A review of urban energy systems at building cluster level incorporating renewable-energy-source (RES) envelope solutions

Xingxing Zhang, Marco Lovati, Ilaria Vigna, Joakim Widén, Mengjie Han, Csilla Gal, Tao Feng

Abstract

The emergence of renewable-energy-source (RES) envelope solutions, building retrofit requirements and advanced energy technologies brought about challenges to the existing paradigm of urban energy systems. It is envisioned that the building cluster approach—that can maximize the synergies of RES harvesting, building performance, and distributed energy management—will deliver the breakthrough to these challenges. Thus, this paper aims to critically review urban energy systems at the cluster level that incorporate building integrated RES solutions. We begin with defining cluster approach and the associated boundaries. Several factors influencing energy planning at cluster scale are identified, while the most important ones are discussed in detail. The closely reviewed factors include RES envelope solutions, solar energy potential, density of buildings, energy demand, integrated cluster-scale energy systems and energy hub. The examined categories of RES envelope solutions are (i) the solar power, (ii) the solar thermal and (iii) the energy-efficient ones, out of which solar energy is the most prevalent RES. As a result, methods assessing the solar energy potentials of building envelopes are reviewed in detail. Building density and the associated energy use are also identified as key factors since they affect the type and the energy harvesting potentials of RES envelopes. Modelling techniques for building energy demand at cluster level and their coupling with complex integrated energy systems or an energy hub are reviewed in a comprehensive way. In addition, the paper discusses control and operational methods as well as related optimization algorithms for the energy hub concept. Based on the findings of the review, we put forward a matrix of recommendations for cluster-level energy system simulations aiming to maximize the direct and indirect benefits of RES envelope solutions. By reviewing key factors and modelling approaches for characterizing RES-envelope...
1. Introduction

In order to deliver urban sustainability, security and resilience, the urban energy system is undergoing an accelerated transition from a predominantly centralized to the highly distributed one. One of the driving forces is the significant growth of integrated distributed renewable energy sources (RES) within the built environment. This growth is predominantly due to the success and popularity of adaptive building envelope solutions, such as building integrated photovoltaics (BIPV) [1] or building integrated photovoltaics/thermal (BIPV/T) [2], solar thermal façade (STF) [3], heat pump components [4] and their accompanying power storage [5] or thermal storage systems [6].

The emergence of these RES envelope solutions not only indicates a shift in the energy landscape towards more sustainable and resilient practices, but also entails an evolution in urban energy planning, modelling techniques, operation/control intelligence and management schemes for matching of energy supply and demand across various system scales. Buildings are becoming prosumers, rather than purely stand-alone energy consuming units of the grid. They are increasingly turning into active elements of the energy network by consuming, producing, storing and supplying energy. Thus, they transform the energy market characterized by centralized, fossil-fuel based national systems to a decentralized, renewable, interconnected and viable system.

Within the context of the European Union (EU), building retrofit provides a great opportunity to meet EU policy goals related to net-zero energy buildings (NZEB) [7] and building integrated RES [8]. Current EU policies promote the reduction of building energy demand by 80% by 2050 by means of building retrofit [9]. The emerging challenges lead to the development of novel approaches that address buildings and their energy systems at different scales: from single buildings to cluster, district and urban levels. It is envisioned that energy planning at the building cluster scale is an effective strategy to combine energy efficiency retrofit and local RES supply, through the enhancement of district energy systems and decentralized energy supply [10]. Similarly to micro-communities in the society, neighboring buildings will have the tendency to form a building cluster with an open cyber-physical system to exploit the economic opportunities provided by distributed RES systems [11]. The cluster scale enables a systematic approach to reduce the unit cost of investment and reach cost optimality in energy planning by considering factors, such as retrofitting and adoption of technologies/strategies for increasing energy efficiency and minimizing carbon emissions [12]. Several benefits of a shared RES-distribution network at cluster level have been demonstrated in a number of existing case studies (e.g. the BedZED eco-community in London, Vauban in Freiburg, and Hammarby Sjöstad in Stockholm [13]), such as increased energy efficiency, higher feasibility of storage and load complementarity due to building function differences (e.g. commercial and residential).

As a result, energy planning at building cluster scale fosters the economic effectiveness and the operation feasibility to maximize the distributed RES harvesting and match with the respective energy demand and supply. It is essential to determine which RES solutions are synergic when clustered, and what modelling methodologies should be implemented for operation in order to fully utilize the potential of distributed RES harvesting, storage, distribution, load aggregation and demand side management. The shift from the single building to the building cluster is crucial for the improvement of local energy resource efficiency, through the interaction between the buildings and the energy infrastructure domain [14]. Thus, this paper focuses on the building cluster approach for urban energy systems when considering the incorporation of RES envelope solutions. First, it aims to define the cluster method and its boundaries. Then, it discusses major influencing factors and modelling methodologies. Therefore, the scope of this paper is limited by the boundary dimensions, methodologies and major influencing factors of RES envelope based energy systems for a group of buildings (referred to as ‘cluster’ in the remainder of the document). Since in the existing studies, modelling is the dominant methodology for the evaluation of the energy systems at such level, this paper focuses on the modelling methods that have been applied in the related assessments.

This paper is motivated by answering the research question, illustrated in Fig. 1, of How is energy matched in terms of demand and supply in the cluster with RES envelope solutions? In order to find an answer, a knowledge based matrix was structured through a literature review by answering the following two questions:

- **What affects it?**
  - energy matching in the building cluster by defining cluster dimensions, and identifying key influencing factors and RES envelope solutions;
  - how to model energy systems by observing existing modelling and

![Fig. 1. Scheme of the research question and research tasks.](image-url)
A comprehensive critical review was conducted based on academic literature, research reports, legislation, and key data bases for RES envelopes and energy systems. The essential body of literature was broken down into thematic categories. The important influencing factors for energy matching in building cluster were either brainstormed by partners in H2020 Energy-Matching project or extracted from the literature. The existing RES envelope solutions at building cluster scale and the related modelling techniques, as well as optimization methods, were observed in the literature and summarized in tables and figures. The remainder of this section describes the scope of the review and delivers our insights.

After clarifying the paper’s scope and review method, we proceed with defining building cluster from energy system point of view. Then, the dimensions of the cluster (e.g., size of cluster area and energy performance resolution) and its influencing factors are introduce. Subsequently, we discuss the most important factors in detail and present the categorization of main RES envelope solutions based on the existing literature. Afterwards, we describe promising modelling techniques for assessing the potential of common RES at cluster scale utilizing solar energy. The density of buildings is then discussed, as it affects both solar energy potential and energy demand. Considering the importance of energy demand estimation within an increasingly varied and sophisticated urban energy system, we critically review a set of emerging modelling techniques. Next, we discuss the modelling and optimization techniques for complex, RES-based cluster-level energy systems and the energy hub concept in detail. Finally, the paper lays out a number of suggestions for future research directions.

There are many existing review papers that address different aspects of urban energy systems, such as the impact of occupants’ behavior [15], energy tools/models at different scales (single building scale [16], district scale [17], urban scale [18], regional/national scale [19]), energy demand (electricity [20], heating and cooling [21]), demand response [22], micro grid [23], solar PV [24], electric vehicles [25], energy storage [26], control strategies [27], energy hub [28], water-energy nexus [29,30], planning and policy [31]. However, none of these studies address RES envelope solutions at the building cluster scale and the corresponding modelling methodologies for the integrated energy systems. Therefore, this paper aims to deliver a comprehensive literature review to fill this gap. The novelty of this paper lies in: (1) defining the concept of building cluster and its boundaries for modelling and assessment; (2) highlighting the main influencing factors across three aspects of urban energy system, including supply, demand and operation; (3) summarizing RES envelope solutions suitable for building clusters; and (4) identifying modelling methodologies for integrated urban energy systems at the cluster level. The findings of the review can provide guidance to utilizing RES envelope solutions in the design or retrofitting of building clusters. The boundaries will help to improve the resolution and accuracy of the complex modelling. The modelling and optimization approaches shall facilitate the maximization of RES harvesting and socio-economic benefits of urban energy systems. Fig. 2 illustrates the review scope and the contents of this paper.

2. Building cluster and its influencing factors

2.1. Definition of building cluster

The building cluster scale, also known as ‘building block or neighborhood’, represents an intermediate level between a single building and district or urban scale. It could be defined depending on different criteria, such as energy system, archetypes, location, building size, density (Low, medium, high), function (residential, offices, mixed), number of stories (low, high), year of construction, geographical boundary and so on. In this paper, we focus on the definition from energy system point of view. As a result, a building cluster is regarded as a group of buildings systemically interconnected to the same energy infrastructure, so that a change of energy performance of a single building affects both the energy infrastructure and other buildings of the cluster either in a synergic or a disruptive way [10]. At this scale, urban building energy simulation (UBES) is a common strategy applied for modelling the interactions of energy structures, urban climate and building energy performance, while building energy simulation (BES) and city energy simulation (CES) are developed respectively for the scales from single building to district/city level or above.

2.2. Why building cluster?

The urban energy landscape is experiencing a major change in which the commonly centralized energy generation is increasingly replaced by a distributed system with dispersed energy recourses, actors, management structures, data sources and software entities [32]. This transition requires and stimulates a large amount of research in a wide variety of fields: distributed resources and infrastructures, energy efficiency renovation, RES solutions, distributed generation performance, energy storage behavior and economics, demand side management and virtual power plants, micro grids, energy hubs and plug-in vehicles, as well as a growing penetration of ICT, artificial intelligence and data-driven management [32], as shown in Fig. 3. As stated in Section 1, energy planning at building cluster scale is regarded as an effective way to tackle these challenges in the current urban energy paradigm. The cluster scale is large enough to address energy matching better than in a single building, but remains small enough to allow concrete examination. It is a scale that allows the systematic aggregation of energy information for different types of vectors, such as construction (buildings, infrastructure), operation (heat, electricity, domestic hot water and networks), and transportation (commutes, shopping) [33]. It is a realistic scale for RES envelope solutions because not all the buildings in practice are possible to integrate RES solutions and those RES
Integrated buildings can then be defined as a cluster (though not a physical district). Fonseca and Schlueter [34] also pointed out it is at cluster scale where most urban transformations in EU take place and where the newest instruments for financing energy efficiency strategies in the building sector exist.

In addition, according to Frayssinet et al. [21], urban energy systems are now very complex to simulate at the city scale, due to the required large amount of input data/computation, the uncertainties of occupant behavior, and the necessary involvement of complex urban environment. On the other hand, simulation at a single building scale is not accurate enough to respond to urban energy system, since buildings are not standing-alone units. Thus, building cluster presents itself as a possible intermediate scale to assess the interaction between buildings and urban energy infrastructures in detail, while also taking into current computational capacity and intelligence. At building cluster level, scenarios, such as energy sharing and competition, can be modelled and studied. With the increase in adoption of RES envelope solutions, research endeavors in building cluster modelling are gaining importance. The aim is to shift from single energy efficient unit to interconnected prosumers, and therefore maximizing the synergies among buildings, RES application, storage systems, and existing heating/electric girds. Some degree in the energy matching ability is required by buildings in order to gain resilience (building performance coupled with grid interaction) [10]. We hypothesize that the study of energy landscapes through the lens of building clusters will result in cost-effective RES solutions, which in turn will well equipped to cope with disruptive new technologies and alterations in the energy system. Fig. 4 interprets the undergoing transformation of buildings into cluster aware units.

### 2.3. Spatio-temporal dimension of building cluster

Understanding spatio-temporal patterns of energy supply and demand are essential to assess the retrofitting strategies for stochastic RES envelope solutions and storage systems within buildings cluster. This is usually achieved though UBES approach, by either top-down or bottom up ways [35]. However, such UBES approach is generally too computationally expensive to simulate building clusters [21]. In order to simulate energy systems in an efficient way, a trade off front in spatio-temporal dimensions is delineating for the energy simulation at cluster scale, as depicted in Fig. 5.

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**Fig. 4.** Evolutionary path of building transformation [10].
Spatial scale is used in this paper for describing the size of a cluster area for energy planning/simulation purpose. In Britter and Hanna’s research [36], they classified studies in urban areas into four spatial scales, i.e. the regional scale (less than 100 or 200 km), the city scale (less than 10 or 20 km), the neighborhood scale (less than 1 or 2 km) and the street scale (less than 100–200 m). Other studies, such as Srebric [37] and Huang’s study [38], indicated that the impacts of urban neighborhoods on the buildings and associated modelling should be resolved within 1 km. The spatial unit of a cluster is usually equivalent with or less than a neighborhood. We hereby recommend that the spatial dimension of a building cluster to be between 100 m and 1 km for energy system simulation purposes, which should be computationally viable in next a few years. The cluster territory is not strictly limited to a specific geometry but indicates a rough area, for instance, a circular territory has the cluster diameter between 100 m and 1 km, a square territory has the cluster side edge between the same two thresholds etc. Currently, detailed computational studies at mas-sing model level for gross parameterization of the energy flow within buildings are feasible at this spatial scale. This is also a scale at which some statistical homogeneity of energy systems may be anticipated. Accordingly, a city can be then regarded as a collection of clusters.

Fig. 5. Spatio-temporal dimension of building cluster.

Nevertheless, the cluster scale is likely to be regarded ineffective from other points of view, such as social or policy targeting [39]. A fine-scale cluster geography for whole-city urban purposes is still confined to the future in terms of research.

Temporal scale is applied in this paper to describe the energy performance resolution of buildings and systems within a cluster. The time required for building components/envelopes to respond and achieve a steady-state condition may take from hours to days. One another hand, the time for energy system/flow to respond a condition could be within seconds or minutes [37]. These different response times suggest that the time steps required to solve the energy matching at a comparable level of detail may differ in their orders of magnitude. At the moment, many studies choose the hourly energy demand for UBES as the minimal temporal resolution to estimate the energy load profiles (thermal load [34,40] and electric load [41,42]). A good knowledge of the transient energy flow and a more accurate energy matching scenario in building cluster requires the order of magnitude of time scale to be reduced down towards minutes or even second level. This shift will only happen if minute-resolution data becomes the standard in UBES and BPS, and would nevertheless increase the computational cost of UBES simulations.

2.4. Influencing factors

The factors that influence the energy landscape are diverse at the cluster scale. Urban morphology parameters, such as plan area density, frontal area density, geometry of the buildings, and topographical features, influence energy use and available resource at the cluster scale [43]. Climate zone, construction period and building type are usually the parameters that serve as selection criteria for the building stock segmentation and thus affect the energy scenario [44]. There are many other impacting parameters that can be divided into four different groups [45], such as geometry (form), construction (fabric), systems (equipment) and operation (program). These parameters are dependent on the energy planning without compromising to each other. As different building clusters may require different parameters to access energy matching strategy, there is the fundamental need for the

Fig. 6. Scheme of main parameters affecting energy characteristic in a building cluster.

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generalized key factors being able to adapt to each country/city characteristics.

A brainstorming session was firstly conducted for the key parameters among well-varied experts from diverse fields, in the H2020 project – ‘Energy-Matching’. After that, a literature analysis into these primary parameters was performed to describe their importance to building cluster concept. The results of the brainstorming session are presented in Fig. 6. The parameters defined as important for building cluster characterization are grouped in three main area of interest: grid, RES production, and building. Among these, we recognize the main interesting parameters as mostly influencing the cluster energy performance, which may include: energy supply side (RES solutions, solar power potential, density of building), energy demand side, and energy operation side (integrated energy systems and energy hub). Each of these factors is discussed in sequence following the logics represented in Fig. 7 in next sections.

3. RES envelope solutions

The range of RES solutions is very broad, which may be categorized in different ways. Within this work, the categorization is mainly performed based on the energy resources and the way those solutions contribute to building energy. The overall RES solutions have been categorized into the following groups as solar power solutions, solar thermal solutions and energy-efficient solutions, illustrated in Fig. 8. The whole framework fits well in the concept of ‘Climate adaptive building shell’ (CABS), according to Loonen et al. [46]. They defined CABS as ‘A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance’. As a result, modern RES solutions shall be able to offer potential opportunities for energy savings and improvement of indoor environmental quality, by drawing upon the concepts of adaptability, multi-ability and evolve-ability, in order to combine the complementary beneficial aspects of both active and passive building technologies into the building envelope [46]. The solar power and solar heat solutions are usually energy generators for buildings, while energy-efficient solutions contribute to reduction in energy use in buildings.

BIPVs are regarded the most important solutions in solar powered envelopes. They offer an aesthetical, economic and technical solution to integrate solar cells harvesting solar radiation to produce energy within the climate envelopes of buildings. The main stream of current BIPVs are crystalline silicon, amorphous crystalline silicon, and copper indium gallium selenide (GIGS)/cadmium telluride (CdTe) thin films. In the future, new cell materials will steer BIPV into a more competitive era, which may include adaptive low-medium efficiency organic based modules (Solar Cells Absorbing Non-Visible Solar Radiation, Polymer Solar Cells, Dye sensitized solar cells), ultra-high efficiency modules (sandwich solar cells, antenna-sensitizer solar cells, quantum dot solar cells), solar trapping systems embedded in solar cell structure (solar cell concentrators, inverted pyramid texturing), material beneath (PV Integration in concrete), and flexible lightweight inorganic thin film (solar cell paint, hybrid solar cells) [47]. BIPV are also flexible to be applied as a concentrator [48] and BIPV/T solutions for both electricity and heat generation [2].

In the group of solar/air sourced thermal solutions, flat-plate and evacuate tubes are the most common technologies applied in the past and existing period. Solar thermal façade [3], heat recovery envelopes [49], and double skin façade (DSF) [50] are more adaptable to buildings, which are often connected by heat pumps for upgrade of heat generation [4]. In terms of energy-efficient solutions, green roof/wall systems [51], thermal insulations [52] and phase change materials (PCM) [53] are widely applied for either new buildings or building retrofit. Dynamic façade (also known as energy frame) [54] and adaptive façade [55] are newly developed concepts by changing the façade properties, or tracking with solar radiation, or controlling daylight/humidity, depending on various climate conditions etc. [56]. In recent years, algae photo-biological facades [57] are developed to reduce energy use by shading, but meanwhile generate heat and biomass for buildings.

It is observed that most of the existing RES envelopes are derived from solar (air) resource. Some of them converts solar energy directly into useful electricity and heat, such as categories of solar power solutions and solar/air thermal solutions, as well as photo-biological facades. While the other types either make uses of sensible heat from solar (air), e.g. thermal insulation, green roof/wall, or the latent heat from solar (air), e.g. PCM; others still indirectly gain advantages from solar (air), such as dynamic façade. As a result, solar energy is regarded as the dominant renewable energy resource for envelope solutions in the building cluster.

4. Solar energy potential

Modelling the energy output of a large set of spatially distributed and building-applied photovoltaic (PV) or thermal systems, as in the case of building clusters, typically requires inclusion of three main components, as outlined in Shepero et al. [58]: (1) the solar irradiance over the systems, in sufficient spatio-temporal detail, (2) a method for identifying and representing the building areas on which the PV or the thermal systems are mounted, and (3) suitable models for solar irradiance on tilted planes and for PV or thermal systems. As component (2) was covered in Section 3 and there are standard approaches for component (3), reviews of which can be found elsewhere (e.g., [59]), this section therefore mainly focuses on component (1), which is also the most challenging part at the cluster level.

Business-as-usual when incorporating simulations of solar technologies in building modelling is to use hourly solar irradiance data for one representative site as input, often in the form of typical meteorological year (TMY) data. Modelling of solar technologies on the spatial and temporal scales proposed here (see Section 2.3) however requires more sophisticated approaches. On the minute and second scale, solar irradiance varies substantially due to variability in cloud patterns and their movements as well as to irradiance enhancement [60]. For buildings dispersed over spatial scales of meters to kilometres, variations on these temporal scales do not occur simultaneously. As a consequence, correlations in power or thermal output between dispersed building-applied PV or thermal systems decrease characteristically over both space and time, effectively smoothing out the total solar power fluctuations to a degree that depends on the overall dispersion and the type of weather [61,62]. For realistic building cluster simulations, the impact of these
features should be measured and, if relevant, included in the data used as input.

We can identify four categories of approaches for obtaining spatio-temporal solar irradiance data suitable for building cluster modelling in available literature, as summarized in Fig. 9: (i) measured solar irradiance data, (ii) data upscaling methods, (iii) physical or semi-physical modelling, and (iv) statistical models.

**Measured solar irradiance data** should be preferred when such exist for a studied site. The two most commonly used sources of solar irradiance data are ground sensors and satellite-derived data. For hourly data and over large spatial scales, radiometer network data are typically measured and made available by national or regional meteorological services. For these spatio-temporal scales, established methods for deriving irradiance from satellite images are also readily available (see, e.g., [63]). These types of data are unfortunately much more scarce on the spatio-temporal scales considered here. Dense networks of solar irradiance sensors have been constructed at various sites for studies of irradiance variability (for an overview see [62]). An example of state-of-the-art is the Oahu solar irradiance grid on Hawaii, consisting of 17 pyranometers, dispersed up to 1 km, that measure global horizontal irradiance with a 1-s resolution [64]. The only available satellite data on the building cluster scale appears to be the Himawari-8 satellite, which covers Asia and the Pacific with down to 2.5-min temporal resolution and 0.5 km² pixel resolution [65]. Awaiting such high-

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**Fig. 8.** Categorization of RES envelope solutions.
resolution satellite imagery for wider regions, as well as validated methods for deriving irradiance from them, methods from the remaining three categories below could be used.

**Data upscaling methods** take data from a small set of reference irradiance sensors or PV (thermal) systems to generate data for a much larger set. One example is the Wavelet Variability Model (WVM), which uses irradiance data from one point sensor to simulate the smoothed-out profile for a larger set of sites [66]. This method would be suitable for describing the aggregated profile from large numbers of buildings with PV systems, but for obtaining unique data for each building-applied system other methods would be required. Bright et al. [65] proposed a method for generating 1-min, spatially resolved data from hourly observation data. In this method, a cloud field representative of each hour was generated based on general weather and cloud statistics and moved over an arbitrary set of dispersed sites. Bright et al. [65] then provided an overview of other upscaling methods based on different spatial interpolation techniques, either through pure interpolation or in combination with system metadata and quality control routines. These methods have been used mainly for nowcasting of solar power in grids, but they should be able to provide irradiance data for building cluster simulation. Future research should be aimed at optimizing these methods in terms of interpolation technique, number and dispersion of reference sites, and type and extent of metadata.

By **physical or semi-physical modelling** we refer to models that do not use measured irradiance but instead derive spatio-temporal irradiance data by modelling the atmosphere and clouds in a physical sense (not purely statistical approaches). Typically, a clear-sky irradiance model is used to model the irradiance after passage through the atmosphere and a cloud model is used to model attenuation due to clouds. Several established clear-sky models exist, varying in complexity but generally performing well [67,68]. Models of clouds and their development and movement over time also span a wide range of complexity. On the most complex extreme, but also among the most mature approaches, we find large-eddy simulation (LES), where the microphysical details of clouds are simulated, down to a spatial scale of tens of meters, by solving the Navier Stokes equations (for applications specifically to solar irradiance, see [69]). Less complex are methods for generation of fractal cloud fields (for an overview of the most important studies see [70]), and even simpler are cloud fields made up of squares [71] and circles [72]. The idea behind all of these latter models is to generate spatial cloud fields that are moved over a set of PV systems to shade clear-sky irradiance, thereby generating realistic and spatio-temporally correlated time series at each system.

Finally, **statistical models** generate synthetic irradiance data using...
purely statistical methods, e.g., machine learning methods. These types of approaches are not yet very common for generation of spatio-temporal irradiance data, but are widely applied for solar forecasting [73]. A statistical method for simulating instantaneous solar irradiance at arbitrary sets of dispersed sites has been proposed by Widén et al. [74,75], in which the irradiance at individual sites is sampled from probability distributions that are spatially correlated according to a correlation model, all of which are dependent only on the daily clear sky index (degree of cloudiness). Full spatio-temporal statistical models of solar irradiance that allow generation of irradiance time series at multiple sites are yet to be developed.

This overview suggests that the preferred methods for obtaining reliable spatio-temporal solar irradiance data for building cluster simulations are either any of the data upscaling methods, which can be applied if at least irradiance or PV system data from one or a few sites in the cluster are available, or a semi-physical model, in which a synthetic cloud field is generated and moved over the cluster. Further research should also go into developing improved spatio-temporal statistical models for solar irradiance and PV systems.

5. Density of buildings

Building density affects the energy planning at cluster scale, such as energy demand, energy transmission/distribution, distributed energy infrastructure, the quantity of RES technologies that can be installed and the degree of self-sufficiency etc. Different measures of building density are available in literature, such as plan area density (the ratio of built to total area [76]), and frontal area density (the ratio of the windward-facing facade area to the area occupied by buildings [77]), as illustrated in Fig. 10. Existing studies at cluster level generally fall within the range of 0.11–0.69 plan area density, and within the range of 0.12–0.33 frontal area density. In extremely dense cities, like Hong Kong, the frontal area density frequently exceed 0.4 and can reach extreme heights, such as 1.07, in cases in which building blocks are attached to each other [37]. Existing literature suggest that higher building density leads to higher night-time urban air temperature, increasing therefore the urban heat island intensity. This in turn may increase cooling loads and decrease, often not significantly, the heating load of buildings [78]. For instance, Liu et al. [79] utilizing CFD simulation found that when the plan area density increased from 0.04 (almost isolated building) to 0.44 (dense cities) the total energy use for cooling increased by more than twice the reduction in heating energy demand. The empirical study of Li et al. [78] found a correlation between building density and household electricity consumption at a cluster level in summer months, but no correlation could be established for winter months. Furthermore, the study found that at higher building density, households in slab and tower apartments consume more electricity in the summer months, partly due to the increased heat island intensity.

However, there is disagreement in the literature regarding the effect of building density on building energy use and the magnitude of the effect. Some empirical studies found no significant increase in energy use at higher density [80,81]. Ewing and Rong [82] established three ways though which density can impact residential energy use: (1) energy losses through electric power transmission and distribution, (2) increased energy demand due to higher heat island intensity, and (3) energy use variance owing to the size and type of the housing stocks. Li et al. [78] postulated that differences between the numerical and empirical findings are owing to the fact that most simulation studies assess the building density-building energy use relationship on an annual basis, while this relationship might differ when simulated on a seasonal or on a higher-resolution basis. The authors also indicated that geographical and cultural contexts, such as demographic, socioeconomic, behavioral, and property-related characteristics, may also influence the relation between density and energy use. Moreover, energy use relates to other planning and design factors even if the density is the same, such as buildings layout, street orientation, urban trees, and building materials [83].

Floor area ratio (FAR) is another important density parameter that influence RES at the cluster level. It is defined as the ratio of the gross floor area of all buildings to the total site area [84]. Traditionally, FAR is obtained from site surveys from building shape and height data. However, this is a quite expensive and time consuming approach. Light Detection and Ranging (LiDAR) is a novel, relatively quick and accurate method that besides the three-dimensional information of buildings also gathers topographic data [85]. The third method of obtaining building information data is from the remote-sensing images. However, good, high-resolution images may also be costly [86]. FAR does not reflect the height or shape of the buildings, nor the open space between them [87]. The same FAR can be achieved with different building configurations, as illustrated in Fig. 11. Nonetheless, the three-dimensional characteristics of the built environment, as described by a variety of physical parameters, influence the availability of both direct solar radiation and daylight within the urban fabric [88,89]. Hence it affects both building energy use and RES power generations. Since a given FAR, lower buildings have a higher relative roof surface and thus a lower relative façade area suitable for RES envelopes, information on the height of buildings is also of great importance. In contrast, taller buildings with the same FAR have greater distances between them, which allows for more direct solar radiation, hence for higher solar gains [90]. In spatial planning, FAR between 1.5 and 2.5 has been identified as the optimal value for achieving high energy efficiency [91]. For instance, Yannas [92] reported 40% heating energy savings in his comparative study of apartments and detached houses. The author concluded that a FAR of 2.5 might be the optimum density for neighborhood development. Capuleto and Shaviv [93] found that at 1.6 to 1.8 FAR it is possible to maintain solar access to all buildings within a neighborhood. Dawodu and Cheshmehzangi [90] argued that a FAR of 1.0 is too low within the context of China, whose paper operates in the context of the major Chinese cities, argued that a FAR of 1.0 is too low, while a FAR between 3.0 and 4.0 is too high for energy-use reductions at the cluster scale. FAR is a universal measure, which is also applied for other purposes, such as analysing urban spatial structure or proposing urban planning policies. For instance, Cao et al. [94] applied FAR as a...
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</tr>
<tr>
<td><strong>Top-down approaches</strong></td>
<td>Support vector machine (SVM)</td>
<td>7 buildings</td>
<td>Hourly temporal cooling demand</td>
<td>Field measurement</td>
<td>[105]</td>
</tr>
<tr>
<td><strong>Top-down approaches</strong></td>
<td>Decision tree</td>
<td>80 buildings</td>
<td>Average temporal heat and electricity demand</td>
<td>Survey and research committee</td>
<td>[106]</td>
</tr>
<tr>
<td><strong>Top-down approaches</strong></td>
<td>Markov chain</td>
<td>200 detached houses and 200 apartments</td>
<td>Temporal electricity demand with 10 min interval</td>
<td>Data sets of TU-SCB-1996/TU/EL-SEA-2007/EL-SEA-2007; diaries</td>
<td>[41]</td>
</tr>
<tr>
<td><strong>Bottom-up approaches</strong></td>
<td>Simplified thermal models, and Energy Plus, TRNSYS</td>
<td>29 buildings</td>
<td>Hourly temporal heat and electricity demand</td>
<td>Similation and measurement</td>
<td>[107]</td>
</tr>
<tr>
<td><strong>Bottom-up approaches</strong></td>
<td>Aggregation model in Modelica</td>
<td>35 buildings</td>
<td>Hourly temporal heat demand</td>
<td>German Meteorological Service</td>
<td>[100]</td>
</tr>
<tr>
<td><strong>Bottom-up approaches</strong></td>
<td>Simplified thermal model and Energy Plus</td>
<td>11 buildings</td>
<td>Monthly temporal heat and electricity demand with 15 min interval</td>
<td>Swiss standard SIA 380/1; SIA 2024; DHW demand profile for medium-load European households</td>
<td>[108]</td>
</tr>
<tr>
<td><strong>Combined model</strong></td>
<td>Statistical clustering, and simplified engineering model (EN1.3790:2007/EN 15316:2007), under GIS framework</td>
<td>172 building archetypes</td>
<td>Hourly Spatio-temporal heat and electricity demand</td>
<td>Weather database from software Meteonorm 7.0; urban GIS database from official database and open street maps; archetypes database, distributions database and measurement database from local collection</td>
<td>[34]</td>
</tr>
<tr>
<td><strong>Combined model</strong></td>
<td>UBEM, a mixed integer linear program, and thermal plant generation model under the GIS framework</td>
<td>0.5 km²</td>
<td>Annual temporal heat and electricity demand</td>
<td>Measurement database from local collection</td>
<td>[109]</td>
</tr>
</tbody>
</table>
parameter for analysing the urban spatial structure of a diversified city in China. Joshi and Kono [95] were able to optimize FAR regulation in a growing city as a practical alternative or supplement to the first-best policy against negative population externality. Barr et al. [96] examined the FAR gradient in New York city over time and space, from the urban spatial structure point of view.

We hence argue that future studies should investigate the combined impacts of FAR on energy use, urban spatial structure, economic and environmental conditions at cluster scale. Since three-dimensional characteristics of the built environment affect the RES potential of a cluster (or even an entire city), it is necessary to identify an adequate building density measure that is capable to capture key characteristics. Based on the literature review and our understanding of the issue, we recommend that future studies adopt three relatively obtainable density measures: mean building height, plan area density and either the measure of façade area ratio or surface area ratio. The former is defined as ratio of all building facades over a given area, while the latter is the ratio of the total building envelope to site area. Table 1 summarizes the characteristics of density parameters in exiting literature from energy use point of view.

6. Energy demand

Energy demand pattern at cluster level is crucial for planning RES harvesting envelopes because it is required to match capacity of energy infrastructures. It influences the stakeholders at various levels, from the development of regional strategies to the detailed design of buildings. Many models have already been developed to estimate the energy demand at the cluster level, categorized as ‘top-down’ and ‘bottom-up’ approaches respectively [21,35]. Top-down approaches, such as [33,97], consider clusters as an entity by only describing the general characteristics of energy demand, rather than the explicit energy use profile of individual building. These approaches rely on statistical and economic theory, correlating energy demand to macroeconomic parameters, such as energy price, income tax, GDP, greenhouse gas, population density and urban morphology. In contrast, bottom-up approaches detail the energy use profile of individual building/component using statistical/data-driven and engineering methods. Statistical [98] and data-driven methods [99] relate the explicit energy demand and historical data depending on field historical measured data, utility metering, governmental statistics or surveys. Engineering methods for power load [11] and thermal load [100] calculate the explicit energy demand of each energy component of individual building, relying on the physical properties of buildings components and characteristics of systems. There are also many case [34] that combined statistical and engineering methods for estimation of energy demand.

Table 2 lists the examples of the main simulation models for energy demand at cluster level. It is observed that most existing models simply evaluate energy demand of buildings in an isolated manner, which don’t include all major energy subsystems in one model, such as buildings, transports, electricity and heat networks, etc. Energy demand is rarely evaluated in a comprehensive and systematic manner. Such narrow sectoral approaches would underestimate the energy demand for exclusive against shared energy resources, and fail to identify the overall patterns of urban energy demand with respect to consumers. This would further result in the unreliable predictions and poor management decisions regarding the energy demand, which may lead to enormous waste in energy distribution and infrastructure investment.
7. Integrated cluster-scale energy systems

Most of these RES solutions have been extensively applied alone at building scale, while some researchers have yet started to explore a wider integrated application in energy generation and energy use reduction at cluster or district scale, as well as the corresponding influence on energy storage and grid distribution [17]. Li and Wen [11] proposed a net-zero building cluster emulator that can simulate energy behaviors of a cluster of buildings and their distributed energy devices as well as exchange operation data and control schemes with building systems; the emulator was developed for four simulation modules: building module (by EnergyPlus), ice tank module (EnergyPlus), PV-battery module (by TRNSYS), and operation module (by MATLAB and BCVTB); they demonstrated a proof-of-concept case to illustrate the possible ways for simulation of complex multi-energy systems at cluster level. The similar work were also conducted by Hachem et al. [110] who applied EnergPlus to assess energy demand of a cluster buildings and used TRNSYS to estimate electricity generation from BIPV. Protopapadaki and Saelens [111] developed a model to assess the impact of heat pump and PV on residential low-voltage distribution grids as a function of building and district properties in a probabilistic way, though the combined approaches of Monte Carlo method, Modelica-based thermal-physical model and three-phase unbalanced loading of the grid network, as well as stochastic occupant behavior model; they indicated that air-source heat pumps have a greater impact on the feeders than PV, in terms of loading and voltage magnitude, and building characteristics prove high correlations with the examined grid performance indicators. Fig. 12 reveals the schematic of their modelling approach.

Hsieh et al. [108] compared the solar thermal systems together with storage from building to a cluster scale of 11 buildings in Switzerland; all the relevant system components, including the buildings energy demand, solar thermal collectors, electrical heaters, storage tanks, and district-heating network were modelled using EnergyPlus, the simulation results depict that the building-level long-term storage configurations perform best over all other system configurations, in terms of solar fraction and system efficiencies. The location of the thermal storage and the separation of short and long-term storage are crucial that affect the performance of building-level renewable energy sources, and thus merit further investigation. Letellier-Duchesne et al. [109] describes a simple 3 step modelling workflow, illustrated in Fig. 13, to balance demand and supply, by integrating cluster-level building load calculations with detailed district energy network analysis models. In their study, they considered a comprehensive heat plants, including solar thermal collectors, heat pump, combined heat & power (CHP), natural gas boilers, heat network and hot water storage. Their model was depending on a Rhinoceros-based plugin (based on Radiance and EnergyPlus) and TRNSYS that targets a network topology optimization, a heat cogen-eration scenario and economic analysis. They foresee this methodology demonstrate a new way of designing for future 4th generation district energy systems in accordance with the concept of RES solutions.

Pinto and Graça [112] presents a study of energy refurbishment measures and a direct geothermal powered district heating system for a cluster of existing residential buildings in Groningen, Netherlands; in the study, they considered the retrofit measures including the improved envelope thermal insulation (walls, roof and windows), the reduced infiltration heat losses and the upgraded boiler. The study uses detailed thermal simulation models in EnergyPlus that rely on accurate building typologies and thermal characteristics, outdoor air infiltration data and occupant behavior profiles. The predicted energy savings and costs show that both the geothermal and the energy refurbishment approaches are economically viable and result in large reductions in the environmental impact of space heating. Applying all refurbishment measures results in an 86% reduction in yearly gas consumption for heating with an investment payback time of fifteen years.

Guen et al. [113] simultaneously optimized the procedures of the integration of renewable energy technologies and building retrofit at a cluster scale in Hemberg, Switzerland; they developed a computational platform, displayed in Fig. 14, by combining software CitySim, HOMER Pro, QGIS and Rhinoceros. The study began with collecting basic information for the buildings using QGIS which is an open-source geographic information system (GIS). The 3D geometries of the buildings in

![Flowchart showing the 3 steps of the methodology](image)
the village are modelled using Rhinoceros, based on the information from QGIS. This is done to prepare the DXF data files as input for CitySim Pro, a building/urban energy simulation tool (citysim.epfl.ch). CitySim Pro is then used to simulate the energy flow of the building stock in the village, including physical properties of the buildings, infiltration rate, occupancy profile, outdoor materials etc. CitySim considers the interaction among buildings, i.e. mutual shadings, and the outdoor radiative environment. HOMER is then used to analyze the renewable energy integration and the energy system improvements. Renewable energy potential, demand for multiple energy services, technical details for energy conversion measures (e.g., insulation of roof, floor walls and windows), market prices of system components, etc. are the input data. The energy demand of buildings (heating and cooling), as well as the electricity produced by renewable energy sources (e.g. BIPV, heat pumps) are the inputs for HOMER. The results show that retrofitting of all buildings after retrofit reduces the space heating demand by 70–85% and reduces the fluctuations in energy demand, thereby allowing the integration of more renewable energy.

### Table 3

<table>
<thead>
<tr>
<th>Modelling approaches</th>
<th>Solar power solutions</th>
<th>Solar thermal solutions</th>
<th>Energy-efficient solutions</th>
<th>Cluster-level energy systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>EnergyPlus + TRNSYS [110]</td>
<td>✓</td>
<td>Possible</td>
<td>Possible</td>
<td>✓</td>
</tr>
<tr>
<td>Mont Carlo method + Modelica-based thermal-physical and grid models + stochastic occupant behavior model [111]</td>
<td>✓</td>
<td>Possible</td>
<td>Possible</td>
<td>✓</td>
</tr>
<tr>
<td>Rhinoceros-based plugin (based on Radiance and EnergyPlus) + TRNSYS [109]</td>
<td>Possible</td>
<td>✓</td>
<td>Possible</td>
<td>✓</td>
</tr>
<tr>
<td>EnergyPlus + measured data + statistical occupant behavior data [112]</td>
<td>Possible</td>
<td>Possible</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>A computational platform combining software CitySim, HOMER, QGIS and Rhinoceros [113]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CityBES platform based on EnergyPlus [103]</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>EnergyPlus + MILP with optimization [115]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mathematical model + linear interactive and general optimizer (LINGO 15.0) [103]</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Note: ‘✓’ means that there are existing examples in the literature. ‘possible’ means it is possible to use the dedicated models in the respective field, even there is no existing example in the literature.

![Fig. 14. Overview of the approach for assessing building retrofit and energy system improvements [113].](image)

![Fig. 15. An example of energy hub concept at building cluster level (by modifying figure in [32]).](image)
According to the simulations, BIPV panels have potential to cover the total annual energy demand of the village. However, the energy system assessment shows that it is difficult to reach beyond 60% when integrating non-dispatchable renewable energy.

Chen et al. [114] developed a City Building Energy Saver (CityBES) platform, in order to simulate urban building energy system during large-scale building retrofitting, using EnergyPlus based on cities’ building datasets and user-selected energy conservation measures, such as energy-efficient windows. CityBES is a bottom-up physics-based detailed energy modelling of every individual building retrofit in a city or district/cluster. There are three layers in the platform: the data layer, the simulation engine (algorithms) and software tools layer, and the use-cases layer. It also provides a 3D visualization with GIS including color-coded simulated site energy use intensity (EUI), which facilitates the energy planning of different stakeholders at the early stage.

Wu et al. [115] conducted a multi-objective optimization of energy systems and building envelope retrofit in a residential community. In their work, building energy systems and envelope retrofit are optimized simultaneously in a bottom-up approach. Dynamic building energy demand is simulated in EnergyPlus, combined with a mixed-integer linear program (MILP) optimization to select retrofit strategies, and size and simulate the operation of different types of energy systems. Interactions between retrofit and building systems, such as the need to replace the windows, insulations, heat distribution system for low-temperature heating technologies at low retrofit levels, are taken into account. The life cycle GHG approach includes embodied GHG emissions in retrofit materials, and differentiates between PV and grid electricity impacts for all electric conversion systems, including heat pumps. Promising retrofit and energy system strategies are explored by scaling typical building strategies to the cluster level. The proposed method can be divided into four steps.

Wu et al. [103] presents a nonlinear model for the optimization of a neighborhood-scale distributed energy system considering both supply and demand sides. They developed the specific mathematical model by considering four modules, namely energy demand simulation, energy supply characterizing and dispatch, constraint analysis as well as...
optimization objectives of primary energy saving ratio, energy cost, and CO₂ emissions. The optimization is based on the commercially available solver linear interactive and general optimizer (LINGO 15.0), which aims at solving the following issues: how will the system combination and building mix be best suited to each other from the energy saving viewpoint; and when land use cannot be changed in an existing district, what will be the best system combination and the optimal heating/cooling transmission network for the building mix.

Table 3 presents an example of the existing modelling approaches for RES solutions and their complex energy systems in cluster level. From these studies, we observe that at cluster level: (1) most studies reply on the existing bottom-up engineering-physical simulation tool/approaches (i.e. EnergyPlus, TRNSYS, Modelica) for estimation of energy demand, owing to in the limitation in obtaining reliable energy load profile and the complexity in prediction required by high-capacity computation; (2) most of studies focus on single objective, i.e. energy saving, while a few of them start to propose multi-objectives functions, such as energy use, economic and environmental indexes, in which optimization algorithms are necessary; (3) most studies only assess part of the energy systems, such as PV and battery, solar heat and thermal storage, RES supply and grid. An integrated evaluation of all the four layers of energy systems in a cluster level, i.e. supply, demand, storage and distribution, is therefore required. A solution for this, ‘energy hub’, has been proposed by several researchers, which will be discussed more in the following section. In addition, upon literature searching, we have not yet found any research addressing the overall spatio-temporal energy system in a cluster that including both building and transportation, which are usually investigated in a separate way [33,116]. These restrict a comprehensive characterization of energy systems in cluster as a whole. According to Section 5, there are a few studies that start to consider spatio-temporal energy demand [33,34]. Thus, one of future challenge in cluster level will be the integrated assessment of spatio-temporal energy systems. An energy hub concept could be the breakthrough point to this challenge.

8. Energy hub

8.1. General concept

Energy hub is considered here as an effective means to closely integrate multi energy systems of different energy carriers through RES/DES convertors, energy distribution and storing components in an optimal manner for various energy use within building clusters [32]. The energy hub could also become the “filling station” for individual or collective autonomous, shared electric or biogas vehicles; within a cluster, the vehicle could be better used and play several roles: mobility, energy transport, office, even living room [117]. Energy hub is a node in overall urban energy system with multiple input and output energy vectors and typically consist of a more elaborate and complex internal arrangement of components, as shown in Fig. 15. The benefits of this close integration are identified as increased reliability, load flexibility and efficiency gains through synergistic effects [118], which suits well in building cluster. Energy hub is also regarded as a practical way to offer more services by sharing and interconnecting household devices so as to reduce the carbon impact of new systems [106]. Thus, energy hub is not a single entity containing all necessary systems for transformation, conversion, and storing of energy, but an amalgam of individual energy consumers and producers distributed over an area. This allows to take into account variable loads, systems, and energy sources of multiple buildings in diverse alternative paths [52].
8.2. Modelling and optimization

The modelling concept of an energy hub describes the interactive relation between input and output energy flows, which can be applied to optimize the energy use and local generation during planning and operation. Existing efforts towards the optimal management of energy hubs have been observed in several studies. Geidl et al. [119] firstly proposed energy hub concept in 2007 by illustrating essential components and main functions; they envisioned energy hub will be a key element for future complex urban energy network. Orehounig et al. [107] integrated the decentralized energy systems based on the energy hub concept in cluster of 29 buildings, including decentralized and local energy technologies such as PV, biomass, or small hydro power, together with district heating systems, building and district conversion and storage technologies; as a result, RES generation, energy supply systems and local energy storage systems can be evaluated in a combined way. The mathematical model of an energy hub is combined with optimization techniques, and balances energy supply and demand in the system boundaries with different design objectives, such as energy use, life-cycle CO$_2$ emission and cost. The method requires a three-step approach, shown in Fig. 16: (1) estimation of demand, (2) estimation of renewable potential, (3) matching of demand and supply. The energy balance between inputs and outputs within certain constraints is the key principle, defined by Eq. (1).

\[
\begin{bmatrix}
L_{\alpha} \\
L_{\beta} \\
\vdots \\
L_{\omega}
\end{bmatrix}
= 
\begin{bmatrix}
C_{\alpha,\alpha} & C_{\alpha,\beta} & \cdots & C_{\alpha,\omega} \\
C_{\beta,\alpha} & C_{\beta,\beta} & \cdots & C_{\beta,\omega} \\
\vdots & \vdots & \ddots & \vdots \\
C_{\omega,\alpha} & C_{\omega,\beta} & \cdots & C_{\omega,\omega}
\end{bmatrix}
\begin{bmatrix}
P_{\alpha} \\
P_{\beta} \\
\vdots \\
P_{\omega}
\end{bmatrix}
\tag{1}
\]

In this equation \([L_{\alpha}, L_{\beta}, \ldots, L_{\omega}]^T\) denotes the hub-output vector, \([P_{\alpha}, P_{\beta}, \ldots, P_{\omega}]^T\) the hub-input vector, and the \(C\) terms make up the converter coupling matrix, where \(\alpha, \beta, \ldots, \omega\) are the different energy carriers and \(T\) is the time. The models of different energy carriers were then developed by Orehounig et al. [107] using bottom-up approaches, respectively, and resolved/optimized them together using Eq. (1) for defined objectives. They simplified the optimization problem as a linear programming problem and the optimization was carried by optimization toolbox in MATLAB. Similar work have been done based on the energy hub concept in cluster, by integrating RES solutions, energy systems and building envelope retrofit, through engineering-physical simulation tool/approaches, operation/control strategies and dedicated optimization solvers, such as CitySim/HOMER [113], MILP framework [115], mixed integer non-linear programming (MINLP) framework [120] and linear coupling matrix [121].

Kuang et al. [122] proposed a collaborative decision model to cooperatively operate building and electric vehicles (EV), based on a similar energy hub concept displayed in Fig. 17, which consists of thermal and electric storage system, combine cooling, heating and power system, PV panel, and a EV charging station. A bi-objective MILP problem was then formulated to study the energy exchange between the building and the EV charging station, in order to minimize the operational cost for the building and the EV charging station simultaneously. They employed a weighted sum approach to solve the multi-objective MILP to obtain Pareto operation decisions for trade-off analysis between the building and the charging station.

Financial and environmental benefits of energy hub have also been investigated [123,28]. For instance, Moghaddam et al. [124] set up the optimization objective as total profit made by energy hub to supply cooling, heating and electricity to building, indicated in Fig. 18; they implemented the MINLP model in GAMS optimization software and solved using the ‘DICOPT solver for MINLP problems. Similarly, Taşkıncıaroğlu [125] considered the objective of the optimization problem in a cluster-level energy hub from the perspective of the household owners’ benefit, by minimizing the total cluster energy cost based

Fig. 20. Typical modelling process for energy hub at building scale.
on a net-metering approach. Davatgaran et al. [126] developed a MILP model to maximize the profit of an energy hub in day-ahead energy market, including electricity selling/buying and the operational cost, using model predictive control (MPC). Roldan-Blay et al. [127] proposed a new distributed energy resource optimization algorithm (DEROP) for energy hub to minimize energy costs by maximizing RESs generation and optimizing the management of energy storage system by non-linear functions; the DEROP algorithm, connecting SQL Databases with real-time data, was executed by VBA code and Microsoft Excel Worksheets were applied to show graphical results.

The optimization problem is usually set up to minimize the total energy cost in the system, within a deterministic framework of load demands, prices, efficiencies and constraints [128]. However, above studies mostly used steady-state parameters as the performance characteristic of energy components in energy hub. Off-design condition performance and non-steady state condition performance have seldom been considered. But optimization of an energy hub with multi energy systems and multi energy carriers is complicated in practice, which has a considerable number of variables that makes a non-linear, non-convex, non-smooth, and high-dimension optimization problem and the optimal solution cannot be achieved by conventional numerical techniques. Therefore, evolutionary algorithms are proposed, such as fuzzy decision making and teaching-learning based optimization algorithm [129,130], multi agents system (MAS) (see Fig. 19) [131], self-adaptive learning with time varying acceleration coefficient-gravitational search algorithm (SAL-TVAC-GSA) [132], robust optimization [128] and memetic algorithm [14].

The energy hub concept is fairly new, it represents an interesting avenue for managing the complexity of multi-energy systems at the cluster level. Studies that give attention to this with a futuristic view on multi-carrier energy systems and achieving energy matching are still lacking. Fig. 20 lists the modelling process of an energy hub and Table 4 summarizes the examples of modelling, control and optimization of an energy hub. It is observed that most studies simplified the energy models of components within the energy hub, and formed non-liner functions under dedicated control strategies (i.e. non-linear control, MPC, scheduling, optimal control, fuzzy logic control, and multi-agent control, etc.) for single or multi-objects, i.e. energy, cost and carbon emissions. MILP is found as the most common way to define steady-state energy hub operation, which can be solved, for instance, by the optimization toolbox in MATLAB. While for dynamic energy flows in an energy hub, advanced optimization algorithms have been proposed for operation and control with complex interactions among components, such as multi-agent systems. Very few studies [122,133] integrated EVs as part of the energy flow within an energy hub. Energy demand estimation in existing studies was unfortunately over simplified, such as ignore of aggregated demand [134]. Future integration of detailed energy demand models described in Section 5 and Section 6 is strongly

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### Table 4

Examples of modelling and optimization of energy hub.

<table>
<thead>
<tr>
<th>Main input</th>
<th>Essential models</th>
<th>Control and optimization method/tool</th>
<th>Objectives</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Building geometry</td>
<td>- Energy demand model</td>
<td>a design platform consisting of several existing (commercial and open source) tools, such as QGIS, Rhinoceros, CitySim HOMER</td>
<td>- Energy</td>
<td>[113]</td>
</tr>
<tr>
<td>- Building details</td>
<td>- PV generation model</td>
<td></td>
<td>- Cost</td>
<td></td>
</tr>
<tr>
<td>- Efficiencies</td>
<td>- Wind power model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Weather conditions</td>
<td>- Conversion model, i.e. heat pump, boiler, CHP, PV, wood</td>
<td>Model predictive control: mixed integer linear program (MILP), such as optimization toolbox in MATLAB, McCormick relaxation</td>
<td>- Energy</td>
<td>[107,136]</td>
</tr>
<tr>
<td>- Occupancy</td>
<td>- District heating network model</td>
<td></td>
<td>- Cost</td>
<td></td>
</tr>
<tr>
<td>- Equipment</td>
<td>- Battery and thermal storage</td>
<td></td>
<td>- CO2 emissions</td>
<td></td>
</tr>
<tr>
<td>- Building details</td>
<td>- Energy demand models</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Weather data</td>
<td>- Energy potential model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Electricity demand measurement</td>
<td>- Energy prices</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Efficiencies</td>
<td>- Carbon generation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Prices</td>
<td>- CHP generation system</td>
<td>Nonlinear operational scheduling: mixed integer non-linear program (MINLP) optimized in GAMS software using DICOPT solver</td>
<td>- Profit (cost)</td>
<td>[124]</td>
</tr>
<tr>
<td>- Share ratio</td>
<td>- Electric heat pump</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Demands</td>
<td>- Absorption chiller</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Energy</td>
<td>- Electrical energy storage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Thermal energy storage</td>
<td>- Natural gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Natural gas sub-network</td>
<td>- CHPs and boilers</td>
<td>Fuzzy logic control and teaching-learning based optimization algorithm (based self-adaptive mutation wavelet) using IEEE 30-Bus and 57-Bus systems</td>
<td>- Cost</td>
<td>[129,130]</td>
</tr>
<tr>
<td>- Electric power plant</td>
<td></td>
<td></td>
<td>- CO2 emissions</td>
<td></td>
</tr>
<tr>
<td>- Device ratings</td>
<td>- Hub agent</td>
<td></td>
<td>- Cost</td>
<td></td>
</tr>
<tr>
<td>- Carbon generation</td>
<td>- Technical Aggregator agent</td>
<td></td>
<td>- CO2 emissions</td>
<td></td>
</tr>
<tr>
<td>- Prices</td>
<td>- Storage models: hydrogen storage, heat storage Transformer model</td>
<td></td>
<td>- Energy demand</td>
<td></td>
</tr>
<tr>
<td>- Operation scheduling</td>
<td>- CHP model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Prices</td>
<td>- Gas Furnace model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Heater Exchanger model</td>
<td>- Compressor air storage model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Temperature</td>
<td>- Energy demand model</td>
<td>Pareto optimal control and Memetic algorithm in MATLAB</td>
<td>- Cost</td>
<td>[14]</td>
</tr>
<tr>
<td>- Solar radiation</td>
<td>- Chiller model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Price</td>
<td>- Ice storage model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Battery model</td>
<td>- PV generation model</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
expected. In addition, future studies of energy hub at building cluster level, as planned in Fig. 21, must consider beyond existing energy systems/carriers, such as different architypes of buildings, RES envelope solutions, EV spatial demand and circular economic etc, maximizing the synergies of all these components.

9. Discussion and future work

9.1. Discussion of the review work

This review work concentrates on building cluster modelling technique. It explains the importance of such method in current urban energy system and characterizes the corresponding features by addressing the main influencing factors. The factors defined as important for building cluster characterization could be grouped in three main areas of interest: grid, RES production, and building. Among these, we recognize the main interesting factors as mostly influencing the cluster energy performance, including RES envelope solutions, solar energy potentials, density of building, energy demand, integrated cluster-scale systems and energy hub. Fig. 22 highlights the most important findings of this review paper by a knowledge based matrix and they are elaborated as below.

Based on the review work, the building cluster modelling is regarded as one of the most important approaches to assess contemporary transit of urban energy system. At this level, a group of buildings can systemically exchange the energy information either in a synergic or a disruptive way, where the existing modelling techniques and capacity are sufficient. Thus, simulations at this level can be applied to evaluate the detailed interaction between buildings and energy infrastructures, as well as the impact of adoption of RES envelope solutions. The building cluster modelling allows a potential shifting of building from a single energy efficient unit to an interconnected prosumer, therefore maximizing the synergies among RES application in buildings and energy systems. This will further reduce the operation cost of RES solutions and result in a wider application.

The spatio-temporal dimension is recommended for energy simulation at cluster scale in the next a few years. Owing to the complexity of energy systems and the limitation of computations, the optimal spatial dimension may range between 100 m and 1 km, while time scale should be reduced down towards minutes or even seconds level if both electricity and heat networks are integrated in the same model. Density of building blocks are generally in the range of: 0.11–0.69 (plan area density), 0.12–0.33 (frontal area density), 1.5–2.5 (floor area ratio). In general, higher density of building results in greater energy use, but it also depends on specific planning and design, urban spatial structure, policy, economic and environmental issues, geographical and cultural contexts, such as demographic, socioeconomic, behavioral, and property-related characteristics.

Solar energy is the most important available renewable resource at the building cluster level, especially in EU building retrofit context, which is directly affected by the density of buildings in the city. Most of the RES envelope solutions are derived from solar and air resources, such as BIPV, BIPV/T, STF, heat pump, heat recovery, DSF, insulation, PCM, green roof/wall, energy frame, algae bioreactor façade, and adaptive facades. The preferred methods available for obtaining reliable spatio-temporal solar irradiance data in building cluster simulations are either any of the data upscaling methods, which can be applied if at least irradiance or PV system data from one or a few sites in
The modelling techniques for energy demand of building clusters can be categorized as top-down (statistical methods) and bottom-up approaches (statistical/data-driven methods, engineering/physical methods, or combined methods). Most of them simply evaluate energy demand of buildings in an isolated manner, without comprehensive consideration in transports and synergies of energy exchange among architype/EVs. When coming to the complex energy system or energy hub level, commercialized simulation tool (i.e. EnergyPlus, TRNSYS, Modelica) or simplified model are the most common ways for estimation of building energy demand, where most studies focus on (1) control/operational strategies, i.e. non-linear control, MPC, scheduling, optimal control, fuzzy logic control, and multi-agent control, etc., and (2) optimization approaches, i.e. MATLAB optimization toolbox, teaching-learning algorithm, multi agents system, SAL-TVAC-GSA, robust optimization and memetic algorithm etc. These studies intent to carry out the integrated investigation of various energy resources and energy carriers within cluster, such as RES envelope solutions, CHP, biomass boilers, batteries, thermal storages, chillers, heat pumps, hydrogen plant, EVs, district networks, and natural gas. The most common objectives for evaluation of these integrated energy systems are reduction of energy use, carbon emissions and costs.
9.2. Future work

RES share is increasing rapidly when urban energy systems incorporate multiple energy sources. The successful integration of multiple RES envelope solutions relies not only on the energy performance of individual buildings (especially retrofitted ones), but also on optimal technologies for conversion, storage, and distribution. The modern urban energy systems consist of different levels of complexity. At the moment, it is difficult to conduct a comprehensive assessment of energy efficiency, renewable energy integration, and energy system improvements for the entire city. Build cluster approach is therefore regarded as one of the breakthroughs. Fig. 23 depicts the basic steps for such approach based on the work in this paper. A physical cluster scale must be initially determined so that the density of buildings can be estimated for assessing RES potentials. By doing so, appropriate RES envelope solutions can be finalized according to their energy generation potentials, which is further linked to energy demand, cluster-level complex energy systems/energy hub and district/urban energy systems. However, available studies are generally limited in their scope as they do not consider all the steps and components together. In the following paragraph, we put forth a few suggestions for incorporating RES envelope solutions, in order to decrease energy cost, and reduce the carbon footprint of the neighborhood.

The combined method of facade area ratio and full spatio-temporal statistical model for solar irradiation would be effective way to estimate the potential power generation of RES envelope, such as BIPV. A surface area ratio is more straightforward to estimate the total available façade areas at building cluster level, which, in return, results in a more accurate solar mapping of RES envelopes. The full spatio-temporal statistical model, such as machine learning, allow the generation of solar irradiance time series at multiple site scale, as a cost-effective and reliable way suiting for building cluster.

High-resolution of energy flow profile: (1) owing to the difference in time required for building components/envelopes and energy system/flow, it is suggested that the time steps required to solve the energy matching should be reduced down towards minutes or even seconds level; (2) the basic model is often used for the optimal energy trade off among group of buildings or from an energy hub for multi-energy carriers, in which the energy flows through the hub are optimized for a single specific period with peak energy demand or annual energy use; in the future, more advanced problems must be defined in terms of transient time series of energy flow capacities in cluster-level energy systems or energy hub.

Spatio-temporal energy demand: most existing models simply evaluate energy demand of buildings in an isolated manner, without comprehensive consideration in transports and synergies of energy exchange among architypes/EVs; there is a need to include building function/location, urban inhabitant behavior in terms of activities and mobility in the models.

Detailed engineering/physical and statistical models in complex energy systems or energy hub using new optimization algorithms: (1) most studies reply on the existing commercialized simulation tool or simplified model for estimation of energy demand in complex energy systems and energy hub, where energy demand estimation is unfortunately over simplified and it needs more detailed models, such as the combined engineering/physical and statistical models; (2) this, however, will result in more complicated non-linear functions that requires new optimization algorithms under dedicated control and operation framework, such as multi agent systems.

Multi-objective optimization of cluster-level energy systems or energy hub: (1) the direct benefits, i.e. reduction of energy use, carbon emissions and costs, are usually the three key indicators for cluster-level energy systems and energy hub; co-benefits are also important to evaluate, such as indoor air quality, thermal comfort, less risk exposure to future energy price increases and so on, represented in Fig. 24; (2) in addition, further scenario-based optimization of energy systems is expected to address uncertainty and risk of energy exchange within the cluster and semantic-interoperability based energy patterns, as well as geographical and cultural contexts, such as demographic, socio-economic, behavioral, and property-related characteristics.

10. Conclusion

The wide-spread implementation of renewable-energy-source (RES)
envelope solutions brought about new challenges to urban energy systems. It not only delivered a new paradigm of energy flow profiles and new requirements for energy matching within complex energy systems, but also uncertainties and risks in energy supply. We conclude that energy planning at building cluster scale has a potential to deliver a breakthrough in this regard. This approach fosters the economic effectiveness and the operation feasibility to maximize distributed renewable energy harvesting, while at the same time match the respective energy demand and supply. The suitable spatial boundary of a building cluster modelling is between 0.1 and ~1 km in diameter, while a temporal scale of minute or second should be realistic within the next a few years. The methodology for building cluster modelling should be comprehensive, consisting of the following three aspects.

Energy supply: assessing the solar energy generation potential within the boundary by combing density of the buildings and upsampling methods or semi-physical model, since most of the existing RES envelope solutions are derived from solar (air) resources at building cluster level.

Energy demand: considering integrated energy demand in transports and syntergeries of energy exchange between buildings and energy infrastructures by using tools (software) such as EnergyPlus, TRNSYS, Modelica or self-developed ones.

Energy operation: optimizing the operational performance of the integrated energy systems at cluster level by focusing on control strategies (i.e. non-linear control, model predictive control, scheduling, optimal control, fuzzy logic control, and multi-agent control etc.) and multi-objective optimization (i.e., MATLAB optimization toolbox, teaching-learning algorithm, multi agents system, self-adaptive learning, robust optimization and memetic algorithm etc.) for reduction of energy use, carbon emissions and operational costs.

The paper raised important research questions and identified important factors influencing urban energy systems at the building cluster scale. It finally put forward several directions for future research development: (1) combining facade area ratio and full spatio-temporal statistical model for solar irradiation, (2) increasing the resolution of energy flow profile, (3) acquiring spatio-temporal energy demand, (4) developing detailed physical and statistical models in complex energy systems/energy hub using new optimization algorithms, and (5) proposing multi-objective optimization of the cluster-level energy systems or the energy hub.

The outputs of the review are useful the simulation and optimization of urban energy systems incorporating RES envelope solutions, which facilitate the transition to sustainable and resilient urban energy systems.

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