since these features add external variables into the project making it more complicated and time consuming.

3.2.2 Resolution:

Because of the inter dependencies in the parameters involved and the complex measurement methods, district level studies are often quite challenging. Such studies are usually based on information-driven process to deal with different scales and domains [117]. The parameters deal with quantitative and qualitative variables including different types of data such as social behaviour, energy consumption of mechanical systems etc. The level of detail varies from material specifications such as U-value to district configurations and layouts, for instance, the location of public spaces and street patterns. Coupling with such huge diversity makes the procedure of data gathering, analysis and modelling more problematic [118].

These difficulties force planners to organize a balanced scenario based on their time, budget and resources. In other words, although decreasing the level of details will reduce the accuracy and validity of results [23]; focusing on a lot of those details renders the quantitative and qualitative analysis methods inefficient [119]. Another approach is to link information from different scales to provide a balanced view of required resolution such as considering interaction between the demand-side of buildings (lower scale) and the supply-side of districts (upper scale) [119–121]. Such links improve the energy assessment of both scales [122]. Consequently, defining the required level of resolution is mandatory at the early stage of project, which can be considered as the grounded criteria covering the whole process.

3.2.3 Target Group

Target groups such as planners, designers and practitioners who use the findings of research need the information suited to their needs in a specific format [73]. They can be external or internal individuals or organizations that can influence or have interest in the project. Consequently, coupling the requirements of all these groups is a difficult procedure, which affirms the need for a management system for the survival of energy efficient districts [123]. Management systems usually monitor the whole process and handle all upcoming challenges in identifying the key stakeholders through special methods such as Information and Communication Technologies (ICT) [23]. ICT has paved the way for integration of different disciplines and approaches towards optimization of energy generation and consumption in districts and buildings [124].

Energy performance evaluation methods using ICTs provide a better platform for large scale energy management [125]. Some projects such as the Digital Agenda for Europe [126] under EU Horizon 2020 [123], have dedicated special focus on this concept by developing programs to accelerate the process of handling all different groups of stakeholders. Other projects such as RESILIENT [127] and Energy management and decision support systems for Energy Positive (EEPOS) [128] have also worked on the implementation of ICTs towards low carbon and intelligent management of districts spanning different groups of stakeholders. In this regard, smart grids and central hubs are emerging as new concepts to deal with the real-time input data, assigning the_appropriate energy resource to consumers, send/receive extra or required energy by connecting to other grids and finally predicting errors and reporting unexpected crashes to find the best solutions [118,119,129–131].

Data handling and management is crucial in energy performance evaluation to verify the validity of the research principles and results which in turn bolsters the importance of choosing the most fitted and applicable methods.

3.3 Methods

As discussed in sections 2.1 and 2.2, the vast range of effective parameters incorporate different kinds of social, economic and environmental variables and hence, complex sets of equations are required to achieve accurate results (Fig. 3). The complexity of the calculations involved deems it mandatory to implement the most effective method for performing these calculations. Parametric methods such as "sensitivity analysis" [85] identify the value of each parameter individually as well as in relation to other parameters. Based on the multi-objective nature of energy issue in districts, there usually exists no single optimal solution [132] or in other words, when a large number of solutions are available, the required evaluation and selection process is more difficult [3].

Problems faced by the existence of multiple and competing objectives and wide variety of solutions require special methods such as Multi-Criteria (MC) analysis or Analytic Hierarchy Process (AHP) [133]. These methods ensure a balance by assigning a proper weight to each parameter based on its priority. Multi-criteria analysis presents the most appropriate solution through defining the appropriate decision variables, targets and constraints for implementation [3]. Linear Program (LP) and Non-Linear Program (NLP) algorithms deal with inputs and goals to achieve approximate results while maintaining the desired level of accuracy [134].

Optimization is another method, which guides the planners and managers to one or more optimised scenarios representing the fittest condition based on the priorities, goals, limitations and delimitations. Optimization methods need a powerful system processor or access to cloud based servers to run huge amount of calculations [85]. Significant studies have developed multi-objective optimization algorithms for district energy systems, such as Multi objective Neighbourhood Field Optimization (MONFO), which deal with the diverse set of solutions based on stakeholder preferences [132]. Multi-criteria analysis utilises mathematical methods such as Pareto analysis to obtain the most fitting solution for the optimum and feasible condition [132]. The multidisciplinary parameters, affecting the energy performance of districts, confirm the necessity of studying the role of each parameter in choosing the whole methodology. The characteristics of energy-oriented problems suggest appropriate methods including single or mixed methods. Different statistical, mathematical or graphical assessment methods have to be distinguished by the process, purposes and type of indices and parameters [135] and then be implemented in the systems with significant number of interactions such as in districts.

4 Conclusions

The drastic rate of urban development and population growth affirms the importance of urban areas in the context of overall energy consumption and greenhouse gas emissions. Energy performance analysis spans different research areas through specialised approaches and methodologies. Concepts such as "zero energy" or "low energy" spotlight different aspects of energy performance in the built environments especially at the district scale which is reviewed in this paper. District level plays a crucial role in the energy analysis as an intermediate level between individual components such as buildings and mega scales such as cities and countries. Analysis at the district scale includes all the necessary components such as transportation system, form and geometry metrics of buildings and district patterns. However, the absence of a comprehensive framework for district studies casts doubt on the delivery of goals. The multidisciplinary and numerous effective parameters of district scale studies make the process of energy performance analysis more challenging. Due to the inter dependencies involved, it often becomes challenging for planners and policy makers to select the best approach for their projects corresponding to the special characteristics of each district. The state of the art methodology presented here addresses the challenges existing in the initial steps of energy performance through highlighting set of criteria for relevant data selection.

The various groups of data which have to be considered in the energy performance analysis are extracted from the literature and reviewed in three groups of basic concepts and definitions, main approaches and themes and finally the interactions between different components. The main concepts of literature are categorised based on the related classification metrics and transformed to three aspects; “Subject and Scope”, “Input Data Management” and “Methods” (Fig. 4). In “subject and scope”, extents of the case and exact horizons of the study are determined by defining the role of each component in the energy performance of districts. Districts as the subject of the study are considered as the intermediate scale between individual components and cities for carrying out the energy analysis. In the second step, classification metrics such as type of required data, level of details and the target group are applied for data gathering process. There are important points which need to be addressed in this step including (1) the type of data which mostly concerns the objective and theme of the research, (2) the mandatory level of details required to ensure the validity and reliability of results and (3) the impact and role of the stakeholders who would benefit from this data. In the third step, the vast range of effective parameters affirms the need for selection of appropriate analytic methods to be used based on complexity of variables, their interactions and the required level of details. The selection of single or mixed methods depends on the number of determined components and their interactions in districts.

Future research has to investigate more details about early stages of energy performance analysis such as data gathering or definition of subjects and scope. Moreover, it is necessary to determine holistic frameworks possessing the ability to handle the complicated interactions of district variables through an appropriate weighting process. These frameworks can focus on the next steps of energy analysis including modelling, simulation and analysing methods. Implementation of these frameworks in case studies to validate and improve the possibility for generalization is another crucial point which should be addressed in the future works.

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